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LASER DIAGNOSTICS OF GAS TURBINE FUEL SPRAYS;
SCALING EFFECTS ON NO_x EMISSIONS AND STABILITY

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ABSTRACT

This thesis first provided strategic recommendations for the research sponsor, Rolls-Royce plc (RR) and then applied optical diagnostics to measure aero gas turbine fuel spray properties in order to predict Oxides of Nitrogen (NO_x) emissions and combustion instability. Analysis of the large civil aero engine sector suggested possible courses of action for RR to protect itself from short-term market volatilities and also prepare for three long term changes in strategic operating context: air traffic growth; tighter United Nations enforced aero engine combustion emissions legislation and entry of civil aviation into the European Union Emissions Trading Scheme. A collaborative game theoretic approach was explored during the pre-competitive, pre-technology, capability acquisition aero engine design phase on unproven future technologies to reduce R&D expenditures, development times and the costs of failure. Lean Prevapourised Premixed combustion demands excellent spray atomisation quality to sustain combustion efficiency, stability and to minimise pollutants. Post development of an improved procedure to calibrate laser signals, methodology to predict NO_x and technique to optimise rig operating conditions that minimised fractional discrepancies in two-phase flow behaviour with corresponding engine conditions, this thesis applied quantitative Planar Laser Induced Fluorescence (PLIF) and Laser Sheet Dropsizing (LSD) to measure the fuel placement and dropsize distribution in the near nozzle regions of RR liquid-fuelled hybrid, airblast and pressure-swirl sprays. Measurements were made under non-combusting, low pressure conditions and results were processed to identify fuel injector designs that exhibited low emissions and high stability for the Affordable Near Term Low Emissions (ANTLE) and Instability Control of Low Emission Aero-Engine Combustors (ICLEAC) engine demonstrator programmes. Results also provided validation data and boundary conditions for spray computational codes. Research findings will improve RR core competencies in fuel injection research to accelerate the development and deployment of low emissions aero engine technology.

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ACRONYMS

AC	Alternating Component
ACARE	Advisory Council for Aeronautics Research in Europe
AFC	Asian Financial Crisis
AIG	American International Group
ANTLE	Affordable Near Term Low Emissions Engine
ArF*	Argon Fluoride Excimer Molecule
ASE	Amplified Stimulated Emission
BA	British Airways
BAe	British Aerospace
BMW	Bayerische Motoren Werke AG
CAEP	Committee on Aviation and Environmental Protection
CAEP1	Combustion Emissions Legislation Limit in 1986
CAEP2	Combustion Emissions Legislation Limit in 1996
CAEP4	Combustion Emissions Legislation Limit in 2004
CAEP6	Combustion Emissions Legislation Limit in 2008
CC	Chicago Convention
CFMI	CFM International
CLIPS	Cranfield Laser Image Processing Software
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
DAC	Dual Annular Combustor
DC	Direct Component
EA	Engine Alliance
EC	European Commission
EC	Expected Costs
EOS	Economies of Scale
ER	Expected Revenues
ETS	Emissions Trading Scheme
EU	European Union
FAA	Federal Aviation Authority
FT	Fischer-Tropsch
FTSE	Financial Times and London Stock Exchange
GASEQ	Chemical Equilibrium Programme
GBP	Pound Sterling
GCC	Global Climate Change
GDP	Gross Domestic Product
GE	General Electric
GS	Goldman Sachs

H1N1	Influenza A Swine Flu Virus
H ₂	Hydrogen
H ₂ O	Water
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
He	Helium
HOMREA	Simulation Code for Homogeneous Reaction Systems
IAE	International Aero Engines AG
IATA	International Air Transport Association
IBM	International Business Machines
ICAO	International Civil Aviation Organisation
ICCD	Intensified Charge Coupled Device
ICLEAC	Instability Control of Low Emissions Aero Engine Combustors
ILFC	International Lease Finance Corporation
IR	Infrared
IPCC	Intergovernmental Panel on Climate Change
ITP	Industria de Turbo Propulsores SA
JAEC	Japanese Aero Engines Corporation
KHI	Kawasaki Heavy Industries
KrF*	Krypton Fluoride Excimer Molecule
LAC	Long-Run Average Costs
LAQ	Local Air Quality
LII	Laser Induced Incandescence
LMC	Long-Run Marginal Costs
LMR	Long-Run Marginal Revenues
LPP	Lean Prevapourised Premixed
LPT	Low Pressure Turbine
LSD	Laser Sheet Dropsizing
LT	Long Term
LTO	Landing and Take-Off
MHI	Mitsubishi Heavy Industries
MRO	Maintenance, Repair and Overhaul
MSR	Main Sprays Rig
MT	Medium Term
M-Terphenyl	Meta-Terphenyl
N ₂	Nitrogen
N ₂ O	Nitrous Oxide
N ₂ O ₄	Nitrogen Tetroxide
N ₂ O ₅	Dinitrogen Pentoxide
ND	Neutral Density

NDP	Non-Dimensional Parameter
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
NO _x	Oxides of Nitrogen
O	Oxygen Atom
O ₃	Ozone
ODG	Optical Diagnostics Group
OH	Hydroxyl Radical
OLH	Ozone Layer Hole
ONS	Office for National Statistics
OPR	Overall Pressure Ratio
OQC	Order Qualifying Criteria
OWC	Order Winning Criteria
P	Price
P-Terphenyl	Para-Terphenyl
P&W	Pratt & Whitney
PC	Personal Computer
PDA	Phase Doppler Anemometry
PDF	Probability Density Function
PEST	Political, Economic, Social and Technological
PIV	Particle Imaging Velocimetry
PLIF	Planar Laser Induced Fluorescence
PMA	Part Manufacturing Authority
PPO	2,5 Diphenyloxazole
PSO	Public Service Obligation
Q	Quantity
R&D	Research & Development
RAM	Relative Atomic Mass
RF	Radiative Forcing
RMM	Relative Molecular Mass
RPM	Revolutions per Minute
RR	Rolls-Royce plc
RRD	Rolls-Royce Deutschland
S&P 500	Standard & Poor's Index (Canada)
SAE	Society of Automotive Engineers
SARS	Severe Acute Respiratory Syndrome
SFO	Serious Fraud Office
SNECMA	Société Nationale d'Étude et de Construction de Moteurs d'Aviation
SO _x	Oxides of Sulphur
SWOT	Strengths, Weaknesses, Opportunities and Threats

TLM	Turbomeca Lean Module
UFR	Unsteady Flow Rig
UHC	Unburnt Hydrocarbons
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USD	United States Dollar
UTC	United Technologies Corporation
UV	Ultraviolet
VW	Volkswagen
XeCl*	Xenon Chloride Excimer Molecule
XWB	Extra Wide Body

ROMAN SYMBOLS

Abbreviation	Description	Units
A	Amplitude	AFR/Pa or $\mu\text{m}/\text{Pa}$
A	Absorbance or Optical Density	
A_{Eff}	Effective Injector Area	m^2
A_{Nozzle}	Effective Nozzle Area	m^2
$\text{abs}/\text{ucert}_{\text{LSDK}}$	Absolute Uncertainty in LSD_K	%
$\text{abs}/\text{ucert}_{\text{PDA}}$	Absolute Uncertainty in PDA Measurement	%
$\text{abs}/\text{ucert}_{\text{Pixel Length}}$	Absolute Uncertainty in Pixel Length	%
$\text{abs}/\text{ucert}_{\text{PLIF, Mie}}$	Absolute Uncertainty in PLIF or Mie Signals	%
$\text{abs}/\text{ucert}_{\text{tSheet}}$	Absolute Uncertainty in Laser Sheet Thickness	%
AFR	Air to Fuel Ratio	
B_{PLIF}	Background in PLIF Image	
$B_{\text{Flatfield}}$	Background in Flatfield Image	
c	Local Sound Speed	m/s
c	Concentration	mol/l
C_c	Cunningham Slip Factor	
C_d	Discharge Coefficient	
C_{Mie}	Mie Constant	
C_{PLIF}	PLIF Constant	
d_2	PDA Diameter of Laser Beam After Expansion	m
d_f	Focal Diameter of PDA Control Volume	m
d_i	Diameter of Droplet i	
dg_i	Droplet Generator Case i	
d_y, d_x, d_z	PDA Measurement Volume	m
D	Orifice Disk Nozzle Diameter	m
D_{32}	Sauter Mean Diameter	m
D_h	Hydraulic Diameter	m
D_p	Prefilmer Diameter	m
D_p	NOx Emissions Quantity	g
E_{INOx}	Emissions Index NOx	g/kg
f	Focal Length	m
f	Focal Length of PDA Launch Optic	m
f_D	Doppler Frequency	Hz
F_{00}	Engine Thrust	kN
F_N	UK Fuel Flow Number	$(\text{UKgal}/\text{hr})/(\sqrt{\text{psi}})$
$H_{\text{Stream}_{\text{PLIF, Mie}}}$	Height of Droplet Stream in PLIF or Mie Image	m
I	Light Intensity After Travelling Through 1cm	

I_o	Initial Light Intensity	
K_{LSD}	LSD Collection Efficiency	
K_{PLIF}	PLIF Collection Efficiency	
l	Cuvette Path Length	m
L	Characteristic Length Scale	m
LSD_K	Laser Sheet Dropzising Calibration Constant	
LVF_K	Liquid Volume Fraction Calibration Constant	
Ma	Mach Number	
M_D	Droplet Mass	N
$\dot{m}_D$	Droplet Mass Flow Rate	kg/s
$\dot{m}_L$	Liquid Mass Flow Rate	kg/s
N	Number of Droplets	
n	Index of Dependence with Droplet Diameter	
NO_{Local}	Nitric Oxide Production	mg/kg
Oh	Ohnesorge Number	
p_D	Droplet Momentum	kgm/sec
P_c	Combustion Pressure	Pa
P_{up}	Air Pressure Upstream	Pa
P_{gauge}	Air Pressure Gauge	Pa
$P_{absolute}$	Air Pressure Absolute	Pa
$P_{atmospheric}$	Air Pressure Atmospheric	Pa
$\tilde{P}$	Fluctuating Component of Airbox Pressure	Pa
Q	Liquid Flow Rate	l/m or (g/s)
R	Gas Constant	J/kg/K
R	Deviation	
Re	Reynolds Number	
r_{LSD}	Path Length to Spray Centreline, LSD Set-up	m
r_{PLIF}	Path Length to Spray Centreline, PLIF Set-up	m
$S_{Flatfield}$	Flatfield Signal	
S_{Mie}	Mie Signal	
S_{PLIF}	PLIF Signal	
$S_{PLIF Pilot}$	PLIF Signal in Pilot Region	
$S_{PLIF Pilot + Main}$	PLIF Signal in Pilot Region With Main On	
$S_{PLIF Signal Loss}$	PLIF Signal Loss in Pilot Region Due to Main	
Stk	Stokes Number	
SMD	Droplet Sauter Mean Diameter	m
t_{Sheet}	Laser Sheet Thickness	m
T_a	Air Temperature	K
T_c	Combustion Temperature	K
T_{Input}	Combustor Inlet Temperature	K

$T_{Local\ Burnt\ Gas}$	Burnt Gas Temperature	K
T_{res}	Combustion Residence Time	s
t	Time	s
U	Global Air Velocity	m/s
U_D	Droplet Velocity	m/s
U_L	Liquid Jet Velocity	m/s
V_c	Combustion Volume	m ³
V_D	Droplet Volume	m ³
$W_{Stream_{PLIF, Mie}}$	Width of Droplet Stream in PLIF or Mie Image	m
We	Weber Number	
X	Downstream Distance from Injector Exit	m
Y	Spray Property: AFR or SMD	
$\tilde{Y}$	Fluctuating Component of Spray Property:	
$\bar{Y}$	Mean Value of Spray Property: AFR or SMD	

GREEK SYMBOLS

Abbreviation	Description	Units
$\Delta P/P$	Injector Pressure Drop	%
ΔP_L	Liquid Injection Pressure Diff. Across Nozzle	Pa
ϕ	Phase Lag Peak in Y wrt Peak in Air Pressure	°
$\emptyset$	Equivalence Ratio	
π	Profit	
θ	Siren Phase Angle	°
ω	Air Perturbation Frequency	Hz
ε	Molecular Absorptivity	m ² mol ⁻¹
θ	Angle Between PDA Beams	°
λ	Wavelength	m
λ	AFR _{Local} / AFR _{Stoichiometric}	
λ^*	PDA Fringe Spacing	m
μ_a	Air Absolute Viscosity	Ns/m ²
μ_f	Fuel Absolute Viscosity	Ns/m ²
π_{00}	Overall Pressure Ratio	
ρ_a	Air Density	kg/m ³
$\rho_{Burnt\ Gas}$	Density of Burnt Gas	kg/m ³
ρ_D	Droplet Density	kg/m ³
ρ_f	Liquid Density	kg/m ³
ρ_L	Fuel Density	kg/m ³
$\rho_{Unburnt\ Air}$	Density of Unburnt Air	kg/m ³
σ_L	Fuel Surface Tension	kg/m ³
$\Phi_{Airblast}$	Fractional Deviation: Airblast Atomisation	
Φ_{Hybrid}	Fractional Deviation: Hybrid Atomisation	
Φ_{PS}	Fractional Deviation: Pressure-Swirl Atomisation	
Φ_{LSD}	LSD Filter Efficiency	
Φ_{PLIF}	PLIF Filter Efficiency	

CHAPTER ONE

THESIS INTRODUCTION

In September 1928, Professor George Granger Brown, Chairman of the First Symposium on Combustion held in Massachusetts wrote: “Combustion is without exaggeration the most important reaction to the human race. All human and animal existence depends upon combustion as its source of energy. The first real progress man made in his ascent or descent from the anthropomorphic missing link depended upon his control of fire or combustion; and in many ways our further progress depends upon more intelligent and efficient control of combustion” (Brown, 1928). With heightened public attention driven by mass media on the topic of Global Climate Change (GCC), only recently debated in the Copenhagen Climate Change Summit in December 2009, increased scientific knowledge and worldwide governmental concerns do the eighty-one year old words of Professor Brown show deep foresight. Although combustion science largely advanced to meet military needs to conquer and commercial aspirations to create wealth, the third requirement to address GCC by reducing combustion-generated pollutants supersedes everything. In response to the ~3.2% yearly growth rate in civil aviation, the United Nations (UN) International Civil Aviation Organisation (ICAO), regulated by its Committee on Aviation and Environmental Protection (CAEP) will tighten combustion emissions legislation in 2012 to limit Soot, Unburnt Hydrocarbons (UHC), Carbon Monoxide (CO) and the Oxides of Nitrogen (NO_x). Further, the European Union (EU) Emissions Trading Scheme (ETS) will include civil aviation, also in 2012 to constrain Carbon Dioxide (CO₂) emissions. To prepare for these incoming changes in strategic operating context, Rolls-Royce plc (RR) has sponsored the work reported in this thesis to investigate fuel spray performance in hybrid and airblast atomisers to predict NO_x and combustion instability for two engine programmes:

- Affordable Near Term Low Emissions Engine (ANTLE)
- Instability Control of Low Emission Aero-Engine Combustors (ICLEAC)

This thesis had three chief objectives:

- To review the aero engine sector and suggest possible courses of action for RR
- Develop a methodology to predict Nitric Oxide (NO) emissions from sprays data
- Deliver fuel concentration and droplet size data to predict combustion instability

Chapter Two met the first research goal. It described the legislation-driven strategic need faced by the oligopolistic large civil aero engine sector to develop low emissions technology. This was followed by a financial health check of RR and its competitors; a

snapshot of RR market share; core strategy and commercial justification for the undertaken work. A comprehensive business analysis suggested courses of action that RR may consider to guard itself against periods of short-term market volatility and prepare for longer-term changes in strategic operating context. A collaborative game theoretic approach was explored during the pre-competitive, pre-technology, capability acquisition aero engine design phases on unproven future technologies to develop joint patents; reduce R&D expenditures; engine development cycles and the costs of failure. Technology transfer into a product would stay independent. This approach is expected to receive little opposition from competition authorities, strong political support and have far-reaching implications for the entire aerospace industry. It has therefore been recommended for publication in a strategic management journal pending RR approval.

The remainder of the thesis was devoted to meeting the second and third objectives. Three well-established laser diagnostics were calibrated to measure key spray properties under non-combusting, low-pressure, scaled rig operating conditions. The rig partially mimicked the confinement of a real combustion system and two-phase flow of the engine operating condition to some extent by using real injector hardware and a judicious choice of rig pressures, air and fuel flow rates to match key flow descriptors in the corresponding engine condition. Whilst it remained certain that spray behaviour appreciably differed in the absence of a flame; accurate combustor geometry and cooling airflows that change stretch factors and vortex shedding effects (Lefebvre, 1985) it was assumed to be similar in the very near nozzle spray regions and therefore a methodology was conceptualised, developed and implemented to correlate spray image data acquired using optical diagnostics with RR measurements of NO_x and instability.

Having set the need for rapid acquisition of low emissions technology, Chapter Three summarised pollutant formation in aero engine combustors, their environmental risks and conflicting abatement strategies that continue to antagonise low emissions aero engine design. The central section reviewed pressure-swirl and airblast atomisation and swirlers since these are integrated in the hybrid ANTLE Weak Modules characterised in this study. The chapter closed with a synopsis of the applied laser diagnostics. Phase Doppler Anemometry (PDA) and Laser Sheet Dropsizing (LSD) measured droplet Sauter Mean Diameter (SMD) and Planar Laser Induced Fluorescence (PLIF) gave fuel placement data that was subsequently translated into Air to Fuel Ratio (AFR) with applicable air and fuel densities and a calibration constant derived in the next chapter.

Chapter Four extracted calibration constants for quantitative SMD and AFR. First, it selected a fluorophor for PLIF measurements at 248nm. Second, it calculated the required fluorophor concentration for PLIF signals to gain a cubic dependence with droplet diameter. Third, it imaged a calibration plate to determine Intensified Charge

Coupled Device (ICCD) array pixel resolution and LSD image manipulation factors where pixels in PLIF images must be divided by corresponding pixels in elastically scattered Mie images. Fourth, an experiment was conducted to acquire a “flatfield” image to define the laser sheet region in LSD images and PLIF image correction factors to eliminate non-uniformities in laser sheet intensity distribution and ICCD intensifier pixel response. The last section was the most important. It applied PDA to measure the SMD of a monodisperse droplet stream from a piezoelectric droplet generator followed by PLIF and LSD imaging of the same streams to extract the necessary calibration constants, LSD_K and LVF_K for quantitative SMD and AFR measurements.

Application of quantitative data acquired at unrepresentative rig operating conditions, or indeed, qualitative data at representative conditions would have impeded any serious attempts to develop a successful correlation between spray properties and RR NO_x and combustion instability measurements. Hence, Chapter Five illustrated the importance of scaling strategy choice to evaluations of fuel spray performance. It investigated strategies that scaled engine operating conditions to the accessible range of temperatures, pressures, air and fuel flow rates within the non-combusting Unsteady Flow Rig (UFR) used in experiments. Good measurement practice demanded that the particular aspect of two-phase flow under measurement was similar between engine and rig operating conditions. A fractional deviation (Φ) was defined to quantify the similarity and hence the success of replicating key flow descriptors in both extremes. Several rig scaling strategies were tested to quantify the faithfulness of fuel patternation in pressure-swirl, airblast and hybrid atomisation to inform strategy selection. Although scaling airblast atomiser fuel sprays was reported in Jermy, Hussain and Greenhalgh (2003), a need now exists for a publication on scaling pressure-swirl and hybrid sprays.

Chapter Six applied LSD and PLIF to acquire qualitative SMD and AFR in the fuel sprays from five ANTLE Weak Modules in the Main Sprays Rig (MSR) under non-combusting, atmospheric pressure conditions. Two injectors were characterised to gauge the effect of several scaling strategies on fuel spray structure. PLIF images from four ANTLE Builds were used to develop the NO prediction method. This basically translated fuel placement data into AFR and equivalence ratio and then applied two commercial codes to predict NO. Experimental and data processing methods were significantly improved and advance warning was gained of a potential source of signal loss due to radiation trapping in pilot only regions when the main spray was introduced.

The foundation to meet thesis objectives had now been laid. Chapter Seven applied the laser signal calibration technique developed in Chapter Four; method to optimise rig operating conditions investigated in Chapter Five and practical image acquisition and data processing lessons learned from the atmospheric pressure measurements in Chapter

Six. PLIF was applied in the UFR to quantitatively measure fuel placement data in ANTLE Builds 34, 43 and 61; each with different injector areas and swirler angles, under non-combusting conditions at constant $\Delta P/P$ of 4%; rig pressures of 200 – 490kPa absolute; fuel flow rates of 0.42 – 0.90 l/m and injector AFRs of 28.4 – 72.3. Introduction of the main airblast fuel spray was indeed measured to have an optical and structural impact in the pilot pressure-swirl spray region. First, each dataset of fuel concentration and placement was averaged; background-subtracted; attenuation-corrected and flatfielded. Second, the LVF_K value calculated in Chapter Four was applied in conjunction with applicable air and fuel densities to generate two-dimensional maps of local AFR and equivalence ratio. Third, GASEQ (Morley, 1995) calculated local adiabatic flame temperatures. Fourth, spatial image resolution was used to calculate spray length. This was divided by Global Air Velocity (U) to estimate residence times. Fifth, the temperature and residence time data was input to HOMREA (Warnatz, 2000) to calculate NO formation as a function of injector design and combustor operating conditions. Finally, LabView fitted all the data and plotted charts of equivalence ratio, temperature and NO to correlate against RR NO_x measurements.

Chapter Eight fulfilled the third research objective. It measured the temporal response of airblast and pressure-swirl fuel injector sprays to acoustic perturbations in the airflow to screen injector designs for combustion instability characteristics fundamental to the ICLEAC programme. Results were reported in ICLEAC (2004), Jermy *et al* (2004a) with sanitised versions in Jermy *et al* (2004b) and Greenhalgh *et al* (2004). LSD and PLIF techniques were applied in the UFR to measure the SMD and AFR response in the fuel sprays from five RR airblast atomisers and one Turbomeca Lean Module (TLM). UFR operating conditions were $\Delta P/P$ of 5.07%, rig pressures of 249kPa absolute; fuel flow rate of 0.46 l/m and injector AFRs of 7.96 – 11.05. A siren located upstream of the injector was used to perturb the air supply. Phase-locked SMD and AFR measurements were made at sixteen measurement points, every 22.5° in the siren cycle at 12, 100 and 200Hz. Datasets were supplied to extract spray transfer functions. These described the relationship between combustion unsteadiness and operating conditions. The strength of the response to each modulation and quality of fit of the sinusoidal transfer functions was correlated against RR instability measurements. The opportunity was also taken to measure the forced response of a pressure-swirl fuel spray from ANTLE Build 61 at two low power conditions. UFR conditions were $\Delta P/P$ of 7.05%; rig pressures of 215 and 247kPa absolute; fuel flow rates of 0.49 and 0.60l/m and injector AFRs of 49 and 64.

Chapter Nine presented the major conclusions from the undertaken business analysis and technical work and closed with recommendations for further work.

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CHAPTER TWO

COMMERCIAL IMPLICATIONS OF AERO ENGINE R&D

2.1 INTRODUCTION

Civil aviation is expected to face three long-term changes in strategic operating context. First, growth in passenger aircraft numbers of ~3.2% per annum over the next twenty years. Second, the tightening in 2012 of United Nations (UN) International Civil Aviation Organisation (ICAO) combustion emissions legislation, regulated by its Committee on Aviation and Environmental Protection (CAEP) to reduce soot, Unburnt Hydrocarbons (UHC), Carbon Monoxide (CO), Nitric Oxide (NO) and Nitrogen Dioxide (NO₂), known collectively as the Oxides of Nitrogen (NO_x). Third, participation in the European Union (EU) Emissions Trading Scheme (ETS) from 1st January 2012 to cut Carbon Dioxide (CO₂) emissions. These changes will have substantial impacts on the large civil aero engine sector, shown in Figure 2.1 to be an oligopoly. This sector is essentially contested by three firms: the research sponsor, Rolls-Royce plc (RR) of the UK; General Electric (GE) of the US; and Pratt and Whitney (P&W) – a division of United Technologies Corporation (UTC), also of the US. Two prominent strategic alliances exist: International Aero Engines (IAE), formed in 1983 and led by RR and P&W each with a 32.5% share, Japanese Aero Engines Corporation (JAEC) with 23% and MTU Aero Engines of Germany with 12%; and CFM International (CMFI), established in 1974 and equally owned by GE and Société Nationale d'Étude et de Construction de Moteurs d'Aviation (SNECMA) of France.

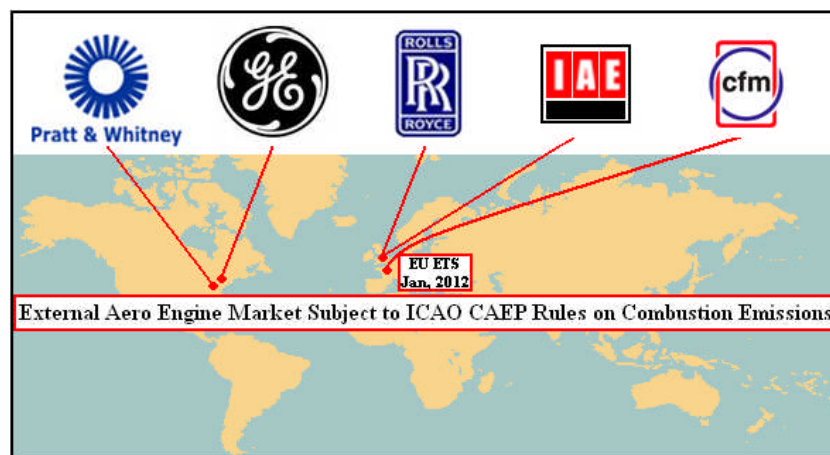


Figure 2.1: Main Aero Engine Suppliers and Headquarters

This chapter opens with a snapshot of RR, GE and P&W financials; market share; RR core strategy and the commercial justification for this study. This is followed by a comprehensive business analysis of the large civil aero engine sector to suggest possible courses of action that RR may consider to safeguard itself against periods of short-term market volatility and also prepare for the anticipated changes in strategic operating

context that face civil aviation, particularly within the EU. Results from a Political, Economic, Social and Technological (PEST) analysis show the current influences on supply and demand to deliver insight into the driving forces that underpin the structure of the civil aero engine market; state of competition; conduct of competitors and overall sector performance. A Porter's Five Forces framework highlights areas where RR may concentrate to gain competitive advantage and build market share (Porter, 1979). Finally, two Strengths, Weaknesses, Opportunities and Threats (SWOT) audits over the short and long-terms depict scenarios where RR successfully aligns to the new context.

Finally, whilst it is recognised that competition spurs innovation to give the highest quality and lowest cost products, many theories also suggest that oligopolists tend to overspend, yet accomplish similar goals (Reinganum, 1989 and Rickard, 2006). Because all aero engine suppliers must develop strategic processes that deliver strategic contents to satisfy changes in strategic operating context to compete, a collaborative game theoretic approach is explored during the lengthy pre-competitive, pre-technology, aero engine capability acquisition design phase. Collaboration to acquire joint patents only pertains to unproven future technologies in areas that preclude an imminent competitive advantage for individual parties but instead serve to reduce overall development times, costs and the risks of failure for all partners. Once a technology is validated the complex technology transfer process becomes independent. Sources of competitive advantage remain traditional such as being the first to market; securing engine certification; customer orders; engine exclusivity and being innovative in their business models. Future collaborations to develop low emissions aero engine technology are expected to receive strong political support and little opposition from the competition authorities. Arguably, this would be a "public good", worth contemplation and wider discussion due to the potential seriousness of global warming and fact that global warming in itself may be regarded as a stimulus for change and improvement.

2.2 CHANGES IN STRATEGIC OPERATING CONTEXT

This section discusses air travel growth, the tightening of ICAO CAEP combustion emissions legislation and inclusion of civil aviation in the EU ETS. Civil aviation is an essential part of modern society, a strong driver of innovation and a key indicator of world prosperity. It employs ~32 million people worldwide and is worth ~\$3.5 trillion at current prices that equates to ~8% of world Gross Domestic Product (GDP) (International Air Transport Association (IATA), 2009). Only two companies, Boeing and Airbus Industrie, have the capacity and capability to develop, design and manufacture large passenger airframes. Demand for airframes determines the demand for large aero engines supplied by one of three prime contractors: RR, GE or P&W, or one of the two strategic alliances, IAE or CFMI. Consequently, aero engine suppliers

compete on technical and commercial terms to secure engine certification on airframes under development and to win orders from airlines and aircraft leasing companies. To maximise sales airframers usually certify more than one engine brand per airframe so customers can streamline fleets to ease maintenance and increase profits. Airframe and aero engine selection typically involves analysis of safety; competitor behaviour; routes; consumers; purchasing vs leasing costs; airport charges; air traffic control capacity; aftermarket agreements; fuel efficiency, in-flight performance; noise and emissions (Morrell, 2005). The new context makes emissions performance a critical aspect of competitive strategy and forces aero engine suppliers to develop more environmentally friendly aero engines to increase probabilities of future engine certification and orders. Figure 2.2 shows three dimensions of strategy in terms of aero engine combustion R&D. Although the chart shows aero engine suppliers must develop strategic processes that deliver strategic contents to satisfy the expected changes in strategic operating context, it fails to communicate that strategic processes developed in these terms may largely ignore high R&D expenditure, discussed more rigorously in Section 2.4.7.

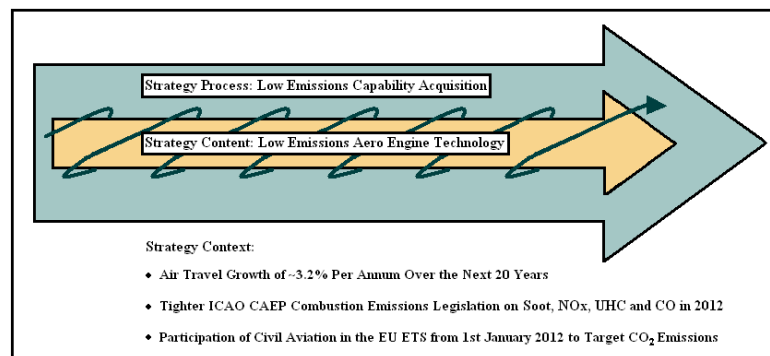


Figure 2.2: Strategic Dimensions of Combustion R&D (de Wit and Meyer, 2005)

2.2.1 Air Travel Growth Forecast

According to Boeing (2009), Figure 2.3 shows passenger numbers will increase in line with world growth by ~4.9% per annum between 2009 and 2028.

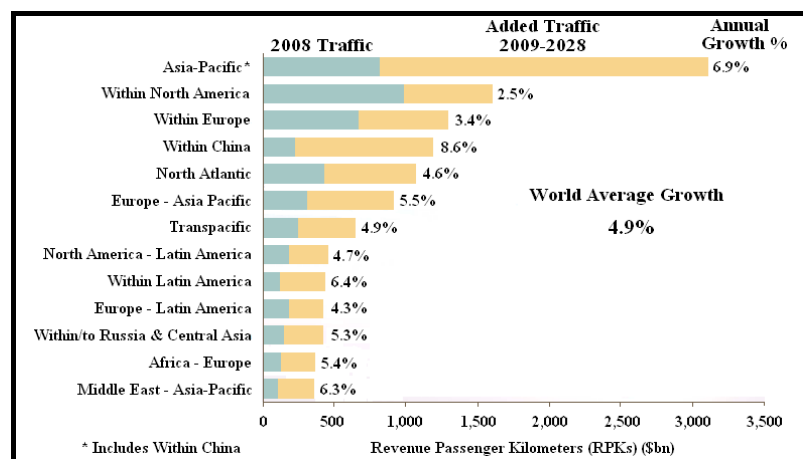


Figure 2.3: Passenger Travel Growth Per Market: 2009 – 2028 (Boeing, 2009)

To help interpret the forecast, Table 2.1 shows the number of seats in each aircraft type:

Aircraft Type	Number of Seats
Regional	Below 90
Single aisle	90 – 240
Twin-aisle	180 – 400
747 and larger	Above 400

Table 2.1: Number of Seats Per Aircraft Type (Boeing, 2008)

Figure 2.4 shows that most demand is anticipated for single and twin-aisle aircraft and Figure 2.5 shows the market value per aircraft type at current prices. The requirement for 29,000 new aircraft consists of ~12,200 replacements and ~16,800 additions. With 6,600 retained aircraft, this yields a global fleet size of 35,600 by 2028. The Airbus estimate is ~17% shy at ~24,100 new aircraft deliveries.

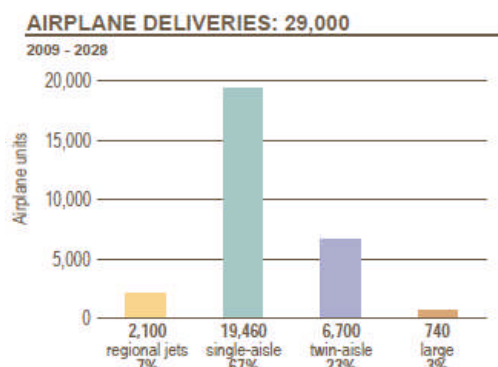


Figure 2.4: Demand by Size (Boeing, 2009)

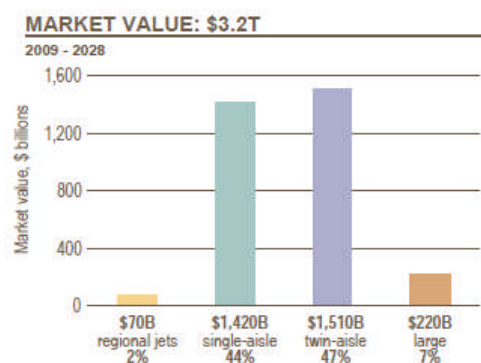


Figure 2.5: Market Value Per Type (Boeing, 2009)

Greatest demand will be for single-aisle aircraft at 67% followed by twin-aisle aircraft at 23%, although both have comparable market values shown in Figure 2.5 at 44% and 47%. Figure 2.6 shows the healthiest demand is from the Asia-Pacific region followed by North America and Europe. In terms of revenue, Figure 2.7 shows the Asia-Pacific region will lead followed by Europe that is trailed closely by North America.

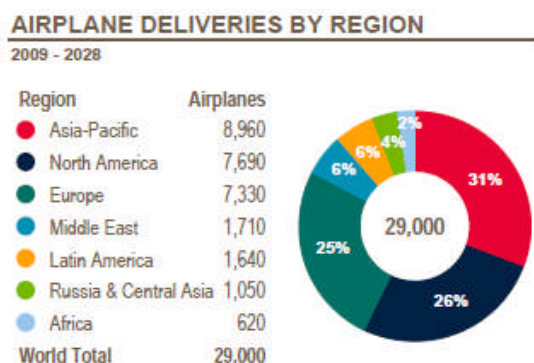


Figure 2.6: Deliveries Per Region (Boeing, 2009)

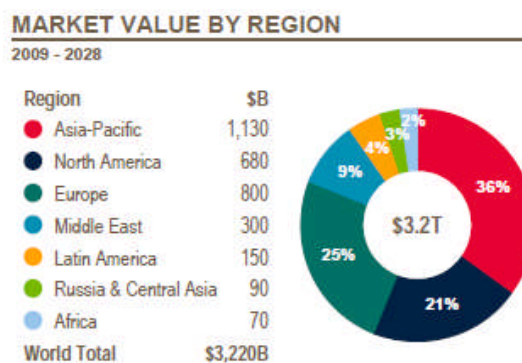


Figure 2.7: Market Value Per Region (Boeing, 2009)

2.2.2 Aero Engine Market Forecast

According to RR, air travel growth between 2009 and 2028 will create a potential market for ~139,000 aero engines worth ~\$810 billion at current prices, with ~\$630 billion expected from aftermarket activity. Figure 2.8 plots engine category against engine units. To mirror the Boeing forecast, most demand is expected for aero engines with a thrust rating of 22,000 – 45,000lbs for single and twin-aisle passenger aircraft.

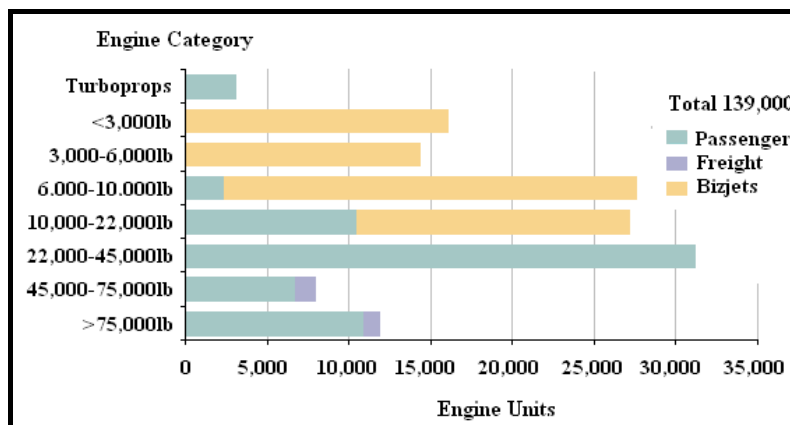


Figure 2.8: Aero Engine Deliveries 2009 – 2028 (RR, 2009)

Figure 2.9 shows the high market value for aero engines with a thrust rating above 22,000lbs for single-aisle, twin-aisle and large passenger aircraft.

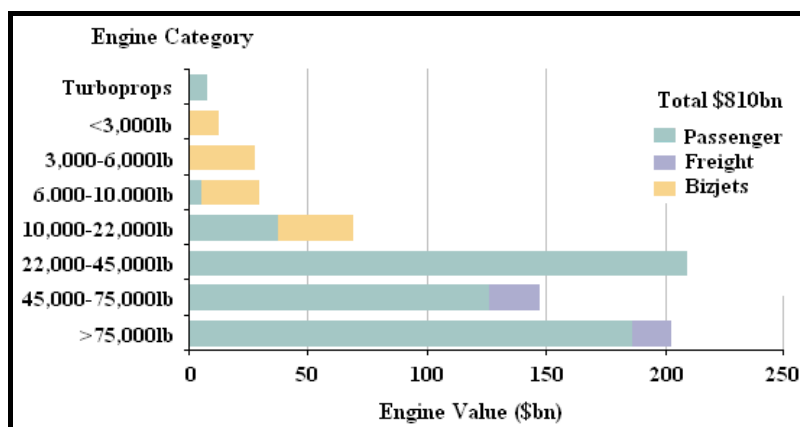


Figure 2.9: Aero Engine Delivery Value 2009 – 2028 (RR, 2009)

2.2.3 ICAO CAEP Aircraft Emissions Legislation

The Chicago Convention (CC) established the UN ICAO in 1944 to set global aviation standards and practices. In 1988, the ICAO formed CAEP to review technologies, operational procedures and market-based measures to mitigate the environmental impacts of aviation. CAEP legislation considers technological feasibility; economic reasonableness; environmental benefits and interrelationships (Holsclaw, 2007). It first introduced aircraft noise legislation. The Chapter 2 Standard in 1971 cut cumulative noise by 6dB; Chapter 3 in 1977 by 10 – 16dB and Chapter 4 in 2006 by another 10dB.

Combustion emissions legislation arrived nearly twenty years later to address the “silent killer” and public concern over Local Air Quality (LAQ) around airports. This still, however, pertains to the Landing and Take-off (LTO) cycle that is defined by the time an aircraft spends in an operating mode: approach 4 minutes; taxi/ground idle 26 minutes; take-off 0.7 minutes and climb 2.2 minutes. It legislates against smoke, NO_x, UHC and CO, since alone or together they affect human health and inflict a serious cost on society. Table 2.2 shows ICAO emissions legislation from 1986 to the present day.

Pollutant		Limit (Dp/F ₀₀) g/kN
SAE Smoke Number ICAO 1989		The lower of 50 or $83.6 \text{ Dp/F}_{00}^{0.274}$
UHC		19.6
CO		118
NO _x	CAEP1 in 1986	$40 + 2 (\pi_{00})$
	CAEP2 in 1996 -20% Relative to CAEP1	$32 + 1.6$
	CAEP4 in 2004 -16% Relative to CAEP2	$19 + (1.6 \times \pi_{00})$ for $\pi_{00} < 30$
		$7 + (2 \times \pi_{00})$ for $\pi_{00} > 30$
	CAEP6 in 2008 -12% Relative to CAEP4	$16.72 + (1.408 \times \pi_{00})$ for $\pi_{00} < 30$
		$-1.04 + (2 \times \pi_{00})$ for $\pi_{00} > 30$

Table 2.2: Combustion Emissions Legislation (Ballal and Zelina, 2003)

Figure 2.10 plots the ICAO NO_x certification metric for certified engines between 1986 and 2008. It plots NO_x emissions quantity, (Dp) divided by engine thrust, (F₀₀) against engine Overall Pressure Ratio (OPR or π_{00}), and shows NO_x leniency as this increases.

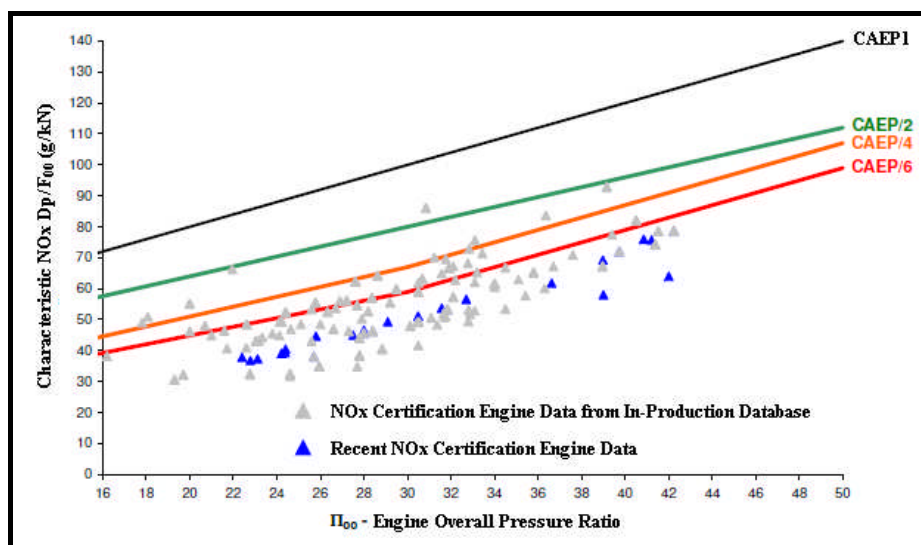


Figure 2.10: Engine Certifications Relative to CAEP Stringency (Ralph, 2007)

Smoke emissions are subject to 1989 rules for engines with a sea-level take-off thrust above 6,000lbs (26.7kN) (Ballal and Zelina, 2003). Whilst modern fuel preparation

techniques largely eliminated smoke, UHC and CO, a series of conflicting combustor design requirements makes NO_x reduction progressively more difficult. According to the limits laid out in Table 2.2, a civil aero engine with an OPR of 30 gives LTO NO_x values expressed in g/kN of 100, 80, 67 and 59, respectively. CAEP2 lowered NO_x by 20% over CAEP1; CAEP4 by 16% over CAEP 2, and CAEP6 by 12% over CAEP4. CAEP8 legislation due in 2012 is expected to cut NO_x by a further 20% over CAEP6. Current in-service combustion technologies meet CAEP6 limits with a 5 – 20% margin. The CAEP Medium Term (MT) 2016 goal is, “a declaration of the level of emissions performance from a specific engine thrust category that can be offered from an engine for aircraft service in ten years time” (Newton, 2007). This is expected to be ~45% under CAEP6 (+/- 2.5%). CAEP Longer Term (LT) 2026 targets are, “an aspirational declaration of improved engine emissions performance in about twenty years” at ~60% (+/-5%) below CAEP6 but will rely on radical new technologies. For greater impact, ICAO legislation must improve in three ways. It must force improvements in combustion technology, address Global Climate Change (GCC) and also apply globally.

First, the ICAO must force improvements in combustion technology with rewards. Efforts to reduce NO_x in the 1970s by 80% over six years resulted in an ~45% cut in thirty years due to the absence of economic incentives (Mongia, 2003). This has created the current situation where industry considers what is feasible and the ICAO then sets rules post hoc to allow continued competition, avoid company lawsuits and political interference. Second, ICAO legislation must extend beyond the LTO cycle to address GCC and also target unregulated high altitude emissions of water vapour, NO_x and CO₂ (IPCC, 1999). Although Ballal and Zelina (2003) reported that aircraft NO_x emissions were minor at ~2% in comparison to ground transport at ~70%, power generation at ~19% and marine engines at ~9%; worryingly Berntsen *et al* (2004) stated that ~90% of all aircraft emissions occurred outside the LTO cycle. At the cruise condition, high combustor pressures and temperatures increase the formation rates of both NO_x and CO₂. Combustor optimisation to meet LTO limits will therefore have negative impacts on pollutant emissions for most of the flight cycle. This makes both ICAO decisions to exclude CO₂ emissions at CAEP5 in 2001 and cruise NO_x at CAEP7 in 2007 highly contentious and a real concern given that between 1990 and 2002 greenhouse gas emissions in the EU dropped by ~3% but international civil aviation emissions increased by ~70% (EC, 2008). Third, ICAO legislation must be globally enforced after the first two points are addressed. If solid legislation then spreads to other places such as South America, India and China, it would increase environmental costs and pricing externalities and then compel airlines to invest in better technology. Currently, only Zurich and Stockholm airports charge aircraft according to the level of emitted pollutants. This forces Swiss and Swedish airlines to use low emissions technology. Global legislation would remove the current economic incentives that foreign airlines

have to pay the fines instead. Airport charges are a step forwards but a more general movement is required in this direction by other countries to forcibly change airline attitudes. As air traffic grows, the pressure to adopt low emissions technology must arrive via the route of governments and market-based measures and not individual airports. As aircraft operate across borders and over the high seas, Bisignani (2009) of IATA, the group that represents 230 airlines and 93% of scheduled international air traffic, recommended that governments should define a sectoral approach in Kyoto 2 for global accounting of civil aviation emissions and fair carbon-trading under the leadership of ICAO in partnership with the United Nations Framework Convention on Climate Change (UNFCCC).

2.2.4 Participation in European Union Emissions Trading Scheme

On 8th July 2008, the European Parliament proposed an amendment to Directive 2003/87/EC to include civil aviation in the EU ETS (European Commission, 2008). This became Directive EC/2008/101 on 2nd February 2009, effective from 1st January 2012 for all flights to, from, or within EU Member States shown below in Figure 2.11.

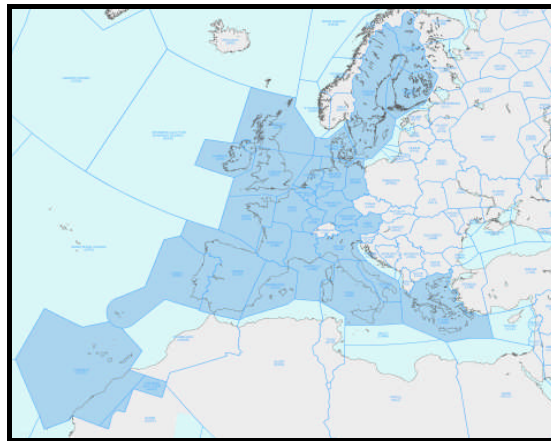


Figure 2.11: EU Airspace (Wit and Dings, 2002)

The Directive exempts flights that are Public Service Obligation (PSO); humanitarian; emergency; police; military; training and scientific; with CO₂ emissions under 10,000 tonnes per annum and maximum take-off weight below 5,700 kg. Airlines must monitor, report and verify tonne-kilometres and CO₂ data to the administering EU Member State that granted their operating licence. Non-EU airlines must report to the State where “greatest estimated aviation emissions” occur. Airlines should have submitted monitoring plans by the end of August 2009; must submit monitor data from 1st January 2010; report data and apply for free emissions allowances by 31st March 2011, and finally surrender 2012 emissions allowances by 30th April 2013. Airlines will receive 85% of emissions allowances and 15% will be auctioned with any surplus openly traded (Meade, 2008). Before inclusion of civil aviation in the EU ETS, Wit and Dings (2002) researched economic incentives to mitigate EU greenhouse gas emissions

from civil aviation. They investigated charges; supply-side measures; legal issues; collection and use of revenues. Supply-side operational and technical policies designed to maintain industry growth however require large investments and were identified as better air traffic control; increased load factor; installation of wingtips and riblets; weight reduction and quicker fleet renewal. On the downside, inclusion of civil aviation in the EU ETS could increase fares, shrink potential markets and slow down the growth of EU airlines. The EU ETS plans to raise ~£72 billion by 2022 to invest in climate research but governments have no legal obligation to link auctioned revenues with environmental actions. Poll (2008) believed participation of civil aviation in the EU ETS will marginally affect GCC as high fuel prices already incentivise CO₂ cuts, e.g. a 1kg gain in fuel efficiency reduces CO₂ emissions by 3.16kg (Cunningham, 2008). Poll argues that GCC is better addressed with more understanding on the processes that drive contrail and cirrus cloud formation in addition to the methane-reducing abilities of NO_x. Although fuel composition may not widely change in the next 10 – 15 years, the need to limit CO₂ may raise investments on alternative, next generation, sustainable fuels to supplement or even replace conventional jet fuels, discussed further in Section 2.4.1.4.

2.3 ROLLS-ROYCE PLC

This section gives a synopsis of the research sponsor, RR. It covers recent financial performance; civil aero engine market share; RR core strategy and commercially justifies the undertaken low emissions combustion research. RR supplies aero and industrial gas turbines to a global market and employs ~39,000 staff in 50 countries (RR Annual Report, 2009). The RR mission statement is, “trusted to deliver excellence” with “reliability, integrity and innovation”. However, this begs the question if RR can actually sustain these goals given current short term market volatilities and the expected longer term changes in strategic operating context that will require step-change technologies to compete. RR operates in four markets: Civil Aerospace; Defence Aerospace; Marine and Energy in two distinct areas: original equipment sales and aftermarket services. Figure 2.12 shows RR businesses and 2008 figures. 2009 results will be published on 11th February 2010.

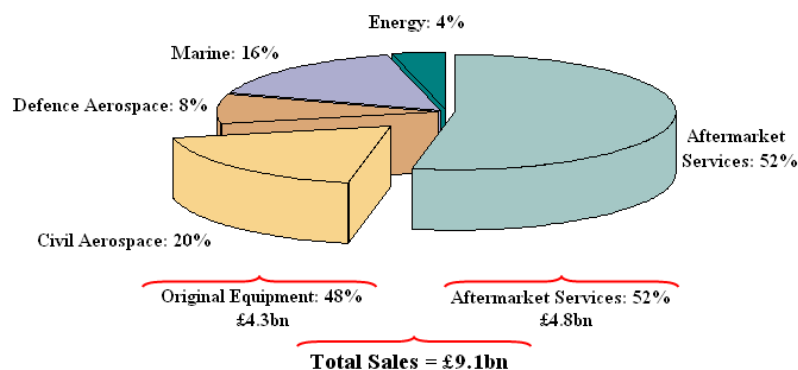


Figure 2.12: RR Group Business Portfolio and 2008 Results (Shilston, 2009)

This study focuses on the RR Civil Aerospace Division. At the end of December 2008, there were ~12,874 civil aero engines in service on over thirty types of aircraft with ~600 airlines and ~4,000 corporate operators. In terms of market share, RR is in second place behind GE. Although original equipment sales provide access to the lucrative aftercare services market for Maintenance, Repair and Overhaul (MRO), market share is strengthened through strategic alliances and more aero engine lease agreements.

2.3.1 **Financial Performance**

On 21st December 2009, RR has a market value of £8,960.72 million and a share price of 483.30p (12 Month High: 500p on 04/12/09 and Low 248.58p on 09/03/09). Current RR share price is ~176% above its 1987 flotation level of 175p; however it is up 2.2% on a month, 0.9% on three months and a staggering 54.5% on a year. This performance reflects the dichotomy of high oil prices in 2008 and onset of the deepest global recession since the 1930s (IATA, 2009). Both factors increased airline operational costs, reduced freight traffic and cut premium passengers to hamper the ability of airlines to invest in new aircraft and aero engines. A strong RR performance during this turbulent period suggests it responded very effectively to this short-term cyclical decline. Figure 2.13 plots RR share price against the FTSE All Share Price Index in UK Pence from 21st December 2008 to 21st December 2009. It shows that RR performance generally followed the FTSE All Share Price Index until July 2009 to significantly improve to the present day, 21st December, 2009 barring the slight dip at the end of September and mid-November that was also shared by the FTSE All Share Price Index.

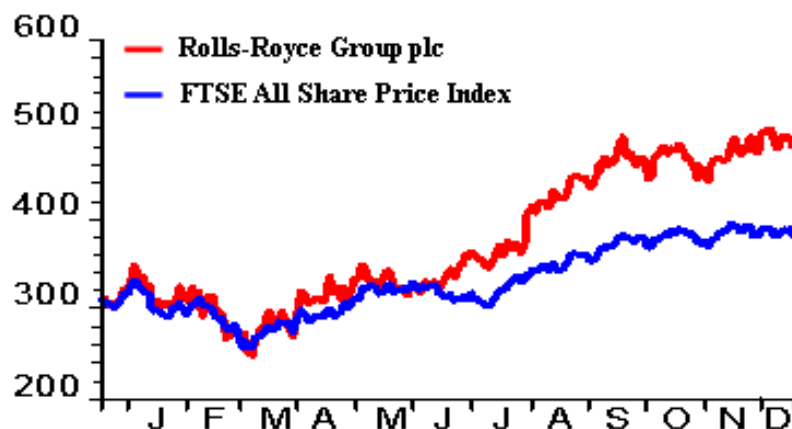


Figure 2.13: RR Share Price vs FTSE All Share Price Index: Dec '08 to Dec '09 (Datastream, 2009)

Relative to the FTSE All Share Price Index, RR share prices are 1.8% up on a month, down 1.2% on three months but 22.8% up on a year. Although share price is not a reliable indicator of business performance, it may suggest that RR business strategy has coped very well with short-term market volatilities that led to order deferrals and cancellations compared to competitors GE and P&W, as reflected overleaf in Figure 2.14 and Figure 2.15 where GE performed quite badly relative to the S&P 500 Index.

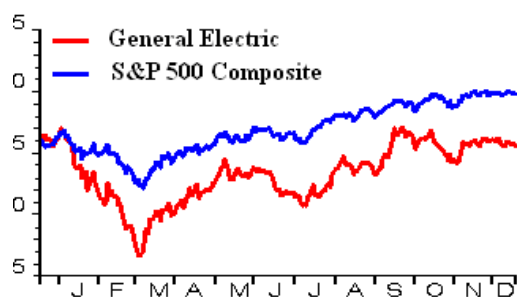


Figure 2.14: GE Share Price vs S&P 500: Dec '08 to Dec '09 (Datastream, 2009)

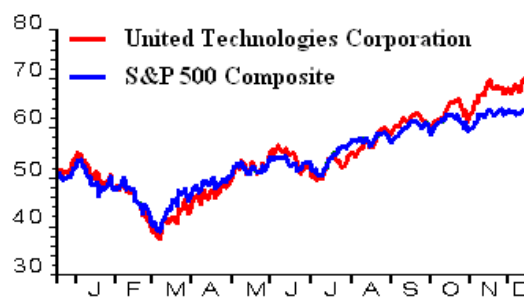


Figure 2.15: UTC Share Price vs S&P 500: Dec '08 to Dec '09 (Datastream, 2009)

Encouraging gains in the RR share price are possibly due to the aftermarket business. Table 2.3 shows RR TotalCare® and CorporateCare® aero engine lease agreements such as, “Power by the Hour” contributed to 61% of underlying services revenues in 2008. Leasing benefits airlines by removing initial aero engine purchase costs of ~\$8 million per engine and by giving both parties scope to adjust capacity with sudden changes in demand. Airlines are also protected from unscheduled maintenance activity. Despite the impressive RR performance relative to the FTSE All Share Price Index, Table 2.3 shows Group pre-tax profits declined over previous years due to the marking to market of various financial instruments and non-cash adjustments. There was an increase of 17% in underlying revenues and of 10% in underlying profit before tax cash, despite weakening of the GBP/USD exchange rate through 2008. RR anticipates a drop in 2009 profits due to parked aircraft; order deferrals; cancellations and slower growth. However, more frequent use of aircraft will perhaps increase RR maintenance revenues.

	2008	2007	2006	2005
RR Group Total Sales (£m)	9,082	7,435	7,156	6,603
RR Group Pre-Tax Profit (£m)	1,892	733	1,391	477
Civil Aerospace Division				
Underlying Revenues (£m)	4,502 +11%	4,038 +3%	3,907 +15%	3,406 +11%
Underlying Profit Before Financing (£m)	566 +0%	564 +9%	519 +14%	454 +118%
Net Assets (£m)	330	2,468	2,165	1,617
Order Book (£bn)	43,5 +21%	35,9 +80%	20 +5%	19 +17%
Engine Deliveries	987	851	856	881
Underlying Services Revenues (£m)	2,726	2,554	2,310	2,016
Underlying Services Revenues (%)	61	63	59	59
Fleet Under Management (%)	57%	55	48	45

Table 2.3: RR Key Financial Data (RR Annual Report, 2009)

High R&D expenditure and low initial returns from the primary aero engine market forced RR to forego a cash dividend payment for the fifth consecutive year. Prior to January 2009, RR issued convertible B Shares but now issues non-convertible C Shares. This reinforces the classic clash between industrial strategy to secure the longer term future of the firm and City short-termism that is driven by the demand of capital markets that leads to insufficient attention to R&D. Figure 2.16 plots RR share price since the firm was re-privatised in May 1987 during the Thatcher administration. Share price is compared against competitors GE and UTC; the World Aerospace Price Index; the FTSE 100 and FTSE All Share Price Index up to 21st December 2009. The plot is presented in UK Pounds Sterling and because GE and UTC both report in US Dollars, it may include some distortions due to currency effects.

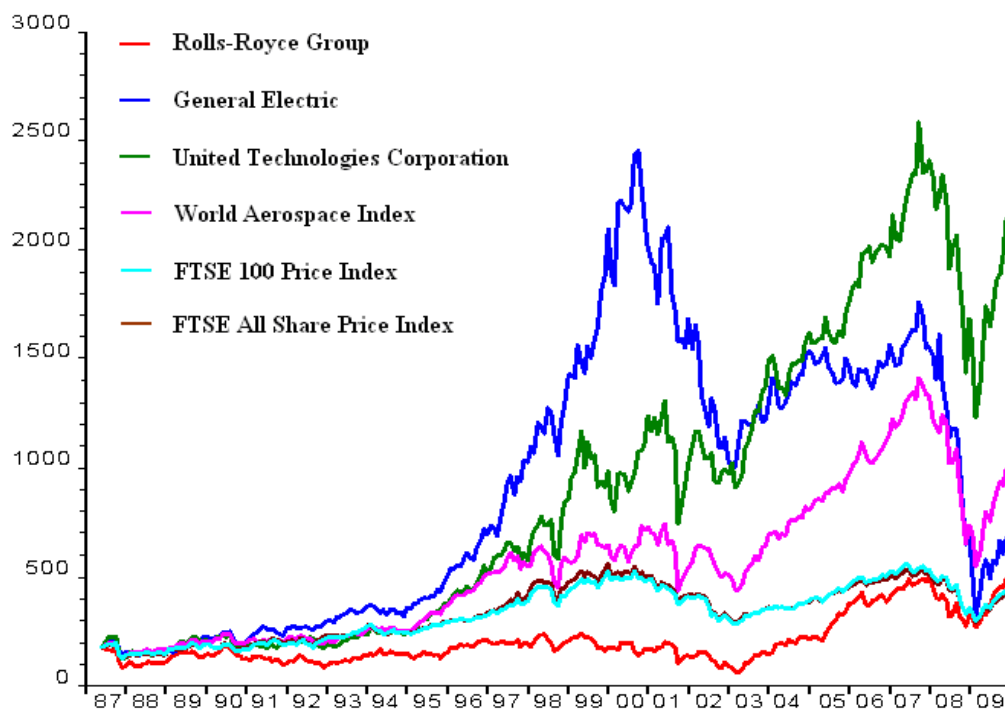


Figure 2.16: Share Prices of RR, GE, UTC vs World Aerospace Index, FTSE 100 Price Index and FTSE All Share Price Index: '87 to '09 (Datastream, 2009)

The plot shows the fortunes of all three aero engine suppliers depend on global cycles. Between 1998 and 2002, both GE and UTC experienced large gains in share price in comparison to RR. GE share price plummeted between 2000 and 2002 at a greater rate than corresponding decreases in UTC and RR share prices. The GE share price then remained uneventful between 2002 and 2006, whilst both RR and UTC performed in line with world growth and experienced steady gains. The chart suggests the bottom of the recession was reached at the end of 2008 as all indices increased from 2009. RR share price mirrors increasing market share but not GE's dominance or decline in P&W market share, as share price measures aggregate performance across businesses. As RR is the least diversified of the trio with four businesses its share price may paint a truer reflection of market share in comparison to that of the more diversified GE and UTC.

2.3.2 Aero Engine Market Share

In the 1960s, P&W had prime position in the aero engine market until GE entered in 1971 with civil engines adapted from military technology. During this period, RR had a slim product range and under 10% of the market. In 1974, GE teamed with SNECMA to form a 50:50 CFMI transatlantic alliance and manufacture the CFM56 family of engines. Consequently, by 1980 the market shares of P&W, GE and RR were 52.4%, 33.3% and 12.8% (Smith, 1997). In the early 1980s, airlines demanded a wider choice of aero engines per airframe to streamline fleets. This intensified competition between aero engine suppliers and led to price wars. During the 1980s, GE increased market share and gained a degree of immunity from the cyclical nature of aerospace through redefinition of the value proposition and by leasing their own and competitor engines.

In response, RR launched a two-pronged attack to win market share. First, the product range was broadened with derivative engines designed around a common core. Second, two strategic alliances were created: International Aero Engines (IAE) in 1983 to produce the V2500 family of engines and compete with the CFM56; and Bayerische Motoren Werke AG (BMW) – Rolls-Royce GmbH in 1990 to develop the BR700 family of engines and replace RR Tay engines in the regional jet market (Smith, 2003). By 1995, IAE and CFMI had 26.6% of the market. Although IAE still operates, BMW sold its stake to RR in 1999. This became Rolls-Royce Deutschland (RRD) and the RR Centre of Excellence for two-shaft aero engines. According to the EC, Table 2.4 shows the installed aero engine base on narrow and wide-body aircraft and order backlog for aircraft still in production (EC, 2001). In 2001 GE was first, with P&W second and RR third. Latest data is undisclosed to prevent courts blocking of mergers and acquisitions.

Installed Aero Engines on Large Commercial Aircraft In-Service at End of 2000			
Model	GE/CFMI	P&W/IAE	RR/IAE
Narrow-Body	51%	22%	27%
Wide-Body	54%	31%	15%
Installed	52.5%	26.5%	21%
Aero Engine Order Backlog Start of 2001			
Model	GE/CFMI	P&W/IAE	RR/IAE
Narrow-Body	2,882 (68%)	543 (13%)	803 (19%)
Wide-Body	660 (53%)	344 (25%)	234 (19%)
Backlog	3,542 (65%)	887 (26.5%)	1,037 (19%)

Table 2.4: Installed Aero Engine Base on Large Commercial Aircraft In-Service at End of 2000 and Engine Order Backlog at Beginning of 2001 (EC, 2001)

To the disappointment of GE, the EC aggregates CFMI market share with that of GE but divides IAE market share equally between RR and P&W. However, the above data is questionable since it suggests a stronger P&W than industry actually believes. P&W lost market share in the late 1990s and early 2000s to both RR and GE because it failed to secure new engine orders, e.g. from Boeing for the 787 Dreamliner (Rigby, 2004). Engine exclusivity is a strong source of competitive advantage. RR has it on the Airbus A350XWB and A340-500/600; and GE on the Boeing 777-300ER/-200LR/-200F, 747-8 and 737 programmes (Thomas, 2008). The RR Trent 1000 has a significant presence on the Boeing 787 Dreamliner due in 2010 and Airbus A350 XWB in 2013. RR market share in the wide-body sector is at ~50% and ahead of GE at ~38%.

Based on engine delivery value, GE has ~39% of the total civil aero engine market, RR is in second place with ~34% and P&W is last with ~27%. Overall, ~87% of installed RR thrust is under twenty years old compared to ~70% for the global passenger fleet (Jet Fuel Intelligence, 2008). As aero engine life increases through technological improvements and RR has a young fleet, RR projected aftermarket revenues are healthy. According to Table 2.3 on page 15, total aftermarket service revenues climbed nearly 7% to 61% to £2,726 million to suggest that RR profits will steadily increase from its installed base of aero engines. To increase market share RR must compete on more aircraft programmes to win orders; secure lease agreements; strengthen strategic alliances, improve in-service performance and increase customer responsiveness. An increased knowledge of Order Qualifying Criteria (OQC) and more critically, of Order Winning Criteria (OWC) may help RR to gain a quality, cost and time advantage over its rivals. Because a high proportion of customers in many organisations are considered to be unprofitable, data mining may help RR to increase knowledge of its most valuable customers so it may understand their OWC and then target its scarce resources more effectively (Ryals, 2003). An “importance-performance” matrix may be used to plot high value customer benefits against perceived RR performance in delivering that benefit compared to competitors. This may help RR to identify OQC and OWC and to understand why a particular airframer, airline or aircraft leasing company would gravitate towards a particular aero engine supplier. Understanding changing customer needs, perceptions and expectations will allow RR to make connections on both an emotional and functional level to safeguard its business.

2.3.3 Core Business Strategy

Core elements of the RR business strategy are to partner with suppliers to improve supply chain efficiency; broaden its product and service portfolio to gain Economies of Scale (EOS); understand its customers to provide integrated solutions that create value; increase revenue per employee; invest for long term business growth and to strengthen

R&D capabilities in collaboration with partners and universities. RR has a strategic posture mixed between “shapers” and “adapting to the future” (Courtney *et al* 1997). The firm strives for a leadership role through achievement of high technical standards in Vision Technology programmes. However, shaping strategies are very risky and may fail. In 1971, when GE entered the market, RR was brought into state ownership after problems with its RB211 composite wide chord fan blade. In May 1987, RR was re-privatised minus the car business that was sold off separately to Vickers in 1973. The Motor Car Division is now, incidentally, a subsidiary of BMW and Volkswagen (VW).

2.3.4 Vision Technology Programmes

In 2008, RR invested £885 million in R&D to reduce the environmental impact of its products. Of this sum, ~£120 million was spent on Vision Technology programmes that focus on step-change combustion technologies over five, ten and twenty year periods:

- Vision 5 – Proven technologies to install during engine upgrades
- Vision 10 – Leading edge validation technologies at demonstration stage
- Vision 20 – Unproven future technologies to meet future EU ACARE targets

The Advisory Council for Aeronautics Research in Europe (ACARE) was launched in June 2001 and has ~40 members that establish and carry forward research programmes. However, high costs restrict the necessary R&D expenditure on unproven future technologies to meet ACARE targets in Vision 20 type programmes. Therefore, Section 2.4.8 explores a collaborative game theoretic approach with competitors during the lengthy, pre-competitive, pre-technology, capability acquisition aero engine design phases to acquire joint patents and cut development times, costs and the risks of failure.

2.3.5 Justification for EngD Low Emissions Aero Engine Research

Reduction of aero engine emissions is at the forefront of applied combustion research and is of extreme strategic value to RR, GE and P&W. The undertaken research pertains to RR Vision 10 combustion technologies that aim to reduce NO_x by ~40% relative to CAEP2 limits. There is growing evidence that emissions legislation is gathering momentum; even if the current global recession causes it to slow down in the next two to three years governments will readdress the issue once normal world growth resumes. If legislation outpaces the ability of civil aviation to meet regulated targets, it is thought that without adoption of the undertaken and similar research, the anticipated growth in new passenger aircraft numbers may subside from ~3.2% to ~2.5% per annum. Down to the point, RR made the intertemporal decision to invest in the undertaken low emissions research with the expectation of making a profit, π . Such

decisions embody a choice between current and future time periods. Eq. 2.1 shows profit increases when Expected Revenues (ER) rise and Expected Costs (EC) fall. This research aims to reduce EC during combustion systems design to increase ER and hence overall profits.

$$\pi = ER - EC \quad \text{Eq. 2.1}$$

Full-scale emissions tests are superior to scaled combustion tests, fuel spray studies and computer simulations because the physics of spray atomisation is difficult to replicate; especially in new hybrid fuel injectors that encompass several atomisation mechanisms. However, full-scale engine test units cost ~£1.3 million and running costs are ~£20 – 100,000 per day (Jones, 2009). High costs prohibit early testing and the huge pressure to certify engines on time to secure orders and recuperate R&D investments gives very little opportunity to make unexpected design changes. This usually leads to a trade-off and modifications post launch at considerable expense and customer inconvenience. The method described in this study to predict fuel spray performance costs ~£2,370 or ~4% of the full-scale test costs, averaged at £60,000 per day. Table 2.5 shows 75% less fixed investment costs and Table 2.6 gives testing and processing costs per fuel injector.

Fixed Costs	Cost (£)
Unsteady Flow Rig	175,000
Laser, ICCD Camera, Optics	110,000
Airbox, Tubing, Fittings, Gas Supplies	1,000
PC	500
Total	286,500

Table 2.5: Research Fixed Costs

Variable Costs	Cost (£)
Technician	120 (4 Hours at £30/ph)
Processing Costs	1,000 (5 Days at £200/pd)
Air	1,000 (4 Hours at £250/ph)
Fuel	250 (50 litres)
Total	2,370

Table 2.6: Research Variable Costs

Experiments in this study applied cutting-edge laser diagnostics to measure fuel injector spray performance at optimally-scaled engine operating conditions. Fuel sprays were characterised in terms of combustion emissions and instability in a new optically-accessible test rig. This research used full-size injector hardware; imitation combustor geometry; surrogate engine fuel and steady or oscillating air supplies. Obtained results

showed good agreement with measured trends from full-scale engine tests supplied by RR for (a) NO formation at engine conditions of 100% Take-off; 85% Climb; Cruise and 30% Approach in three hybrid fuel injectors reported in Chapter Seven; and (b) combustion instability in five conventional airblast injectors and one hybrid injector presented in Chapter Eight. This research does not remove the need for full-scale engine tests; instead, it forms part of a broader RR strategy to increase simulations and limit rejections and unexpected design iterations at late design stages. Optical measurement of key spray features has the potential to inform the design and development of low emissions, instability-free fuel injector designs at less risk, cost and time than traditional design methods and therefore reduce delays in obtaining the type, production and airworthiness certificates necessary to substantiate engine design, manufacture and operational safety.

2.4 CIVIL AERO ENGINE BUSINESS ANALYSIS

This section conducts a comprehensive business analysis of the large civil aero engine sector to suggest possible courses of action that RR may consider to safeguard itself against periods of short-term market volatility and also prepare for the three longer term changes in strategic operating context that face civil aviation. A Political, Economic, Social and Technological (PEST) analysis shows the current influences on supply and demand to deliver insight into the driving forces that underpin civil aero engine market structure; state of competition, conduct of competitors and sector performance. Next, a Porter's Five Forces framework gives explicit consideration to the competitive arena and pinpoints areas where RR may concentrate to gain competitive advantage and build market share (Porter, 1979). This is followed by two Strengths, Weaknesses, Opportunities and Threats (SWOT) audits that cover both the short and long-terms to depict probable scenarios if RR successfully aligns itself to the anticipated changes in strategic context, circumvents threats and takes advantage of all available opportunities. Competition in every sense does not always give a competitive advantage. Therefore, the final section explores a collaborative game theoretic approach with competitors during the pre-competitive, pre-technology, capability acquisition aero engine design phase to acquire joint patents to reduce overall aero engine development times, R&D expenditures and the risks of failure.

2.4.1 Political, Economic, Social and Technological

A Political, Economic, Social and Technological (PEST) analysis of the large civil aero engine sector illustrated overleaf in Figure 2.17 highlights the external trends that impact supply and demand. It shows the key driving forces that underpin aero engine market structure, state of competition, competitor conduct and overall performance.

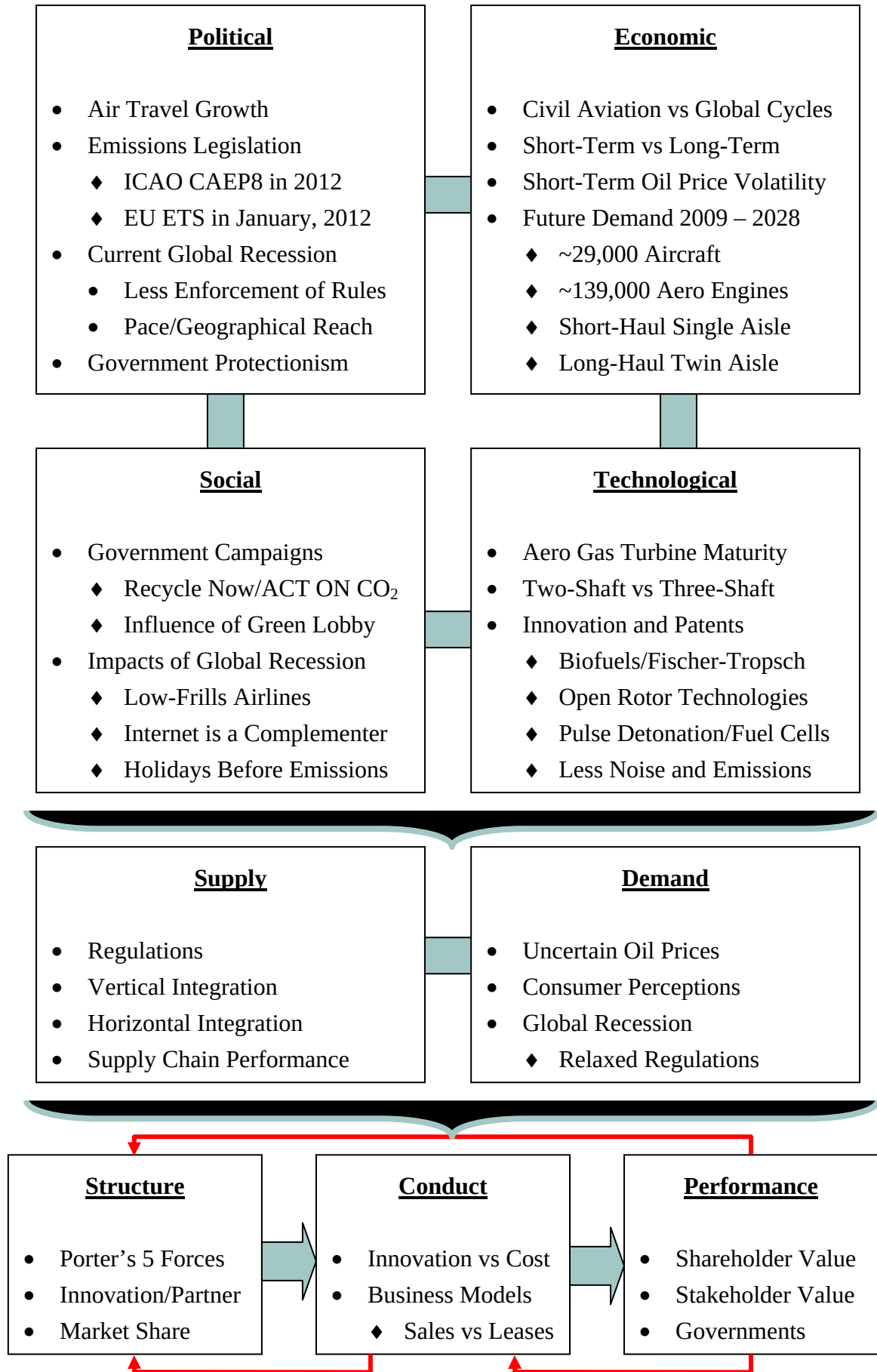


Figure 2.17: RR PEST Analysis

2.4.1.1 Political

Environmental concerns are the largest constraint to civil aviation growth. If scientists reconcile prevailing uncertainties regarding the environmental impacts of aviation on LAQ and GCC, the expected growth in air travel will pressurise politicians into tightening emissions regulations and extending its global reach. Already, ICAO CAEP8 legislation, due in 2012 is expected to reduce NO_x by a further ~20% over CAEP6 and the EU ETS will target civil aviation CO₂ emissions from 1st January 2012. The current global recession will slow down the profitability of airlines and perhaps regulators will go a little easier on their demands to meet higher environmental standards over the next two to three years. British Airways (BA) posted a pre-tax loss of £401 million in 2009 compared to a record profit of £922 million in 2008 (Done, 2009). IATA (June, 2009) expects aircraft emissions to decline by ~7% in 2009 over 2008 with ~5% from capacity reductions and ~2% from new technology. The call to reduce emissions will not disappear although the rules may not be enforced as strictly. Expected growth in developing countries and better living standards will increase demands for air travel and create new airlines. One uncertainty is how quickly environmental legislation will spread from the richer to poorer countries. This will be critical to prevent the sale of older, less efficient aircraft to new entrants from countries with huge land and population masses such as Brazil, Russia, India and China.

Superior RR low emissions aero engine technology may threaten the basic tenets that underpin GE stability and number one position in the sector. However, GE has both the financial muscle and political influence to entice airline orders by offering discounts. For example, GE controversially won a BA order in 1991 worth £1.4 billion (Eglin, 1992). In the same year, the UK Conservative Government rejected calls for a protectionist, interventionist policy through fears that it would spark similar actions by other countries and damage UK exports (Leigh, 1991). BA subsequently bought RR engines in 1998. In 2004, the UK Labour Government and some EU Member States suggested that CAEP6 NO_x legislation should be set at ~20% under CAEP4 rules, while the US and IATA requested an ~10% cut (House of Commons, 2004). Subsequently, CAEP6 NO_x rules were set 12% below CAEP4. In 2006, the UK Labour Government cancelled the Serious Fraud Office (SFO) investigation into the £50 billion Al-Yamamah defence contract between British Aerospace (BAe) and the Saudis (Russell and Morris, 2008). Furthermore, the US Federal Aviation Authority (FAA) believes EU legislation is unworkable and illegal (Burleson, 2008). By and large, OWC within the aerospace industry are very closely guarded secrets with occasional political undertones.

2.4.1.2 Economic

Performance of the civil aviation industry strongly depends on global cycles. As the aero engine sector closely lags behind boom and bust periods in this industry, RR must align itself with these trends to raise efficiency and understand customer perspectives. Aircraft demand increases during periods of world growth and vice versa. Figure 2.18 shows global commercial airline profitability since 1996 (IATA, 2009). Short-term declines followed periods of global unrest, e.g. after the Asian Financial Crisis (AFC); 9/11 terrorist attacks; Severe Acute Respiratory Syndrome Virus (SARS); wars; high oil prices; banking crisis and currently the H1N1 Swine Flu pandemic and global recession.

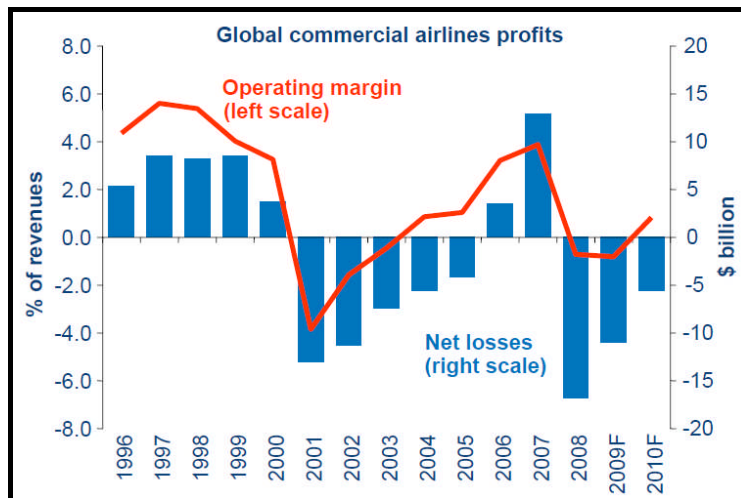


Figure 2.18: Global Commercial Airline Profitability (IATA, Dec. '09)

IATA posted a loss of \$16.8 billion in 2008; \$11 billion in 2009 and expects losses of \$5.8 billion in 2010 due to lower yields, slower growth and the prospect of high oil prices, as reflected below in Figure 2.19 that affected civil aviation in 2008 combined with the recession that cut air travel and poor fuel hedging that raised operational costs.

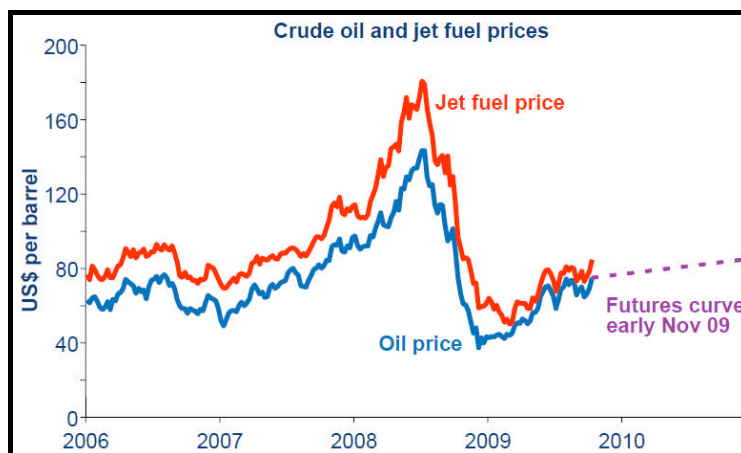


Figure 2.19: Jet Fuel and Crude Oil Price (IATA, Dec '09)

The average fuel bill in 2008 was \$128 per barrel, up ~\$69 billion on 2007 to \$165 billion and represented ~65% of airline operating costs. Fuel hedging largely proved

counter-productive when both oil prices fell by ~50% in the fourth quarter of 2008 to below hedge levels and the US dollar strengthened since oil is bought in this currency (Pearce, 2008). In 2008 many airlines cut capacity but some externalised rising fuel costs and entered the classic “death spiral” where incremental increases in ticket price met progressive reductions in demand to result in twenty-four bankruptcies in the first six months of 2008 (Brothers, 2008). In contrast, the average fuel bill in 2009 was \$70.6 per barrel, down \$30 billion on 2008. Between April 2008 and April 2009, Table 2.7 shows available seat capacity, actual passenger traffic and load factor for airlines by region. Capacity fell 2.5% but the corresponding 3.1% decline in passenger numbers outpaced efforts to unite supply with demand to give an average load factor of 74.4%. Market shares for passenger traffic in Europe were 33.8%; Asia Pacific 31.1%; North America 17.5%; Middle East 11.1%; Latin America 4.8% and Africa 1.8%.

April 2009 vs April 2008	Available Seat Km Capacity (%)	Revenue Passenger Km Actual Traffic (%)	Passenger Load Factor (%)
African	-5.0	-7.1	73.4
Asia/Pacific	-7.4	-8.6	71.6
Europe	-2.6	-2.7	75.9
Latin America	6.0	7.5	71.2
Middle East	12.3	11.2	73.8
North America	-4.0	-4.2	78.1
Industry	3.1	2.5	74.4

Table 2.7: Seat Capacity, Passenger Traffic and Load Factor (IATA, June '09)

In hindsight, the precipitous decline in air traffic from January 2008 within most regions heralded the beginning of a world recession – ahead of the global banking crisis now reported to have a bailout cost of ~\$4.2 trillion (Chancellor, 2009). IATA predicts freight traffic to decline by ~17% and passenger traffic by ~8% over 2008. However, the overall pace of decline is now slowing. Kumar (2009) reported that the global banking giant, Goldman Sachs (GS) now believes that improved aircraft financing conditions; stability in aircraft values and activity in the business jet market suggest a “significant medium and long-term upside” for investors looking at the 2011 – 2015 timeframe. GS also predicts that civil aerospace earnings will bottom in 2010 and for 2011 to show strong aftermarket growth; the benefits of cost reduction and better foreign-exchange hedges. This reinforces the twenty year long term forecast given in Sections 2.2.1 and 2.2.2 for ~29,000 new aircraft and ~139,000 aero engines worth ~\$3.9 trillion at current prices. Most demand is expected for short haul single-aisle and long-haul twin-aisle aircraft in the Asian-Pacific region, North America and Europe.

2.4.1.3 Social

UK 2004 “Recycle Now” and 2007 “ACT ON CO₂” campaigns and similar initiatives elsewhere increase public awareness of environmental issues (Keynote, 2008). To attract investment companies must reduce the environmental impact of their businesses. The current recession has reduced disposable incomes, increased price sensitivity, and generally led to sacrifices in ethical behaviour. Although there has been growth of low cost airlines and the Internet has complemented ticket sales, the Office for National Statistics (ONS) (2009) reported that between March 2008 and March 2009 the UK had 7% fewer overseas visitors and 6% less visits abroad. Seasonally adjusted figures between January and March 2009 showed a mild recovery with 2% extra overseas visitors and 4% more visits abroad compared to the same preceding period. Airlines and politicians both understand that most people are happier on long-haul holidays and that future growth in developing nations will increase holidaymakers. Providing it is affordable, this reinforces the belief that most people will place holidays before worrying about LAQ or GCC. Whilst passengers begrudgingly accepted baggage and fuel surcharges due to high oil prices, this still restricts how far airlines can go to externalise future combustion emissions charges and critically, how far governments will go to enforce more stringent combustion legislation since politicians cannot go too far beyond what people will be prepared to accept and then also expect to stay in power.

2.4.1.4 Technological

Nearly eighty years have elapsed since Sir Frank Whittle patented the kerosene-fuelled gas turbine for jet propulsion in British Patent No. 347,206 on 16th January 1930. Testing of the W2/700 engine began on 12th April 1937 (Whittle, 1945). Successful proof of concept led RR, GE and P&W to base their engine businesses on the Whittle design. Commercial civil aero engines are essentially two-shaft and three-shaft. The best examples of two-shaft engines are the GE90 and P&W4000 series of engines. Figure 2.20 shows a cross-section of the RR Trent 800 and GE90 aero engines.

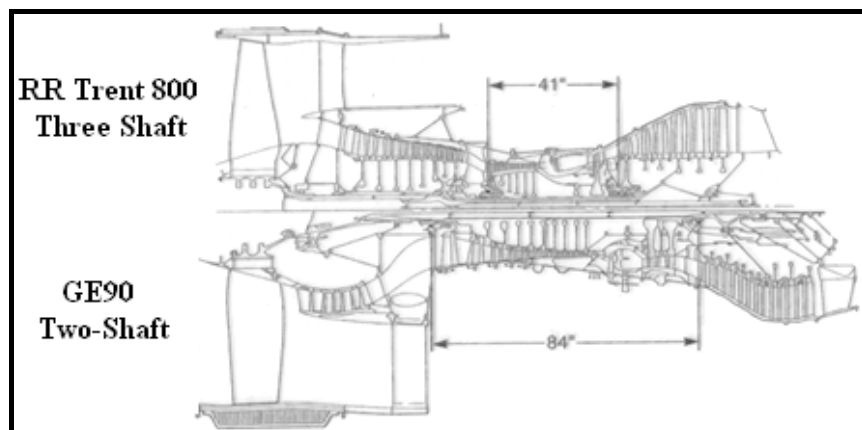


Figure 2.20: Cross-Section of RR and GE Engines (Ramsden, 2005)

The Trent 800 has a three-shaft arrangement typified by the RR Trent series of engines. It has a single fan with no booster stages because there is an intermediate pressure compressor and high pressure compressor on separate shafts. The GE90 has a single stage fan. Compressor fan booster stages on the same shaft effectively supercharge the single shaft core. GE and P&W engines are longer; more susceptible to instabilities; have a shorter turbine life and offer less scope to increase OPRs to reduce fuel burn and CO₂ emissions. In contrast, the RR Trent engine family has fewer low pressure turbine stages, a clean inter-compressor duct and more scope to increase OPR. Over the past forty years, all RR information, experience and background within large civil aero engine design has been based on three-shaft technology. High switching costs and lack of experience makes GE and P&W retain the less versatile two-shaft architecture but this also permits RR to differentiate itself. Aero engine technology now builds on seventy years of extensive research efforts by governments, aero engine suppliers and academics to satisfy military interests and commercial pressures. This has led to significant improvement in terms of design; manufacture; cost of ownership; safety; performance; reliability; life; noise and fuel efficiency. Over the past forty years, noise has reduced by ~90% and fuel efficiency has increased by ~70% (Koff, 2003; Singh, 2007 and IATA, 2009). IATA predicts an ~25% improvement in fuel efficiency by 2020 over 2005; use of ~10% alternative fuels by 2017; an ~50% cut in CO₂ emissions by 2050 in comparison to 2005 and finally, carbon-neutral growth beyond 2020.

Biodiesel is manufactured by the transesterification of vegetable oils with short-chain alcohols to give monoesters with similar properties to petroleum-based fuels (Tat and Gerpen, 2000). These may replace conventional jet fuels and be certified in the next few years. However, high initial costs may prevent their widespread adoption before 2015. Biofuels will gain a foothold only if they are carbon-neutral; competitively priced; do not compete with food products and do not cause deforestation. Next generation biofuels must be made from sustainable sources such as algae; switch grass; jatropha; babassu; halophytes; manure, food waste and sewage (Miller, 2008). *Atropa* and *jatropha* grow on wasteland; halophytes on salt ground; switchgrass can grow in areas with little water; babassu offers a high oil-yield nut and camelina grows in rotation with wheat and other cereal crops. Four airlines carried out successful trials with one engine part-powered on biofuels: Virgin Atlantic used an 80:20 mix of kerosene and babassu/coconut oil; Air New Zealand tried a 50:50 mix of kerosene and *jatropha*; Continental Airlines tested a 50:50 blend of kerosene and algae/*jatropha*; and Japanese Airlines operated a 50:50 mix of kerosene and camelina/*jatropha*/algae (IATA, 2009). IATA states biofuels may cut greenhouse gas emissions over conventional jet fuels by ~80%. However, deforestation, harvesting, refining and transportation suggest biofuels may be questionable in terms of carbon footprint and an example of where the politics has overcome the science. Fischer-Tropsch (FT) synthetic liquid fuels are made from

Hydrogen (H₂) and CO extracted from coal, methane or biomass. A 50:50 mix of FT fuel with conventional jet fuel was successfully tested in all engines of a B-52 aircraft (US Department of Energy, 2008) and FT Gas to Liquid Fuel was used in one engine of an A380 (IATA, 2009). In the medium term open rotor technology will cut fuel burn at the cost of less speed and higher engine noise. In the long term, pulse detonation and fuel cell technology may replace conventional aero engines. Pulse detonation involves the intermittent release of fuel energy through supersonic constant-volume rather than constant-pressure combustion and will remove complex turbomachinery. Fuel cell technology may arrive if cell power density increases. Both pulse detonation and fuel cell technology may first be introduced in hybrid format in the next thirty to forty years.

2.4.1.5 Supply and Demand

Aero engine supply and demand will lag behind global economic performance. Environmental legislation and CO₂ trading quotas will influence the supply of technology and the level of demand. Demand pertains to absolute growth in demand in terms of who requires it; structure of the contract; profit and risk sharing; financing, key account management and co-operative arrangements. Low emissions regulation influences supply and demand because it changes customer perceptions and habits. Currently, aero engine supply exceeds demand and forces aero engine suppliers to reduce their workforce to increase efficiency and perhaps focus more on engine lease agreements to sustain their businesses as sales of original equipment subside. As leasing is more profitable than selling engines, suppliers tend to prioritise their maintenance and also incorporate modifications to extend their lives and maximise resale values. Already, RR cross subsidises original equipment sales with aftermarket sales and implicitly absorbs an element of risk from a given airline. A full risk and revenue sharing partnership through leasing is a WIN-WIN as both RR and airlines rely on air traffic and engine reliability for profitability.

Demand for air travel will increase as the recession ends in the next couple of years. As mentioned, global financial indices suggest it ended at the end of 2008 but this will take time to filter through. If demand increases faster than supply, new airlines and leasing companies will attempt to enter the market. A new entrant is very unlikely to emerge in the aero engine manufacturing sector because of formidable entry barriers in terms of reputation; expertise; patents; high infrastructure costs; less tacit knowledge and the fact that under similar circumstances no entry occurred in the past. Although it is likely that an existing aero engine supplier will cease to trade or be taken over by a competitor, national strategic interests coupled with the fact that a duopoly may collude to behave as a monopoly, discussed further in Section 2.4.6 make both prospects highly unlikely.

2.4.1.6 Structure, Conduct and Performance

A change in aero engine market structure affects the allocation of RR, GE and P&W market shares. This is broadly due to innovation, new partnerships and alliances: innovation versus cost in both technology and in business models that improve supply chain performance, responsiveness and reduce waste. Performance is judged by shareholder and stakeholder value. The structure of the aero engine market drives a particular strategy and now the recession makes it more attractive to lease engines. If GE or P&W pose a threat, RR must innovate, differentiate and adopt a certain competitive stance; the specific economics dictate how the structure will drive RR conduct and performance. If RR strategy and conduct fits the structure, it will deliver superior performance for its shareholders and stakeholders such as governments, employees and all members of its supply chain. Red feedback loops in Figure 2.17 on page 22 showed the structure, conduct and performance paradigm was dynamic since it is driven by politics, global economic performance and competitors. Structure affects the required strategy to be adopted by the RR board, i.e. its conduct in terms of partnering, pricing and overall performance. The key result here is for RR to create an innovative business model. It must strengthen R&D and strategic alliances; nurture its talent; understand its core and critical businesses to avoid knee-jerk decisions for short-term gains; increase WIN-WIN engine lease agreements; identify OWC for profitable customers; constantly align to changes in strategic operating context; increase supply chain efficiency, reduce supplier switching costs and seek new ways to eliminate waste.

2.4.2 Porter's Five Forces

Overleaf, Figure 2.21 shows a Porter's Five Forces analysis of the aero engine market. It gives the background to allow a systematic study of the forces that RR must control to reduce the competitive powers of GE and P&W to gain a competitive advantage.

2.4.2.1 Competitive Rivalry (HIGH)

In the oligopolistic aero engine sector all players make strategic decisions under considerable uncertainty and then anticipate scenarios, competitor actions and reactions. Currently, all competitors use combustion technologies that meet ICAO CAEP rules. Since lawyers and governments intervene if new legislation affects the ability of a given supplier to compete, the rules do not force technological improvements, as discussed previously in Section 2.2.3. Although they currently appear to favour the US, a sure source of future competitive advantage for RR would be for it to reduce emissions and fuel burn whilst simultaneously increasing engine performance, reliability and customer service better than its rivals. This may help RR to secure engine exclusivity on airframes and win launch orders from prominent airlines. This signals other airlines that

perhaps cannot afford to perform a detailed purchase analysis to also use RR engines. A trade-off exists in how RR, GE or P&W acquire, validate and transfer new technologies into aero engines. They can spend huge amounts of funds and attempt to do this very quickly, or perhaps, do it at a more measured pace and not invest quite as much. In the second option they all face the danger that a rival develops low emissions or a more fuel efficient technology first and files their patent a day earlier than themselves. To avoid this scenario all aero engine suppliers make large R&D investments. *Ceteris paribus* by being the first to market one supplier can stay ahead of the game because prices usually fall with experience. However, in the civil aero engine business history has proven that no clear black and white answer exists regarding first-mover advantage. Although RR first developed the composite fan blade in 1971 and others followed suit, high R&D costs led to the UK Government bailout and state ownership for sixteen years. In some cases, the second mover gains the advantage, e.g. P&W were first to develop two-shaft civil aero engines but were superseded by the second-mover, GE (Pilidis, 2005).

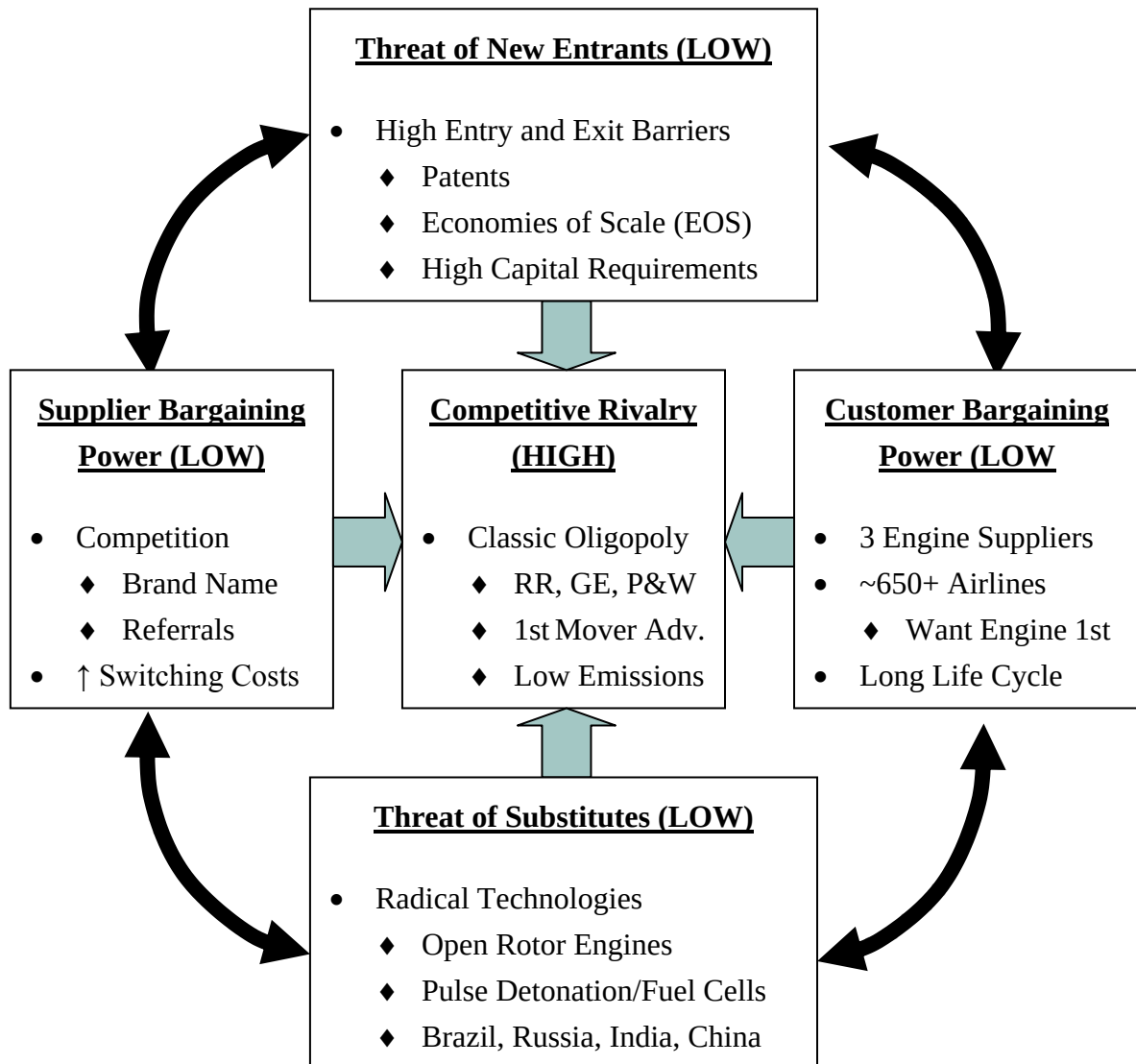


Figure 2.21: Porter's Five Forces Framework (Porter, 1979)

2.4.2.2 Threat of Potential Entrants (LOW)

Figure 2.22 plots cumulative cashflow for a typical aero engine and shows that brand new engine development has a substantial lead in period and costs ~£1 billion.

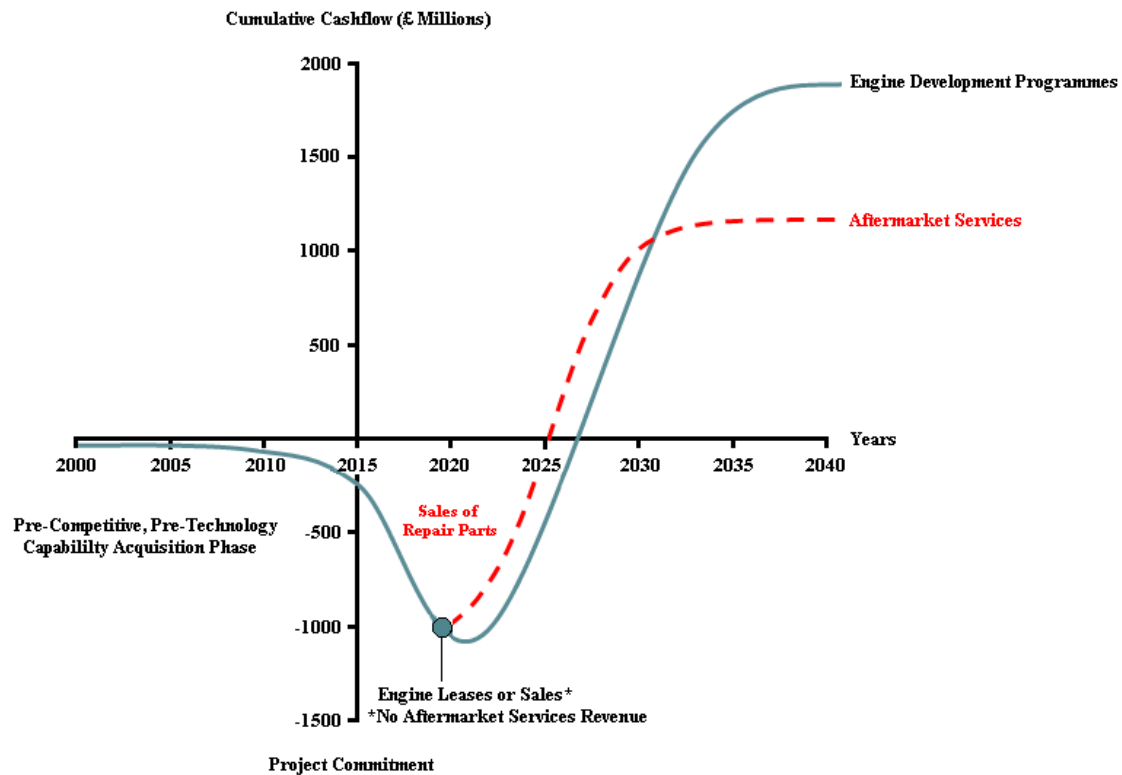


Figure 2.22: Typical Aero Engine Development

Modest funds are invested over a ten to fifteen year period during the pre-competitive, pre-technology evaluation of unproven future technologies. After project commitment investment levels usually increase to ~£100 – 130 million per year. Translation of generic or project specific validated technologies into a new aero engine may take a further four to five years of complex multidisciplinary analysis. A popular approach, also used in this research is to merge preliminary design methods with analysis at a system and sub-system level to reduce engine demonstrator test costs; time to market; re-work expenditure and overall risks. Typically, engine sales occur at a loss and discounts of ~70% are quite common given that airlines begrudgingly accept inflated prices for repair parts. Net profits arrive slowly through aftermarket services (Singh, 1996). Balance sheets, however, exclude these potential aftermarket revenues to distort actual business performance but this will change as more airlines begin to lease rather than buy engines. Aero engine development programmes represented by the blue line in Figure 2.22 above may increase the 20 – 30 year life cycle and potential revenues. The need for a strong knowledge base and reputation coupled with high capital costs of entry and lengthy investment period creates very high entry and exit barriers to give each aero engine supplier a strong degree of monopoly power. Patents guard the technology and EOS can reduce production costs. The threat of potential entrants is very low.

2.4.2.3 Threat of Substitutes (LOW)

In the medium term, high fuel prices may relax ICAO Chapter 4 noise rules to increase the popularity of radical open-rotor aero engines that aim to cut fuel burn by ~30 – 35%. Open rotor technology is once again under review after the 1970s oil crisis by all suppliers. Two drawbacks are less forward speed and more noise, however, better air traffic control and aircraft design can compensate. Open rotor concepts may arrive parallel to flying wing concepts under review by Boeing (Cunningham, 2008). There is a distant but growing threat of a large scale switch to turboprop aircraft for short-haul journeys and it is possible that new entrants from China, India or Russia may develop such engines. In the much longer term, pulse detonation and fuel cell technology may replace conventional aero engine technology. The threat of substitutes is low.

2.4.2.4 Bargaining Power of Customers (LOW)

Only three aero engine suppliers serve over 650 plus airlines that are all desperate to have the latest technology first to meet environmental legislation, cut fuel burn and stay inside EU CO₂ quotas to increase profits. Industry consultants usually persuade airlines to invest in aero engine technology to remove the difficulties suppliers have in recommending a new aero engine every few years given the very long engine life cycle. Supplier negotiating power increases if emissions legislation tightens and that particular supplier has best emissions performance. However, the paradigm shift towards engine leasing will reduce airline allegiances but this does not pose a particularly serious threat to RR because an airline can only go to two other suppliers and may still have to wait for ordered engines. Suppliers can also control supply to specialist leasing companies such as International Lease Finance Corporation (ILFC), a subsidiary of US insurance giant American International Group (AIG); currently selling its assets, possibly to Onex Group to help repay a bailout loan (Niles, 2009). Customer bargaining power is low.

2.4.2.5 Bargaining Power of Suppliers (LOW)

Many firms compete to provide the high technology aero engine sector with specialist components. An association with aerospace is considered to be prestigious because it incites orders from other sectors. High switching costs exist on both sides of the buyer-supplier relationship. Dual sourcing strategies reduce supplier bargaining power and discourage opportunistic price rises. The fact that repair aero engine parts are sold with an ~1000% mark-up may infuriate some aerospace parts suppliers when undue cost and time pressures are imposed by the buyer. Rossetti and Choi (2005) reported that abuse of this relationship may force suppliers to bypass traditional supply chains and sell repair parts directly to airlines. If this occurs, RR should collaborate or vertically integrate, enter the market and substitute from within. The FAA grants Part

Manufacturing Authority (PMA) to firms that can manufacture repair parts to certified standards. Aviation Week and Space Technology (2007) reported P&W gained FAA certification on nineteen parts for CFM56-3 engines for Boeing 737-300/400/500 aircraft. Further, a new entrant to the repair parts market, Heico Corporation of the US gained PMA authority on unpatented parts for GE and P&W engines (Hemlock, 2007). The repair parts market is huge and may eventually appeal to new entrants from China, India or Russia as demand for air travel grows and the extra capacity generated by the slump in traditional export markets grows. Currently, supplier bargaining power is low.

2.4.2.6 Comments

Porter (1979) may be criticised for excluding the synergistic benefits of collaboration; the geographical advantages of localised clusters; national strategic considerations and government aid that is repayable if a project succeeds or classed as a subsidy if it fails.

2.4.3 Short-Term SWOT

Table 2.8 shows a Strengths, Weaknesses, Opportunities and Threats (SWOT) audit for the short-term. This shows the main internal and external factors that may influence RR performance to help co-ordinate a set of rational responses to probable developments.

<u>Strengths</u>	<u>Weaknesses</u>
• Number 2 Supplier • ~34% Market Share • Outperforming FTSE 100 • Agile and Responsive • Good R&D / MRO Capability • Strong Collaborations	• Low Returns • No Cash Dividends for 5 Yrs • Increasing Inventory Levels • OWC of Profitable Customers • Core/Critical Business • Impact of Short-Term Actions
<u>Opportunities</u>	<u>Threats</u>
• Innovate Business Model • WIN-WIN Lease Agreements • Learn from Competitors • Strengthen R&D • Biofuels	• GE and P&W • Global Recession ◆ Reduced Demand ◆ Uncertain Oil Prices ◆ Cancellations/Delays • Increasing Material Costs • Job Losses/Redundancies

Table 2.8: RR SWOT Analysis – Short-Term

2.4.3.1 Strengths

RR has ~34% of the civil aero engine market, behind GE with ~39%, but ahead of P&W with ~27%. RR is currently outperforming the FTSE 100 All Share Index. According to GS, RR “moved faster than other European civil aerospace companies to reduce costs in response to the current economic crisis” (Kumar, 2009). The company has very high brand equity; strong bargaining power; solid technology track record; successful collaborations with academia and industry, good R&D capability and robust MRO structure. RR collaborations strengthen core capabilities from cost and supply chain management to the design, manufacture, sales and leases of its products.

2.4.3.2 Weaknesses

RR has low returns because the primary aero engine sales market has a long payback period and is the main reason for not paying shareholders a cash dividend for five years. Although expansion of the product range satisfies strategic aims to increase market share, this may lead to obsolete inventory and issues in production planning to require the transfer or manufacture of new production and test facilities. RR is less diversified than its rivals and therefore less immune from any short-term declines in civil aviation. The company is also believed to trail GE in terms of engine surges; in-flight shutdown rates and aborted takeoffs and must eliminate aero engine faults, clock stops and late deliveries to improve customer satisfaction. RR should use data mining to identify OWC for its most profitable customers to gain a quality, cost and time advantage over its rivals. Finally, RR senior management should take a much longer term strategic view of the organisation to understand their core and critical businesses and the consequences of short-term decisions on its longer-term future.

2.4.3.3 Opportunities

The recession made it unlikely for airlines to place large aircraft and aero engine orders over the next two to three years. In this period RR must focus on its aero engine leasing business; learn from competitors; strengthen collaborations; improve R&D capability and finally, make all its aero engines compatible to use 100% sustainable biofuels.

2.4.3.4 Threats

GE and P&W pose a threat alongside the global recession and uncertain oil prices that reduced the demand for air travel and the ability of airlines to invest in new aircraft and aero engines. Escalating raw material costs and delays in major aircraft programmes resulted in 2,300 RR job losses in 2008 (Waller, 2008). RR expects to reduce its

workforce by a further 1500 – 2000 in 2009 (Terrett, 2009). Similarly, GE and P&W expect to cut ~1,000 staff (Geoghegan, 2009).

2.4.4 Long-Term SWOT

Table 2.9 shows a long-term SWOT analysis and the scenario if RR successfully adapts to the changes in strategic context, circumvents threats and grasps all opportunities.

<u>Strengths</u> • ~38% Market Share • Best Commercial Terms • High Technical Performance ◆ Lowest Emissions ◆ Best Fuel Efficiency ◆ Highest Engine Reliability • WIN-WIN Lease Contracts ◆ High Returns ◆ Cash Dividends ◆ City Confidence ◆ R&D Launch Capital • Best R&D and MRO • Understands and Aligns to ◆ Strategic Operating Context ◆ Most Profitable Customers ◆ Core and Critical Businesses	<u>Weaknesses</u> • Little Diversification • Political Interference • Susceptible to Global Cycles
<u>Opportunities</u> • Civil Aviation Growth ◆ New Strategic Alliances ◆ ~139,000 Aero Engines ◆ ~\$810 Billion Value • WIN-WIN Lease Agreements • Improve Supply Chains • Instils City Confidence ◆ More Launch Capital	<u>Threats</u> • GE and P&W • Reversion to Buying Engines • Future Recessions • Oil Price Volatility • Little R&D Launch Capital • New Entrants in MRO • Raw Material Costs • Open-Rotor Concepts • China, Russia, India

Table 2.9: RR SWOT Analysis – Long-Term

2.4.4.1 Strengths

Low emissions aero engine technology may increase RR market share by ~4% to ~38% because all aero engine suppliers will meet the emissions legislation to compete. Fuel efficiency, engine performance and reliability will become key differentiating factors in cohort with offering the best commercial terms. Leasing aero engines that meet current combustion emissions legislation removes many uncertainties from airlines because they will no longer need to factor in future changes in legislation over the entire engine life cycle; rather they will procure the most cost-effective solution to satisfy their shareholders. Collaboration during the pre-competitive, pre-technology aero engine capability acquisition phase will cut costs and the time to develop low emissions and other technologies. More lease agreements will increase returns, satisfy shareholders, instil City confidence and provide R&D launch capital for new projects. An increased agility and responsiveness coupled with a greater knowledge of core and critical businesses and profitable customers will help RR to target resources for maximum gain.

2.4.4.2 Weaknesses

Increasing inventory; less diversification than competitors, political interference and susceptibility to global economic cycles will remain key weaknesses for RR.

2.4.4.3 Opportunities

Civil aviation growth over the next twenty years will create a market for ~139,000 aero engines worth ~\$810 billion at current prices. RR must seek new strategic alliances to build market share and secure funds to invest in alternative fuels and new technologies.

2.4.4.4 Threats

RR will remain under threat from GE and P&W. However, both RR and GE will be threatened if there is a relaxation in ICAO Chapter 4 noise legislation and a mass switch to turboprop aircraft to reduce fuel burn and CO₂ emissions as the P&W geared turbofan engine, under development since the 1990s may be the “game changer”. However, all suppliers may confront new competition from Russia, India or China in this area. Currently, aero engine suppliers and airlines prefer WIN-WIN lease agreements but as reliability increases and purchase costs fall some airlines may to revert to buying aero engines. In this event, RR must take proactive steps to protect its aftermarket business. First, it must patent parts that sell at higher prices than patenting costs to reduce demand for rival aftermarket service providers such as Heico Corporation of the US that offered a ~25% discount over named brands to levels where new entrants were unable to profitably enter the market. Second, RR must calculate the total costs of ownership in

terms of buying versus leasing and adopt a limit pricing strategy that encourages airlines to lease engines or only buy with locked in maintenance contracts. Although this will protect the RR aftermarket business, other firms may supply parts for GE or P&W. If airlines revert to traditional methods of engine procurement, GE may sell aero engines at a loss until RR and P&W fold. Although governments and competition authorities will oppose the creation of a GE monopoly, RR and P&W would significantly weaken before government intervention. Airlines must be discouraged from buying aero engines. Future threats may come from Russia, India and China; future recessions; more oil price volatility; pandemics; terrorism; rising costs of steel, copper, aluminium and scarce metals such as rhenium, chromium, cobalt and titanium (Blas, 2008).

2.4.5 Aero Engine Collaborations

Space, military and civil programmes have largely benefitted from collaborations. Successful collaborations enable partners to commit less expenditure for potential rewards at the opportunity cost of reduced pay-offs. Although joint ventures may be contrary to the public interest they are increasingly vital to remain globally competitive. In the civil aero engine sector strategic alliances help aero engine suppliers to broaden their product range and increase market shares by providing access to markets in partner countries. It also increases overall knowledge and understanding of competitor working practices. The modular nature of modern aero engines particularly suits strategic alliances as each partner provides a tried and tested module. The engine core contains the most critical technology and consists of the compressor, combustor and turbine. Because these are considered to be the “crown jewels” of an aero engine company, the latest core technology is never used in collaborations to prevent reverse engineering. Two prominent strategic alliances are CFMI and IAE. CFMI was established in 1974 as an equal venture between GE and SNECMA to produce the CFM56 family of engines. Figure 2.23 shows GE supplies the core and SNECMA the Low Pressure Turbine (LPT) and Fan. Currently ~19,000 CFM56 engines are in service on Boeing 737-300/400/500 and Airbus A318/319/320/321 aircraft with ~500 customers (CFMI, 2009).

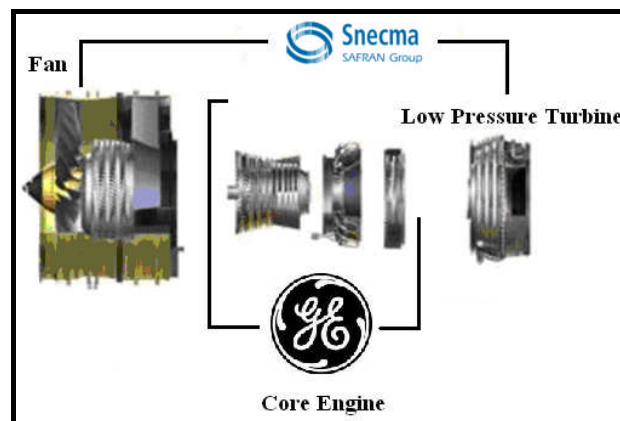


Figure 2.23: CFM Work Split (CFM56, 2009)

IAE was formed in 1983 and is led by senior partners RR and P&W each with a 32.5% share, Japanese Aero Engines Corporation (JAEC) with 23% and MTU Aero Engines of Germany with 12%. IAE produces the V2500 engine family to compete with CFMI. It currently has ~3,500 V2500 engines in service on ~1,400 Airbus 319/320/321 series of aircraft with ~155 airlines (IAE, 2009). Figure 2.24 shows partner contributions:

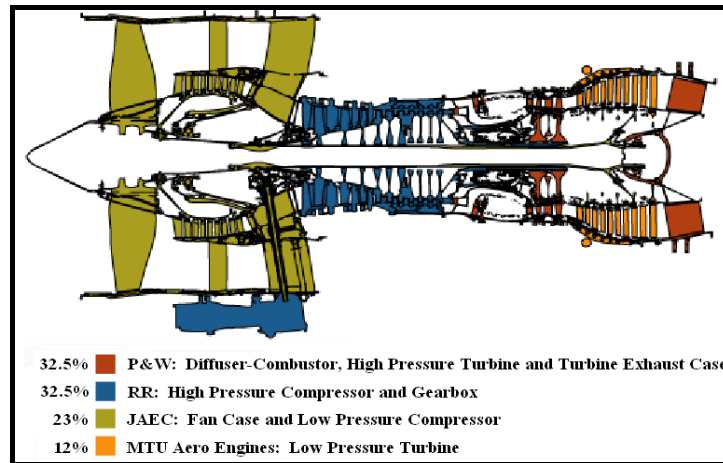


Figure 2.24: V2500 Work Split (IAE, 2009)

Less significant collaborations are the Engine Alliance (EA) between GE and P&W to develop an engine for the A380; and RR partnerships on the RR Trent XWB engine for the Airbus A350 XWB: ~40% will be shared by Kawasaki Heavy Industries (KHI) and Mitsubishi Heavy Industries (MHI) of Japan; Industria de Turbo Propulsores SA (ITP) of Spain; Volvo of Sweden, Hispano-Suiza of France and Parker Hannifin of the US.

2.4.6 Hypothetical RR Monopoly

The following hypothetically describes the impact of a single aero engine supplier in the aero engine market. If RR was a monopoly, it would perhaps allocate a set amount of funds to develop a new engine and quite possibly engage in opportunistic behaviour to extract maximum economic rent from the market and gain super-profits. Figure 2.25 shows how a monopolist RR may restrict its output to control demand and prices.

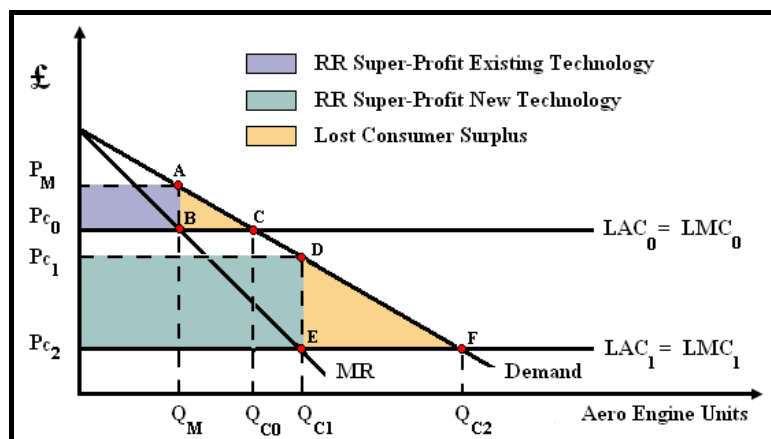


Figure 2.25: Monopolist Profits and R&D Investment (Rickard, 2000)

RR would operate at constant returns to scale and have a horizontal Long Run Average Cost (LAC) curve. Since costs would not increase with output, the Long Run Marginal Cost (LMC) curve would also be horizontal. To maximise profits, RR would reduce output until LAC_0 equals Long Run Marginal Revenues (LMR), or Q_M to sell at price P_M and reap super-profits shown by the purple rectangle P_MABPC_0 . Super-profits are a loss of consumers' surplus equivalent to the orange triangle, ABC . Although a firm has private interests to build market power, the point of this section is to demonstrate that a monopolist RR or indeed any single aero engine supplier is in fact against the public interest because it would reduce economic welfare and misallocate resources. Although governments may decide to tax super-profits, the orange area is considered to be a "dead-weight loss", although its magnitude lessens with increased EOS.

Under perfect competition the aero engine sector would produce a level of output determined by supply and demand and marginal costs would equal the industry supply curve. The demand curve would locate at point C , raise output to Q_{C0} and reduce price from P_M to P_{C0} . A monopolist RR would invest some super-profits in R&D to acquire patents and hence improve its technology and processes to drastically reduce LAC_0 to LAC_1 . These measures would raise entry barriers and discourage new entrants. Output would increase from Q_M to Q_{C1} and prices drop from P_M to P_{C1} . Because of the investment, the expected increase in profit is the difference in area between the blue rectangle, PC_1DEPC_2 and purple rectangle, P_MABPC_0 . Although it marginally benefits consumers, the new price P_{C1} is higher than P_{C2} of the competitive market structure. In this situation, governments must trade-off the potential cost savings to consumers because of new technology: P_M minus P_{C1} against the loss of consumer surplus, P_{C2} minus P_{C1} . For this reason, it is better that several aero engine suppliers compete.

2.4.7 The R&D Race

The window of opportunity to reverse or stop GCC is slim and technically uncertain. Currently, combustors are small, light, durable and close to 100% efficient. However, growing concerns over LAQ and GCC make low emissions design a prominent feature of RR, GE, P&W, IAE and SNECMA competitive strategy. Whilst it is recognised that competition gives the lowest cost and highest quality products, it also assumes perfect competition where many players compete and individual changes in output do not influence prices. It is a very different world in an oligopoly; although aero engine manufacturers are extreme rivals it is wasteful on the world's precious resources to spend large amounts of money in activities that tantamount to essentially the same thing – society deserves productive efficiency, even though the aero engine sector satisfies national strategic interests. Many theories suggest that oligopolists tend to overspend

and yet accomplish similar goals without having any serious impacts on the long run competition (Reinganum, 1989 and Rickard, 2006) in attempts to mitigate two risks:

- The prospect of coming second
- The failure to develop a winning technology

Invention and innovation represent an intertemporal decision to invest in the expectation of making a net return at a future point. Technical change alters the basis of competition and consists of:

- Invention – the generation of new ideas
- Innovation – transformation of those ideas into a marketable product or process
- Diffusion – the spread of use and ownership of the new technology

Models of perfect competition and perfect information imply that in general, R&D expenditure is irrational because of immediate diffusion. In reality, competitors take a long time to emulate and improve upon an available technology. Innovation that leads to a patent gives a true competitive advantage. Although financially rewarding, it is a complex, lengthy and risky process. A patent safeguards intellectual property rights on information for a period of time. However, to acquire a patent may take several years and competitors may seek legal action to dispute its originality (Hermida, 2005) or argue its lifespan (Shankar, 2008). A successful patent instils a degree of monopoly power and delivers economic rent. As super-profits lead to innovation and vice versa, both a monopolist and new entrants have large incentives to innovate. The monopolist seeks to protect the current value of its super-profits whilst new entrants strive to build market share. In general, monopolists innovate faster and cheaper than new entrants can do either and often play a fast second, e.g. International Business Machines (IBM) in mainframes (Rickard, 2000). In truth, a monopolist has more incentive to innovate since it raises entry barriers and keeps new entrants out for much longer. In the aero engine sector all suppliers are consistent in the belief that high R&D expenditure is critical to patent, validate and transfer new technology into aero engines and follow the argument that more R&D expenditure, although it will never guarantee, increases probabilities of:

- Being successful
- The first to market

In going down this path, all aero engine suppliers are exposed to the danger that the day before they solve a problem one of their competitors files their patent. The trouble is that all three follow the same reasoning; none may get the patent but a substantial

amount of time and money is spent in efforts trying to get there at the cost of reduced profits or dividend payments to shareholders. Figure 2.26 considers hypothetical R&D expenditure for a low emissions technology in a RR and GE duopoly. It reflects the R&D race to be first by increasing expenditure and shows benefits of a co-operative solution to acquire joint patents to cut development times, costs and the risks of failure.

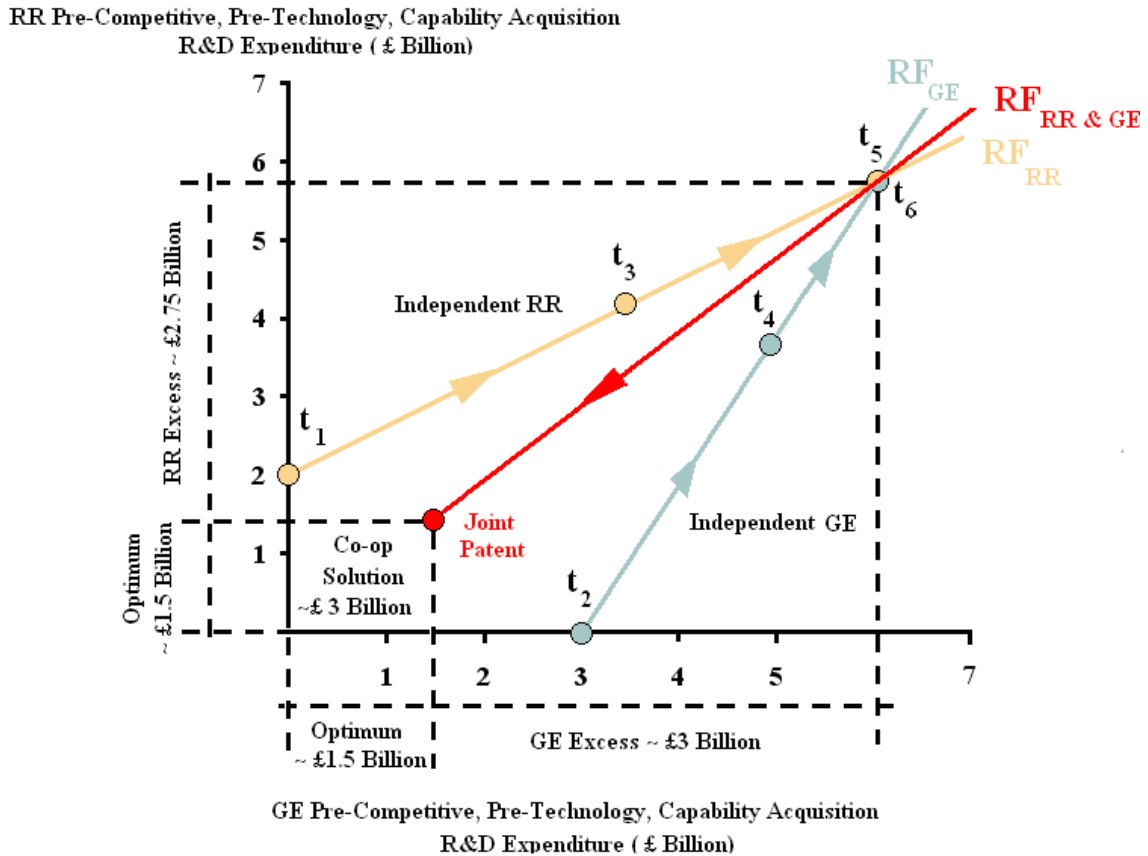


Figure 2.26: RR and GE Research Expenditure (Reinganum, 1989)

At time t_1 , RR decides to spend £2 billion to acquire low emissions technology, represented by the orange circle on the y-axis. At t_2 , GE learns of the RR investment and decides to spend £3 billion to achieve a similar capability, shown by the blue circle on the x-axis. RR now discovers that GE has jumped on board and is trying to develop a similar product but is spending more. To beat GE to market, RR research expenditure now moves up along the RR reaction function, RF_{RR} at t_3 to £4 billion. GE notices the increased RR investment and reacts by increasing its own investment at t_4 to £5 billion and the blue circle moves up the GE reaction function, RF_{GE} . GE has thus signalled to RR that it has found a promising technology and is undertaking more complex analysis to prove its merit. It forces RR to spend more to catch up with GE. Both firms however believe they are in similar positions with promising technologies and the sequence continues until a natural equilibrium point is reached at times t_5 and t_6 , where both RR and GE have acquired a potential technology that may reduce combustion emissions. RR and GE have jointly spent a total of £12 billion in getting to this stage. The red circle shows the actual investment cost of ~£3 billion to acquire the technology. In

conclusion, RR and GE have both spent an extra £4.5 billion each by working alone and in trying to outdo each other. In this sense, rivalry and some market power encourages non-cooperation but also increases individual R&D expenditures because both firms relay false signals. To reinforce this argument, Jones (2009) reported that between 1972 and 1980 the US commissioned 15 full-scale large engine fuel-staged combustors and spent \$200 million in R&D activity, while the UK commissioned just one and the EU spent \$50 million. Jones concluded that neither programme justified the lengthy timescale or high R&D expenditures although GE did continue with its research and launched the staged combustor in 1990 for the CFM56 engine. However, these efforts had evolutionary rather than revolutionary impacts on combustor design.

2.4.7.1 Competition Law

Aero engine manufacturers are subject to competition law. In the past, competition authorities prohibited co-operation over fears that consumers would be conspired against. Courts assumed that an exchange of information resulted in collusive behaviour and that oligopolists hand-in-glove together were likely to form a cartel, raise entry barriers, increase prices and economic rents. The Scottish economist Adam Smith stated: “People of the same trade rarely meet together, even for merriment or diversion, but the conversation ends in conspiracy against the public or in some contrivance to raise prices” (Smith, 1776). However, in recent times anti-collusion laws are rarely enforced as large businesses can bring economic benefits to a nation. In the US and Europe the courts consult the “Rule of Reason” that states “every contract, combination in the form of trust or otherwise, or conspiracy, in restraint of trade or commerce among the several States, or with foreign nations, is declared to be illegal” (Hartley, 1999).

Courts now interpret the rule more leniently and examine co-operation on a case-by-case basis to test reasonableness and the legality of business conduct. Section II of the US Sherman Antitrust Act (1890) and Article 86 of the EU Treaty of Rome (1957) prevents firms from engaging in non-cooperative strategic behaviour and acting akin to a monopoly. Article 85 of the EU Treaty exempts any agreements to set market share; price; stifle investment, or technological development if these promote efficiency in production, distribution or technical progress to benefit consumers. There is a growing recognition that not all co-operation per se is bad and against the public interest. Given the political drive to improve LAQ and attempts to reverse GCC, the law is unlikely to oppose collaborations in low emissions aero engine design; especially during the pre-competitive, pre-technology, capability acquisition phase on unproven future technologies. Firms that may actually refrain from joining together to fight climate change due to culture, intense rivalry and mistrust may be perceived as being less moral.

2.4.8 Game Theoretic Approach

Game theory has broad application in all fields of strategic decision-making. Since the early 1950s it has been used to study war, economics and business strategy. The discipline concerns the mutual interdependence of player decisions and helps remove residual uncertainties in competitor responses. Essentially, it assumes that all players behave in a rational manner to identify acceptable risks and uncertainties in competitor decisions. The forthcoming analysis uses a game theoretic approach to portray the benefits of collaboration during aero engine design. In this context it can reduce R&D costs; time to market; the price of failure and increase the knowledge base.

A player can therefore pre-empt competitor responses and adapt their own behaviour by learning from mistakes and competitor reactions. To construct the game, players must be identified, available strategies described and the pay-offs for every combination of strategies described. A mechanism must also exist to detect and deter cheating. Firms may use game theory for mutual gain. The prevailing view taken by all aero engine suppliers is to keep information private and hence willingly run the risk of engaging in R&D activity that competitors may have already investigated and subsequently rejected. Figure 2.27 shows independent and co-operative strategic behaviour during a hypothetical collaboration in the pre-technology, pre-competitive capability acquisition phase pertaining to any unproven future technology:

	GE Independent B1	GE Co-operate B2
RR Independent A1	$R\&D_{RR}$ £1million / $R\&D_{GE}$ £1million	$\alpha R\&D_{GE}$ £2million / $\beta R\&D_{RR}$ £0.25million
RR Co-operate A2	$\alpha R\&D_{RR}$ £2million / $\beta R\&D_{GE}$ £0.25million	$\lambda R\&D_{GE}$ £0.5million / $\lambda R\&D_{RR}$ £0.5million

Figure 2.27: RR and GE Pay-Off Matrix

The matrix shows a market contested by RR and GE in a duopoly where $\alpha > 1 > \lambda > \beta$. In this example, $\alpha = 2$, $\lambda = 0.5$ and $\beta = 0.25$. The pay-off is reduced monthly R&D expenditure for each firm. The matrix is read as follows: Cell A_1B_1 represents the status quo where both firms work independently and have a monthly R&D expenditure, $R\&D_{RR}$ and $R\&D_{GE}$ of £1million each. Cell A_2B_1 shows the outcome if GE remains independent, RR co-operates and shares information. The result of GE non-cooperation is $\beta R\&D_{GE}$ and a pay-off that reduces monthly GE expenditure to £0.25 million. GE may achieve this through pinching some RR ideas or by suggesting a failed technology for RR to investigate to increase RR R&D expenditure, $\alpha R\&D_{RR}$ to £2 million. Cell

A_1B_2 shows the reverse situation where GE suffers from RR non-cooperation and increases its research expenditure by the corresponding amount of $\alpha R\&D_{GE}$. Faced with the set of alternative strategies, both firms know that if they co-operate they halve their monthly R&D expenditure in one information exchange period. Cell A_2B_2 shows the case if RR and GE genuinely co-operate and share all information; tangible and intangible because the financial and technical benefits of doing so far outweigh keeping it private and $\lambda R\&D_{GE \text{ or } RR} = \text{£}0.5 \text{ million}$.

If GE cheats in the first information exchange period it saves $\text{£}0.25 \text{ million}$ but if discovered, RR will punish it in the next period and vice versa. For GE and RR the total R&D bill over both periods will be $\beta R\&D_{GE \text{ or } RR} + \alpha R\&D_{GE \text{ or } RR} = \text{£}2.25 \text{ million}$. As a result of non-cooperation, both will spend an extra $\text{£}1.25 \text{ million}$ over two information exchange periods. It will therefore be irrational for either party to cheat since $(\beta R\&D_{GE \text{ or } RR} + \alpha R\&D_{GE \text{ or } RR}) > 2R\&D_{GE \text{ or } RR} > 2\lambda R\&D_{GE \text{ or } RR}$. If GE and RR both cheat in the third information exchange period they receive no additional benefit than having worked independently and $R\&D_{GE \text{ or } RR} = \text{£}1 \text{ million}$ as in Cell A_1B_1 .

This is the theoretical underpinning behind why RR and GE should co-operate. However, backward induction implies that if the game is to end the dominant strategy for both GE and RR would be to cheat in the final information exchange period. To cheat in this last period is obvious to both parties so cheating is likely in the penultimate period and then the third to last until cheating is the most logical outcome from the very onset of the collaboration; hence it is illogical to co-operate in a game with a finite ending. The lengthy pre-competitive, pre-technology capability acquisition design phase would theoretically involve many information exchange periods to give little incentive to cheat. Although the damage will not be permanent and trust can be restored, its collapse may result in a temporary removal from the game and in the extreme, jeopardise future partnerships. Multiple, concurrent collaborations on future technologies, however, do give the scope to continue and broaden a game but this relies on firm cultures and the managerial skills and foresight of rival oligopolistic managers.

Overleaf, Figure 2.28 shows the beneficial impacts of collaboration during the pre-competitive, pre-technology capability acquisition phase of aero engine development on any future technology. Historically, the initial investigation of unproven technologies attracted little company resource until the technology was close to validation. The chart shows that joint R&D investments amount to more than a single company can afford in the current economic climate to acquire a patent. It also shows that extra funds result in a faster engine launch at about half the overall cost and time to each partner.

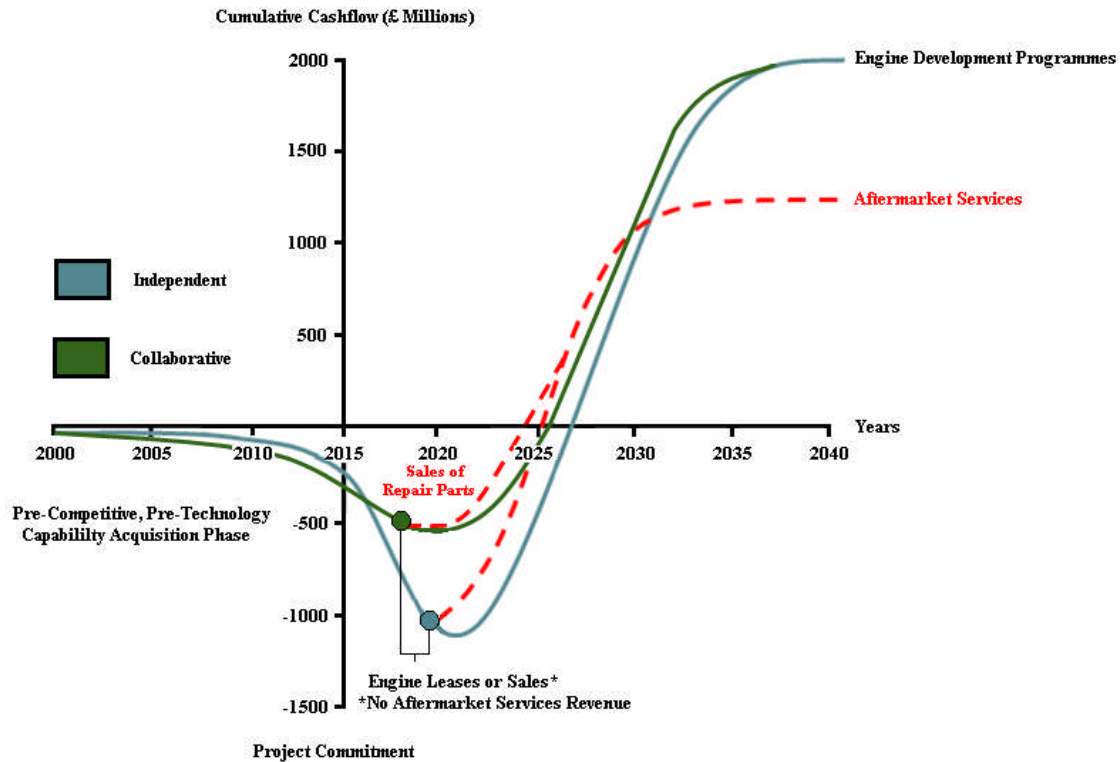


Figure 2.28: Pre-Technology Co-operation in Aero Engine Development

The proposed collaboration is on future unproven technologies and for joint patents where various approaches are under consideration. It does not advocate collaboration in areas that may bring an imminent competitive advantage such as in RR Vision 5 or Vision 10 Programmes. Under the “Rule of Reason” it makes economic sense for aero engine suppliers to save millions of pounds over the lengthy engine development period on future unproven technologies. The proposed collaboration ends once a joint patent is acquired; indeed, nearer to market competition law and firm culture will strictly forbid its continuation. By altering the basis of competition the main source of competitive advantage will become the pace of technology transfer into a product and in being the first to market; securing engine certification; engine exclusivity and the most orders.

Although Lord Duncan of RR briefly explored co-operation with GE in the 1980s, some personalities may strongly oppose it because of intense rivalry and mistrust. It is not necessary for partners to like each other providing they can sensibly delegate work to take advantage of individual strengths. Despite a reluctance to co-operate due to firm culture and all the arguments and mindsets, a joint venture in the form of a research club to thrash out new ideas and test unproven concepts will reduce costs, time to market and the risks of failure for all parties. One company cannot possibly know everything but several working together might produce better answers.

Aero engine suppliers have a moral responsibility to reduce emissions. If manufacturers can co-operate and understand how to achieve this and share initial development costs it surely becomes a WIN-WIN and a way forward that would benefit from a wider discussion. Some may give the idea to collaborate short shrift but in low emission design the combustor is largely insensitive to the physical arrangement of an aero engine; if it receives an adequate quantity and quality of air from the compressor the same technology can be read across competitor aero engines with few adjustments. Having lifted this major environmental constraint, competition could focus on other aspects. This idea is expected to receive strong political support and little opposition from competition authorities. Arguably, collaboration to develop joint patents in future low emissions technologies is a “public good” that is worth contemplation and further discussion due to the seriousness of global warming and fact that this approach may be regarded as a stimulus for change and improvement throughout the aerospace industry.

2.5 SUMMARY

Civil aviation will face three long-term changes in strategic operating context: air travel growth of ~3.2% per annum over the next twenty years despite the current economic downturn; tighter combustion emissions legislation due in 2012 and finally, participation in the European Union (EU) Emissions Trading Scheme (ETS) from 1st January 2012. These changes have significant impacts on the civil aero engine sector, essentially contested by three firms: the research sponsor, Rolls-Royce plc (RR), General Electric (GE) and Pratt and Whitney (P&W). Two prominent strategic alliances are CFM International (CFMI) and International Aero Engines (IAE). Market shares are approximately GE 39%, RR 34% and P&W 27%. Currently, RR is outperforming the FTSE All Share Price Index from July 2009 to the present day, 21st December, 2009. UTC performance, the parent company for P&W is mirroring the S&P 500 whilst GE is faring significantly worse. This suggests that RR responded better to the harsh economic climate in 2009 than GE or UTC; although it is uncertain how their individual civil aero engine divisions performed within both organisations.

Aero engine suppliers must constantly align to incoming changes in strategic operating context. A critical aspect will be the development of low emissions aero engines. The undertaken research presents a novel method to predict fuel spray performance to attain low combustion emissions at ~4% of traditional running costs per fuel injector. This will cut overall costs; time to market and the inherent risks in low emissions, stable combustion systems design. Best low emissions capability and customer service will give RR access to a global market for ~139,000 aero engines worth ~\$810 billion at current prices. The Political Economic Social and Technological (PEST) analysis suggested that calls to reduce aircraft emissions will increase as the recession ends.

Governments can only enforce legislation that people are immediately prepared to accept. Sector performance depends on global cycles that impact supply and demand. Globally, airlines made a loss of \$16.8 billion in 2008; \$11 billion in 2009 and are forecast to lose \$5.5 billion in 2010. Aero engine technology is improving and second generation alternative fuels may be certified in the next five years although they may not be widely used for the next fifteen years. A Porter's Five Forces Analysis shows high competitive rivalry. Legislation appeared to favour the US; no clear cut answer existed regarding first mover advantage; and threats from potential entrants, substitute technology, customer bargaining power and supplier bargaining power were all low. The main threat is from new entrants in the aftermarket business. Whenever threatened, RR must collaborate or vertically integrate, enter the market and substitute from within.

In the short term, RR must maintain its agility and responsiveness to market conditions; improve its low emissions core competency and also invest in alternative fuels; strengthen its strategic alliances; improve customer service by minimising in-service problems; clock stops and late deliveries; use data mining to identify Order Winning Criteria (OWC) for its most profitable customers to gain a quality, cost and time advantage over rivals; take a longer term strategic view of the organisation to understand its core and critical businesses and the many consequences of short-term decisions on longer term interests; secure more WIN-WIN engine lease agreements; patent parts that sell at a higher price than patenting costs to protect its aftermarket business; employ dual sourcing strategies to limit supplier power and improve supply chain performance to increase efficiency and eliminate waste.

In the mid-term, RR should seriously consider collaborating with competitors in the lengthy ten to fifteen year pre-competitive, pre-technology capability acquisition aero engine design phase to acquire joint patents in Vision 20 type programmes. This will alter the basis of competitive advantage to the pace of technology transfer into a product and being first to secure engine certification, exclusivity and securing the most orders.

In the long term, RR must diversify; create innovative business models that constantly align to changes in operating context; increase WIN-WIN engine lease agreements to instil City confidence and provide extra R&D launch capital for the open rotor contra-rotating fan blade engine to compete against possible entrants from Russia, India or China; discourage airlines from buying aero engines but lock them into maintenance contracts if this occurs; expand to cope with increasing inventory; cut supplier switching costs; seek cheaper raw material suppliers; use lobbyists and consultants to win sales in emerging markets and most critically, learn from competitor mistakes and successes.

CHAPTER THREE

REVIEW OF AERO ENGINE EMISSIONS, LIQUID FUEL INJECTION AND LASER DIAGNOSTICS

3.1 INTRODUCTION

Aero gas turbine fuel injector development is driven by the triple need to eliminate combustion emissions, improve performance and cut operational costs. Chapter Two identified the urgent strategic need for the sponsor, RR to quickly and economically develop low emissions aero engines to protect sales and lease agreements since UN ICAO CAEP combustion emissions rules will tighten and eventually spread globally.

Aero engines use liquid fuel for practicality. In contrast to gaseous flames, spray flames have complex structures as the fuel must be broken down; sprayed; vaporised; mixed with air and ignited to provide enough heat release to drive the turbine and rotate the compressor. Eddies situated in the interface of the liquid and surrounding air influence the momentum, heat and mass transfer between the liquid fuel droplets and air to affect combustion instability and pollutant formation. Both undesirables are particularly sensitive to fuel patterning and to the degree of fuel and air mixing. Further, the quality of compressor delivery air to the combustor in terms of its velocity profile, pressure distribution and circumferential uniformity (Barker and Carotte, 2002) coupled with fuel injector design and size, fuel properties, combustor operating conditions and aerodynamics critically influences the quality of spray atomisation; as reflected in local temperature gradients, species residence times and concentration histories that influence the non-equilibrium products of combustion.

Principally, these include soot, Unburnt Hydrocarbons (UHC), Carbon Monoxide (CO), Oxides of Sulphur (SO_x) and the Oxides of Nitrogen (NO_x). NO_x emissions in the middle and upper stratosphere (17 – 20km) catalyse Ozone (O₃) destruction to raise ultraviolet (UV) radiation levels on Earth. In the upper troposphere and lower stratosphere (9 – 13km), NO_x forms O₃ and contributes to GCC. This chapter reviews pollutant formation and conflicting abatement strategies that antagonise low emissions design before describing pressure-swirl and airblast atomisation that are used in tandem with axial swirling airflows in the hybrid injectors characterised in this study. It closes with a synopsis of Phase Doppler Anemometry (PDA) and Laser Sheet Dropsizing (LSD) used to measure droplet Sauter Mean Diameter (SMD) and Planar Laser Induced Fluorescence (PLIF) for Air to Fuel Ratio (AFR) applied under cold flow, scaled conditions to develop the NO_x prediction tool and gain a priori knowledge of instability.

3.2 GAS TURBINE EMISSIONS

Figure 3.1 shows the typical location of a combustor in the high pressure core between the compression and expansion stages of an aero engine. Liquid fuel is injected in the combustor, mixed with air and ignited to generate the heat release to drive the turbine that rotates the compressor. Eq. 3.1 shows steady-state combustion of a hydrocarbon fuel produces Carbon Dioxide (CO_2), water vapour (H_2O) and Nitrogen (N_2). However, variations in local temperatures, species residence times and concentration histories also produce some non-equilibrium products. Ballal and Zelina (2003) stated that by mass, these are chiefly the Oxides of Nitrogen (NO_x) at ~86%; followed by Carbon Monoxide (CO) at ~12.4%; Unburnt Hydrocarbons (UHC) at 1.5% and Soot at 0.1%. Figure 3.2 shows UHC and CO emissions are greatest at the low power condition yet diminish as engine power increases, whilst the reverse trend is true for NO_x and smoke emissions.

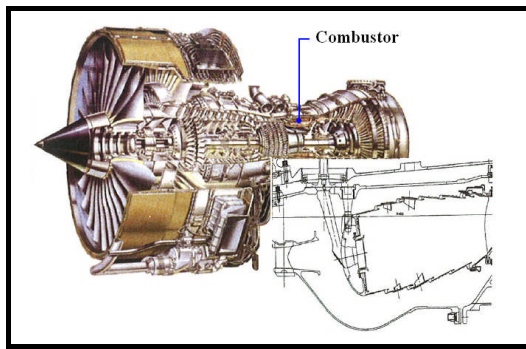
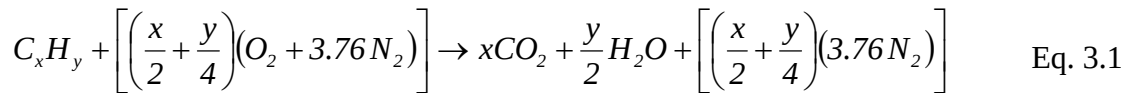


Figure 3.1: Combustor Location in an Aero Engine (Jones, 2009)

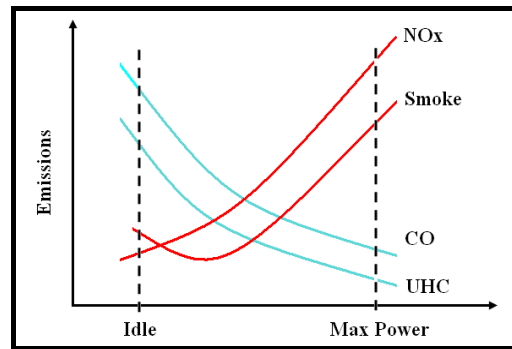


Figure 3.2: Emissions vs Engine Power (Lefebvre, 1989)

Figure 3.3 shows CO and NO_x emissions decrease at 1700 – 1900K to oppose current trends shown in Figure 3.4 to increase combustor pressures, inlet and outlet air temperatures for efficiency. Despite a CO_2 cut, conducive to airlines entering the EU ETS in 2012, this practice increases NO_x emissions that must be reduced due to GCC.

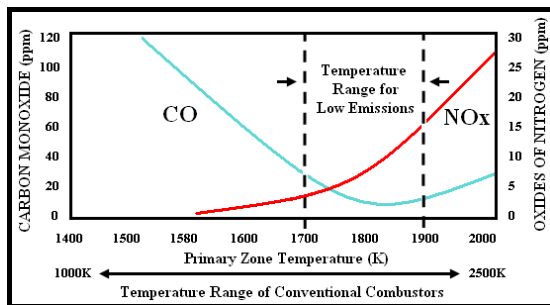


Figure 3.3: Low CO and NO_x Range (Lefebvre, 2000 and Singh, 2009)

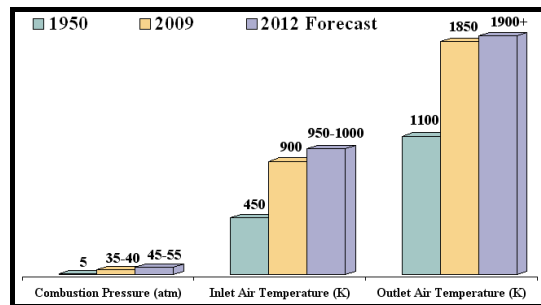


Figure 3.4: Combustor Cycles (Lefebvre, 2000 and Jones, 2009)

Table 3.1 shows four key pollutants formed at low and high powers in aero engine combustion along with their environmental risks, formation characteristics and conflicting abatement strategies. Pollutant formation is influenced by the combustion temperature (T_c); residence time (T_{res}) set by combustion volume (V_c); combustion pressure, (P_c) and fuel and air mixture strength determined by equivalence ratio (ϕ).

Pollutant		Environmental and Health Risks	Formation Characteristics	Abatement Strategy
• Low Power Condition	CO	• Toxic • Cuts O₂ Absorbing Capacity in Blood to Cause Asphyxiation	• Fuel Rich Zones, $\phi > 0.8$ With Less O₂ to Oxidise CO into CO₂ • Fuel Lean Zones, $\phi < 0.8$ With Low Temperatures to Slow Oxidation Rates • Insufficient T_{res} to Oxidise CO into CO₂	• Burn at ϕ of 0.7 – 0.9 • Increase V_c, (T_{res}) • Increase T_c • Increase P_c • Improve Fuel/Air Mixing
	UHC	• Toxic • Combines with NO_x to Form Urban Smog	• Inadequate Burning Rates • Low Temperatures • Excessive Air	• Burn at ϕ of 0.7 – 0.9 • Increase V_c, (T_{res}) • Increase T_c • Increase P_c • Improve Fuel/Air Mixing • Reduce Cooling Air
• High Power Condition	NO _x	• Toxic • Precursor to Smog • Destroys Ozone at 17 – 20km to Raise UV Radiation Levels • Creates Tropospheric Ozone at 9 – 13km to Warm Earth • Causes Skin Cancers, Allergies, Cataracts, Hearing Disorders and Harms Crops and Marine Life	• Thermal NO – Oxidation of Atmospheric Nitrogen in Post Flame Gases • Prompt NO – High Speed Reactions at Flame Front • Fuel NO – Oxidation of Nitrogen Within Fuel • Forms at High $T_c > 1800K$, Long T_{res} and High P_c	• Burn Lean at ϕ of 0.5 • Burn Rich at ϕ of 1.5 • Reduce V_c, (T_{res}) • Reduce T_c • Reduce P_c • Improve Fuel/Air Mixing
	Smoke	• Cloud Formation in Stratosphere that Contributes to Radiative Forcing and Global Warming • Polyaromatic Hydrocarbons that Condense on Soot Cause Cancers and Respiratory Diseases • Increases Detection by Infrared (IR) Missiles in Military Engines	• Forms in Rich Zones • Forms at High T_c • Forms at High P_c that Contract Spray Cone Angles to Increase Droplet Sauter Mean Diameter (SMD) and Richer ϕ	• Burn Lean • Improve Fuel/Air Mixing • Increase T_c • Increase V_c, (T_{res}) • Reduce P_c • Less Aromatic Fuels

Table 3.1: Pollutants: Environmental and Health Risks, Formation Characteristics and Abatement Strategies (Greenhalgh, 1998 and Singh, 2009)

3.2.1 Carbon Monoxide, Unburnt Hydrocarbons and Smoke

At low power excess air quenches some regions in the flame to let some hydrocarbons escape partially pyrolysed. According to Nagle (1962) and Neoh (1980), the first stage of soot oxidation yields CO. CO₂ does not form unless all the soot disappears. Detailed reviews on soot formation are available in Grigorian (2002) and Beyer (2006) who applied Laser Induced Incandescence (LII) to measure the very low soot concentrations typical in modern engine exhausts. Blevins (2003) and Ballal *et al* (2003) reviewed soot formation in efforts to develop fuel and chemical additives to limit its production. High power operation replaces flame quenching with rich burning to virtually guarantee the combustion of most hydrocarbons. However, incomplete mixing gives fuel rich zones that lead to incomplete combustion and smoke emissions that consists of finely divided soot particles, recently termed “nanoparticles” (Greenhalgh, 2009). Decreases in fuel flow and pressure reduce soot formation that occurs through pyrolysis; inception; surface growth; oxidation; coagulation and aggregation into clusters (Smith, 1981). Smoke legislation applies in the low power mode as heavier UHCs are thought to be less harmful to human health than the lighter UHCs formed at higher power conditions.

3.2.2 Oxides of Nitrogen

Oxides of Nitrogen (NO_x) consist of Nitric Oxide (NO); Nitrogen Dioxide (NO₂); Nitrous Oxide (N₂O); Nitrogen Tetroxide (N₂O₄) and Dinitrogen Pentoxide (N₂O₅). However, NO_x commonly refers to NO and NO₂. NO_x emissions are exponentially dependent on flame temperature and near linearly dependent on residence time. Relative contributions of thermal NO are largest, followed by prompt NO, nitrous oxide reactions and fuel NO. NO_x emissions concern scientists and governments because they participate in catalytic reactions that deplete stratospheric ozone and increase tropospheric ozone. The trends to increase combustor operating temperatures for fuel economy may decelerate given the need to reduce NO_x to result in higher CO₂ emissions. As mentioned in the previous chapter, an in-built mechanism already exists to reduce CO₂ in the price of fuel. Bowman (1992); Correa (1992); Lefebvre (1995); Steele *et al* (1997) and Faeth *et al* (1998) reviewed mechanisms of NO_x formation in flames whilst Schumann (1997) and Grooß *et al* (1998) simulated its impact on atmospheric chemistry. Emissions in the middle and upper stratosphere (17 – 20km) catalyse ozone destruction to increase ultraviolet (UV) radiation levels on Earth. NO_x emissions are implicated in growth of the Ozone Layer Hole (OLH) over the Antarctic that is now approximately the size of the US. Another hole in the Ozone layer has also been discovered over the Northern Hemisphere (Singh, 2009). In the upper troposphere and lower stratosphere (9 – 13km), particularly north of 30°N according to Schumann (1997). NO_x forms Ozone (O₃) and contributes to global warming, although Hydroxyl

(OH) radicals cut lifetimes of strong greenhouse gasses such as Methane (CH₄) to help cool the planet. Overall, CAEP (2007) reported that aviation emissions contribute ~2% to all CO₂ emissions and ~3.5% to Radiative Forcing (RF).

3.2.2.1 Thermal NO

Aircraft fly at high altitudes to raise fuel efficiency and avoid poor weather systems. However, NO emissions in the middle and upper stratosphere (17 – 20km) participate in chain reactions that catalyse O₃ destruction and increase harmful UV radiation levels on Earth. Over-exposure to UV rays is implicated in skin cancers; cataracts; weakened immune systems; reduced crop yields and disruptions in the marine food chain. The extended Zeldovich mechanism shown between Eq. 3.2 and Eq. 3.6 describes the catalytic reaction sequence that creates Nitric Oxide (NO) (Zeldovich *et al*, 1947). The NO reaction mechanism requires high activation energies and proceeds if combustion temperatures exceed 1800K. In the first reaction, molecular oxygen dissociates into oxygen atoms. The second reaction shows atomic oxygen reacting with molecular nitrogen to form atomic nitrogen and nitric oxide. In the third reaction, atomic nitrogen reacts with molecular oxygen or hydroxyl radicals to form even more nitric oxide and atomic oxygen. The fourth stage of most concern shows the reaction between nitric oxide and stratospheric ozone that forms nitrogen dioxide and molecular oxygen and converts ozone into oxygen. Finally, nitrogen dioxide reacts with atomic oxygen to produce even more nitric oxide and molecular oxygen to repeat the sequence. Bowman (1992) reported that 50% of stratospheric ozone depletion was due to aviation. Predicted air travel growth over the next twenty years discussed in Chapter Two will only increase the present imbalance between sources and sinks in the stratosphere.



Lee and co-workers (1995) reported that NO production declined at equivalence ratios (ϕ) just above unity as fuel and nitrogen compete for the available oxygen. Although temperatures are slightly higher at richer conditions, oxygen consumes the fuel in preference to the nitrogen. NO emissions are comparable in lean mixtures where ϕ is

0.5 and also in rich mixtures where ϕ is 1.5. Lefebvre (1995) reported that thermal NO production was largely independent of residence time when $\phi \leq 0.5$. Providing the Zeldovich mechanism is suppressed with combustion at temperatures below 1800K, removal of the linear dependency with residence time allows the combustion time to extend long enough to also prevent the emissions of smoke, CO, UHC and NO_x.

3.2.2.2 Prompt NO

Prompt NO formation is more complex and less understood than thermal NO. This forms close to the flame zone in reactions between hydrocarbon fragments and molecular nitrogen. Although its generation is dominated at lower temperatures associated with lean combustion where O and OH radicals can attack nitrogen, it also forms in the fuel-rich pockets of diffusion flames. Eq. 3.7 to Eq. 3.13 show the reaction sequence of prompt NO formation (Faeth *et al*, 1998). First, molecular nitrogen reacts with a CH radical to produce HCN as the chief product that undergoes several oxidation steps. Eq. 3.10 shows production of more nitrogen atoms that react to produce more NO through reactions with OH or oxygen. Eq. 3.12 and Eq. 3.13 shows that prompt NO can also form through recombination reactions.



Bowman (1992) identified three reactions and flame conditions for prompt NO. First, in reactions where non-equilibrium concentrations of O atoms and OH radicals accelerate thermal NO in non-premixed flames, stirred reactors for lean conditions and in low-pressure premixed flames. Second, in reactions of hydrocarbon radicals near the reaction zone with molecular nitrogen that dominate in fuel-rich premixed flames and diffusion flames. Finally, in the reaction of oxygen atoms with molecular nitrogen to form N₂O and then NO that dominate as Air to Fuel Ratio (AFR) increases as the

burned gas temperature decreases or as pressure increases. Although the literature lacks data on the influence of pressure beyond an exponent, n of 0.5, Lefebvre (1995) proposed that prompt NO formation was largely independent of pressure below ϕ of 0.6.

3.2.2.3 Fast Nitrous Oxide Mechanism

NO production is significant under lean, low temperature conditions and is initiated by Eq. 3.14 shown below. Eq. 3.15 to Eq. 3.17 show nitrous oxide is an intermediary product; oxidised in the presence of free oxygen and hydrogen to form nitric oxide.

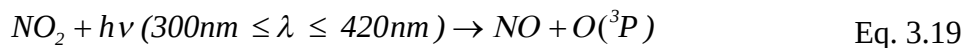


3.2.2.4 Fuel NO

Conversion of organically bonded nitrogen into NO steadily increases with flame temperature to make removal of all nitrogen content in the fuel refinery the best option.

3.2.2.5 Ozone Formation in Troposphere

Eq. 3.18 shows the production of nitrogen dioxide. Eq. 3.19 shows nitrogen dioxide reacts under the action of sunlight in the troposphere to yield nitric oxide and atomic oxygen. In the presence of a third body, Eq. 3.20 shows atomic oxygen combines with molecular oxygen to produce ozone. Eq. 3.21 conveys how ozone formation continues with production of more nitrogen dioxide to repeat the reaction in Eq. 3.18 and set up the dynamic equilibrium of Eq. 3.22.



3.3 COMBUSTOR DESIGN CRITERIA

Figure 3.5 shows the RR RB211 Phase 2 Combustor that was in service between 1975 and 1990. Figure 3.6 compares the design with the Phase 5 Combustor to reduce NO_x.

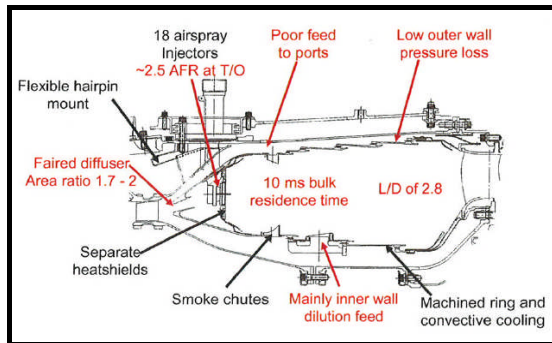


Figure 3.5: RR Phase 2 Combustor (Jones, 2009)

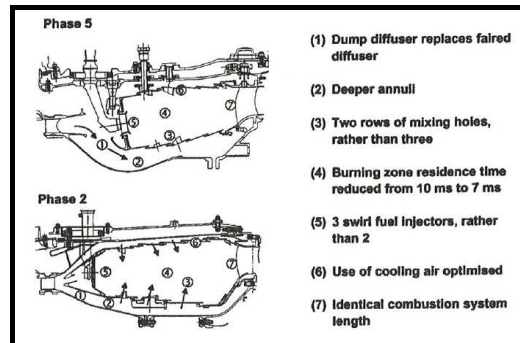


Figure 3.6: RR Phase 5 vs RR Phase 2 Combustors (Jones, 2009)

Although low emissions are an increasing priority, combustors must meet airworthiness requirements, be appropriately sized for other engine components; be 100% efficient; have stable operation; allow cold day ignition and altitude relight; have low pressure losses; good exit temperature quality; match the fuel sprays with aerodynamic flowfields and not rumble. Low emissions design requires fuel to be mixed with excess air before combustion but this reduces the air to cool other components (Low, 2004). Next, lower flame temperatures and short residence times to limit NO_x make cold day ignition and altitude relight difficult as lean fuel and air mixtures become harder to ignite in the smaller volumes necessary to reduce residence times. A large pressure loss improves fuel and air mixing control but incurs a fuel penalty. Finally, a priori knowledge of thermo-acoustic oscillations simply does not exist and LPP more strongly encompasses the possibility of oscillations that may be driven by subtle changes in combustion chamber acoustics from a variety of sources. A small change in the diffuser upstream of the combustor can allow compressor noise into the combustor, or a minor change in fuel injector design may cause eddy shedding from one of the wakes of the fuel injector stems to change the acoustics. The staged combustors in Figure 3.7 from RRD and RR-UK are more complex but they reconcile the aforementioned conflicts in low emissions design with separate zones to control temperatures and residence times.

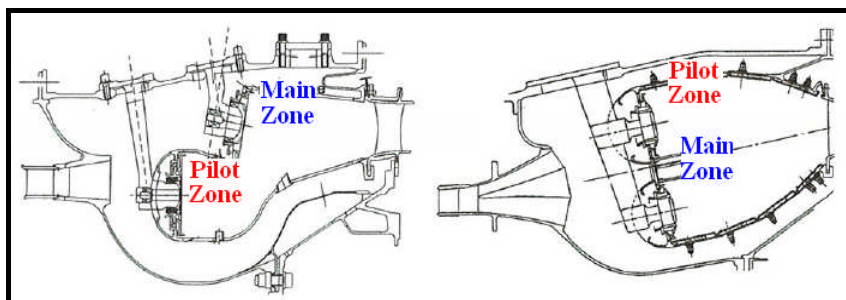


Figure 3.7: Staged Combustors RRD (L) and RR-UK (R) (Jones, 2009)

3.4 REVIEW OF LIQUID FUEL INJECTION

Detailed reviews on liquid fuel injection strategies are available in Lefebvre (1989, 1995 and 2000) and Lightfoot (2006). Basically, fuel injector designs evolved to satisfy changes in combustor operating cycles for efficiency and in response to emissions regulations. One key change from the late 1970s onwards was the steady migration from pressure-swirl to prefilming airblast atomisers with shear and swirl; although pressure-swirl atomisation combined with airblast atomisation is still widely used to expand stability limits conducive to engine start-up and altitude relight. For example, the GE SNECMA CFM56 combustor uses two co-axial counterswirling airstreams to deliver fuel from a simplex pressure-swirl atomiser located at the centre of a swirlcup. Although some droplets travel axially downstream, most contact the inner surface of a primary venturi that separates the swirling airstreams to form slim liquid sheets that undergo secondary atomisation (Wang *et al* 1993, Jasuja, 2004 and 2006). This action yields smaller fuel droplets and improves fuel and air mixing. The following section discusses pressure-swirl and airblast atomisation and swirl flows that help stabilise lean flames and also match fuel patterning with combustor aerodynamic flowfields – all three components are integrated in ANTLE weak modules. RR supplied several builds in kit format for the spray characterisation studies reported in Chapters Six, Seven and Eight. Figure 3.8 shows a typical kit of parts for the hybrid injector shown on the right; where the pressure-swirl atomiser is located at the centre of the large airblast atomiser and three axial air swirlers. It operates alone at low power for the aforementioned reasons. At higher powers the majority of fuel is supplied to the airblast circuit. This simplicity allows fuel staging at the nozzle and installation in a single annular combustor. The injector is a step towards full LPP combustion that will enter into service once issues of autoignition, weak extinction, flashback and rumble are solved.



Figure 3.8: Kit of Parts (L) and Assembled B61 (R)

3.4.1 Pressure-Swirl Atomisation

All pressure-swirl atomisers discharge high-velocity fuel into a lower-velocity airflow and atomisation improves as the velocity differential increases. The simplex design

delivers liquid to a swirl chamber via tangential ports to increase its velocity and impart a rotation as it exits the orifice; whilst duplex designs feature two tangential ports to broaden operability limits. Dual orifice atomisers are another permutation and have two simplex nozzles in one unit. The sprays do not mix internally but coalesce downstream. Figure 3.9 shows schematics of each design.

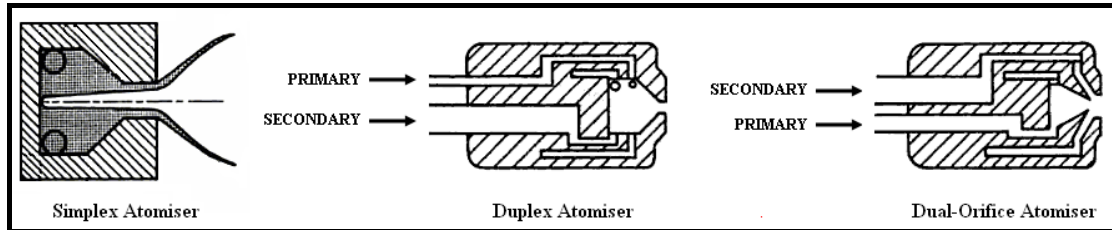


Figure 3.9: Simplex, Duplex and Dual-Orifice Atomisers (Lefebvre, 1989)

In each case the liquid breaks down according to the five main stages of Figure 3.10 into smaller droplets by shear forces exerted by aerodynamic drag and hydrodynamic forces. After the “dribble” and “distorted pencil” regimes, the centrifugal forces created by the swirling action of the air form and slim out an annular fuel sheet. Mean droplet diameters are proportional to the square root of initial sheet thickness. This deforms via hydrodynamic forces and breaks up into droplets to produce a hollow conical spray.

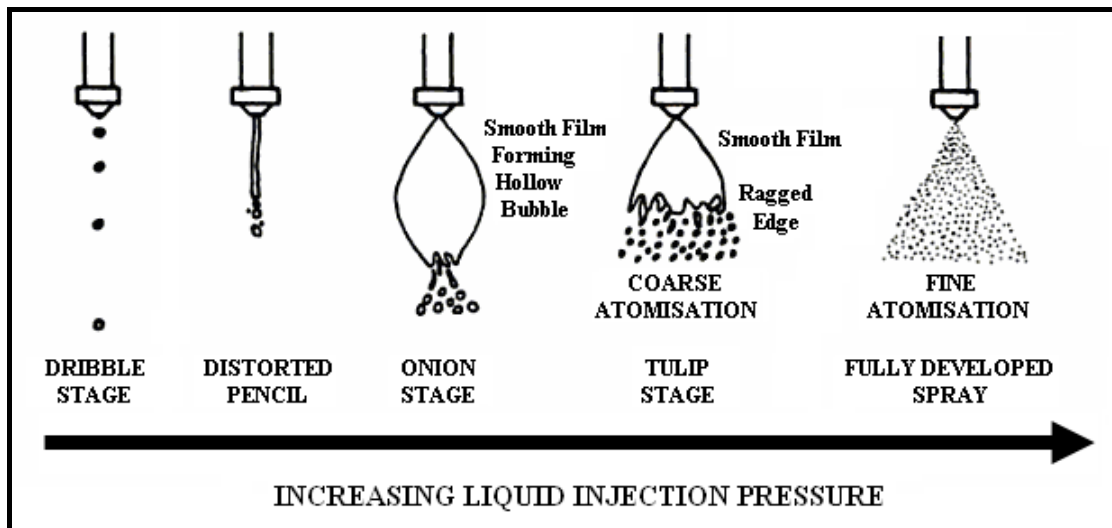


Figure 3.10: Spray Development Stages (Lefebvre, 1989)

In the first stage of atomisation, turbulence causes the smooth liquid sheet to wrinkle. Advantage is taken of instabilities within the liquid sheet itself to advance atomisation. The relative velocity difference between the liquid and air encourages waves to develop on the sheet surface. In airblast atomisation the liquid velocity contribution is negligible but in pressure-swirl atomisation it decreases over time due to aerodynamic drag until it matches the air velocity according to Newton’s Second Law. During the second stage of atomisation surface tension forces inside the liquid sheet oppose evolution of local anomalies into ligaments. However, the pressure difference across the nozzle eventually provides enough energy to overcome these reforming forces. Once created,

ligaments rapidly disintegrate into droplets. Greater turbulence intensities enhance the rates of wave formation on sheet surfaces. This results in a larger number of smaller unstable ligaments that enhance fragmentation to yield smaller droplets conducive to low emissions. In practice, smaller droplets require higher liquid velocities and flow rates; smaller orifices to reduce flow numbers; lower surface tension and viscosity liquids and larger spray cone angles to prevent droplet coalescence. Advantages of pressure swirl atomisers include operational simplicity; reliability; mechanical robustness; existence of well-documented design rules and principally, wide stability limits. The latter justifies their continued use in various guises to assist start-up where chamber velocities are low and for altitude relight where lean mixtures are difficult to ignite (Singh, 2009). Main disadvantages are poor exit temperature traverse quality and larger propensity to produce smoke and soot at high pressure when cone angles contract.

3.4.2 Airblast Atomisation

Airblast atomisers deliver liquid fuel at low velocity into an annular fuel gallery. Figure 3.11 shows schematics of the classic low-shear laboratory configuration; the second are conventional, industrial high-shear designs; the third is a high-shear version with four concentric swirling airflows and two concentric convergent prefilms in a hybrid unit to allow fuel staging without a pressure-swirl atomiser, and the final schematic is of the hybrid device characterised in this study that features a central pressure-swirl atomiser.

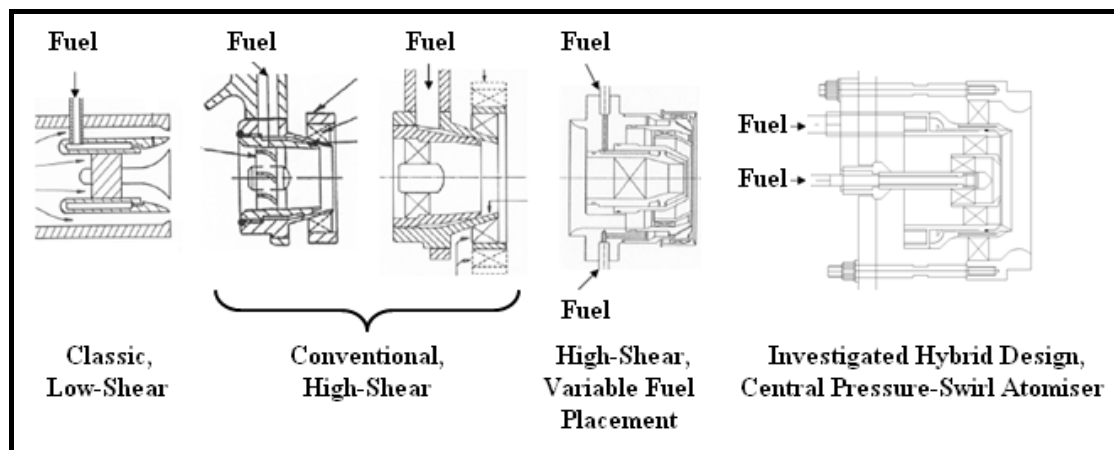


Figure 3.11: Airblast Atomiser Schematics (Jasuja, 2006) and Hybrid Injector

In the classic design the prefilmer is longer, diverging and the fuel gallery exit has a sharper lip than the industrial designs. This ensures fuel emerges as a slim, continuous, circumferential sheet before being sandwiched by airflows that are travelling in the same direction. Surface instabilities are excited on each side of the sheet. Eventually surface waves develop and amplify on each side. Thin sections of the sheet strain into the shear layers of both outer and inner airflows. The liquid first strips away into ligaments and then fragments into droplets. In later versions, the prefilmer is shorter, converging and has no lip. The prefilmer exit and geometry is neighboured on each side

by swirling airflows that transport liquid into regions of high aerodynamic shear to instigate instantaneous or prompt sheet break up. Swirler airflows then transport the atomised droplets radially outwards into the combustion zone as a hollow cone spray in accordance with swirler airflow trajectories and combustor aerodynamics. During this stage the inner airflow also deflects the liquid sheet radially outwards against the outer airflow. Centrifugal forces of the inner airflow push surface protrusions inside the sheet back into the sheet. At the same time, centrifugal forces of the outer airflow encourage formation of protrusions on the outside of the sheet and promote instability (Ibrahim and Jog, 2006). Spray measurements under forced oscillations in this study suggested shorter prefilms promoted combustion stability although only five samples were used.

Swirling flow characteristics have been reviewed in Syred and Beer (1974) and Gupta *et al* (1985). Beer defined swirl as the ratio of axial to angular momentum. In a confined flowfield a swirling flow has little decay and this can profoundly alter the combustion. Swirl angle; vane height; mass flow splits and swirl orientation relative to the fuel sheet impact turbulence levels; droplet size; flame positioning; flame stability; heat release rates; combustion efficiency and pollutant formation. When the angular component of swirl is increased, the flowfield geometry changes to form a central vortex at the critical swirl number along the combustor centreline. Its onset and breakdown is governed by the length of the converging and diverging lengths of the combustion chamber. If the axial component of swirl velocity reduces, the vortex spreads outwards and breaks down. This twisting motion instigates a toroidal flow reversal by creating an axial zone of low pressure some distance downstream of the injector and is useful for stabilising lean flames in LPP combustion. The vortex entrains and recirculates portions of hot gas to preheat fuel-air mixtures in the low pressure core. Vortex breakdown, however, is sensitive to pressure gradients that may couple positively with the heat release rate to create feedback loops that lead to combustion instability and rumble.

Airblast atomisers can use radial or axial inflow swirlers that co-rotate to twist the airflow in the same direction or contra-rotate to twist the airflow in opposite directions. Uncertainties exist regarding the best arrangement. Axial swirlers use straight blades to maximise air velocities whilst radial swirlers use curved blade passages to avoid flow separation and trailing edge wake effects (Jones, 1979, Alkabie *et al* 1988 and Halpin 1993). Halpin (1993) reported that swirl angles above 60° increased recirculation length and strength but this also reduced the swirler discharge coefficient. An increased swirler vane height and size compensates for this loss. Radial swirlers have lower axial components of velocity than axial swirlers. Although they create more intense recirculation zones to improve flame stability and less NO_x, their larger size compared to axial swirlers can prove restrictive. Gupta *et al* (1992) reported that contra-swirl improved recirculation strength, flame stability and fuel-air mixing to reduce NO_x.

Halpin (1993) also found that contra-rotating airflows increased turbulence levels and enhanced fuel and air mixing rates. Chin *et al* (2000) stated that relative to the rotational direction of the fuel sheet, a co-rotating inner and contra-rotating outer airflow gave a finer spatially dispersed spray. Lefebvre (2000) found co-swirl gave satisfactory atomisation over a wide range of fuel and airflow rates but was more prone to spray collapse at the lower fuel flow rates. Rizk and Lefebvre (1982) reported airblast atomisers were less expensive than pressure-swirl atomisers and performed better in terms of cost; pollutant emissions; exit pattern factor and mechanical robustness. Disadvantages, however, are narrow stability limits and poor atomisation at engine start-up but this is remedied with limited use of pressure-swirl atomisers. Airblast atomisation also suffers because of insufficient intrinsic energy levels in the airflow. Although swirlers shatter liquid fuel sheets and manage airflow patterns, swirler design changes only yield incremental changes to spray atomisation quality. For a step-change it is recommended that high pressure injectors are used with very small holes to increase the available energy; reduce drop sizes and improve fuel and air mixing. However, the trade-off is that smaller holes will result in less fuel penetration and vice versa but the fuel could be placed in desired locations to improve stability and the smaller drop sizes would drastically improve fuel and air mixing to reduce NO_x.

3.5 REVIEW OF LASER DIAGNOSTICS IN THIS STUDY

Spray measurements in this study used three well established laser diagnostics. Phase Doppler Anemometry (PDA) and Laser Sheet Dropsizing (LSD) to measure droplet Sauter Mean Diameter (SMD) and Planar Laser Induced Fluorescence (PLIF) to measure fuel placement and hence the Air to Fuel Ratio (AFR). The experimental campaign had two aims. First to acquire pertinent fuel concentration data to predict NO formation in hybrid sprays; and second to deliver quantitative SMD and AFR data to provide advanced knowledge of combustion instability. Detailed reviews on each laser diagnostic are widely available. Therefore, only a brief synopsis of these techniques is given. Information on PDA is available in Bachalo and Houser (1984), Wigley (1994) and Berrocal (2006). PLIF and LSD techniques are comprehensively described by Le Gal *et al* (1999); Kelman *et al* (2000); Jermy and Greenhalgh (2000); Greenhalgh and Jermy (2002) and Réveillé (2005).

3.5.1 Phase Doppler Anemometry

PDA is a point-wise measurement technique that evolved from Laser Doppler Anemometry (LDA) to measure droplet diameter in addition to velocity. PDA served two purposes in this study. Its prime function was to calibrate LSD and PLIF signals by measuring the SMD of a monodisperse droplet stream that was subsequently imaged to

extract transfer standards for calibrated SMD and AFR measurements. The technique was called upon a second time to confirm or reject the suspicion of severe secondary atomisation in the very near nozzle region of a pressure-swirl fuel spray from a hybrid atomiser. In brief, the PDA technique creates a measurement volume that consists of an interference fringe pattern where droplets pass. The phase difference of scattered light is used to measure droplet velocity and diameter. Pierson *et al* (2000) and Kershaw (2007) calculated PDA measurements uncertainties to be 9% and 11.2%. However, once the measurement volume is obscured by a spray mist the PDA beam attenuates and uncertainties can potentially rise to ~40%. Hence, PDA was primarily used for calibration purposes and LSD was used to measure the SMD in denser sprays where PDA measurements are suspect.

A Continuous Wave Coherent Innova 70 5-watt Argon Ion laser was used to generate the PDA light beam with a wavelength of 514.5nm. A Bragg cell split the light into two parallel beams. These travelled through a spherical lens of focal length, f of 600mm and intersected at the focal point to create the mentioned fringe pattern and measurement volume that typically measures 200 x 200 μ m perpendicular to and 1000 μ m parallel to the transmitter axis. Figure 3.12 and Figure 3.13 shows the PDA interference fringe pattern and mathematical model.

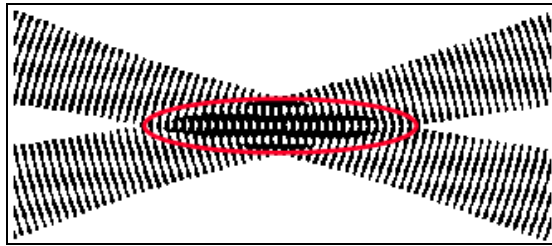


Figure 3.12: PDA Interference Fringe Pattern
(Jermy, 2002)

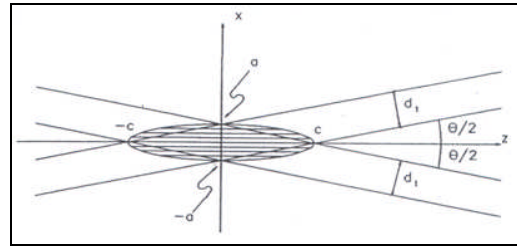


Figure 3.13: PDA Interference Fringe Model
(Grigorian, 2002)

Eq. 3.23 assumes a Gaussian intensity distribution to calculate the focal diameter, d_f at the control volume, where λ is wavelength, f is the focal length of the launch optics lens and d_2 is the diameter of the laser beam waist after expansion.

$$d_f = \frac{4}{\pi} \lambda \frac{f}{d_2} \quad \text{Eq. 3.23}$$

Eq. 3.24 gives dimensions of the measurement volume:

$$d_f = d_y = d_x \quad \text{Eq. 3.24}$$

and Eq. 3.25 shown overleaf gives the length d_z :

$$d_z = \frac{d_f}{\sin\left(\frac{\theta}{2}\right)} \quad \text{Eq. 3.25}$$

Eq. 3.26 shows the fringe spacing, λ^* is a function of laser wavelength and angle, θ between both beams:

$$\lambda^* = \frac{\lambda}{2 \sin\left(\frac{\theta}{2}\right)} \quad \text{Eq. 3.26}$$

Intensity modulated light can be scattered in several ways when a droplet travels through the measurement volume. Light is scattered by refraction between $30 - 70^\circ$; by reflection between $80 - 110^\circ$, and second order refraction from $135 - 150^\circ$. In this study PDA receiving optics were configured to measure droplet velocity and diameter in one-dimensional mode and to collect light from refraction. The frequency of scattered light is proportional to the component of the particle velocity normal to the fringes divided by their spacing. This is collected by a spherical lens focussed on the measurement volume. Light is detected by a multiplier tube and converted into an electronic signal. A Bragg cell incorporates a fixed frequency difference between the two beams. This causes the fringe pattern to move and forces the Doppler shift to add to or subtract from this shift. The frequency or “Doppler Burst” is measured using a spectrum burst analyser. Eq. 3.2 gives the droplet velocity, U_D :

$$U_D = f_D \frac{\lambda}{2 \sin\left(\frac{\theta}{2}\right)} \quad \text{Eq. 3.27}$$

PDA measures droplet diameter by analysing the phase difference of scattered light as a droplet sweeps through the measurement volume. A droplet acts as a lens and the intersecting fringes as light rays that rotate about a point in the middle of the droplet. When a droplet travels through the measurement volume it magnifies the light rays that alternately dim and brighten to give “on-off” signals at the Doppler frequency. The diameter of a spherical droplet is proportional to its focal length. At large distances from the measurement volume this is inversely proportional to the projected fringe spacing. Multiple detectors at fixed distances detect the same frequency but with a phase shift. This shift is proportional to the detector separation divided by the fringe spacing in Eq. 3.27. Fringe spacing is determined by droplet focal length. This is a function of its diameter. Phase shift is therefore proportional to droplet diameter. Using two detectors gives PDA a limited range. At the lower limit the droplet size can match

the instrument resolution. At the upper limit large particles can increase the phase shift above 360° but addition of a third detector can reduce these uncertainties. Of the three detectors, the two closest together determine if the phase shift is above or below 360° and the two furthest apart give an accurate measurement of droplet diameter. PDA does not require calibration as the phase shift depends on laser wavelength and optical configuration. Two drawbacks to PDA are only a single point is measured within a spray at a time to increase the time needed to map a spray and so compromises in spatial resolution must be made if data needs to be acquired quickly. Secondly, PDA measures droplet concentrations to $1000 \text{ particles/mm}^3$ but fails in dense sprays as the loading approaches $5 \times 10^4 \text{ particles/mm}^3$ (Greenhalgh, 2000). Higher density sprays also attenuate the laser beam. System noise can also reject weak signals from the smaller droplets to give dubious velocity measurements and lead to overestimations in SMD. These limitations are addressed by planar laser sheet based measurements.

3.5.2 PLIF, Mie Scattering and LSD Signal Characteristics

Planar Laser Induced Fluorescence (PLIF) is a non-intrusive laser diagnostic that measures concentration distribution in flows. It was applied in this study to measure local AFR to predict NO_x formation. Fluorescence measurements are preferred over absorption measurements due to their much lower backgrounds and increased sensitivity. A fluorophor applicable to the laser excitation wavelength is dissolved into a solvent that contains non-fluorescing compounds. Light from an excimer laser excites electrons in the fluorophor molecule and promotes them to a higher energy level. Appendix B shows fluorescence emission occurs during electronic transit down to the ground state. If light absorption is under a certain threshold, PLIF signals are proportional to the droplet diameter cubed, and hence liquid volume fraction (LeGal *et al*, 1999 and Jermy and Greenhalgh, 2000). This holds under cold flow conditions. Chapter Four gives criteria to select the most appropriate fluorophor for PLIF at 248nm. At low resolutions, each pixel detected by the ICCD registers contributions from several droplets. Eq. 3.28 shows PLIF signal, S_{PLIF} is:

$$S_{PLIF} = C_{PLIF} \sum_{i=0}^N d_i^3 \quad \text{Eq. 3.28}$$

C_{PLIF} is a constant including parameters such as the laser fluence and signal collection solid angle and d_i is the diameter of droplet i . This holds providing laser light absorbs equally across a droplet width. The same imaging system collects the Mie scattered signal from droplets. This is an elastic surface-scattering process and for spherically absorbing particles larger than $1\mu\text{m}$, S_{Mie} is proportional to the droplet area shown overleaf in Eq. 3.29.

$$S_{Mie} = C_{Mie} \sum_{i=0}^N d_i^2 \quad \text{Eq. 3.29}$$

Photons larger than the laser excitation wavelength are scattered at the excitation wavelength. PLIF and Mie signals are collected on the same camera chip and because fluorescence is red shifted it is readily discriminated from the Mie scatter with a filter. Mie signals are proportional to droplet diameter squared. Eq. 3.30 below shows the LSD technique divides volume-dependent PLIF signals by area-dependent Mie signals. This yields a two-dimensional map of SMD. Application of a calibration constant from an advanced knowledge of signal characteristics or PDA data yields quantitative SMD.

$$LSD = \frac{S_{PLIF}}{S_{Mie}} = \frac{C_{PLIF}}{C_{Mie}} \frac{\sum_{i=0}^N d_i^3}{\sum_{i=0}^N d_i^2} \propto \frac{\sum_{i=0}^N d_i^3}{\sum_{i=0}^N d_i^2} : D_{32} \quad SMD \quad \text{Eq. 3.30}$$

3.6 SUMMARY

This chapter described pollutant formation in aero engine combustion, its environmental risks and conflicting abatement strategies that impact and perplex combustor design. It then reviewed pressure-swirl and airblast atomisation used together in the hybrid fuel injection technology investigated in this thesis. This hybrid concept was conceived to increase flame stability and reduce harmful NOx emissions. The chapter closed with a synopsis on three well-established laser diagnostics used to characterise the fuel sprays in this study. These were Phase Doppler Anemometry (PDA) and Laser Sheet Dropsizing (LSD) to measure droplet Sauter Mean Diameter (SMD) and Planar Laser Induced Fluorescence (PLIF) to measure Air to Fuel Ratio (AFR). These techniques were applied under cold flow, low-pressure scaled rig operating conditions to develop the NOx prediction tool and also predict the prospect of combustion instability.

CHAPTER FOUR

LASER SIGNAL CALIBRATION

4.1 INTRODUCTION

In 1883 Lord Kelvin addressed the Institution of Civil Engineers and stated: “I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be.” (Sir William Thomson, 1st Baron Kelvin, 1883).

In this context, calibration constants were determined for quantitative measurements of Planar Laser Induced Fluorescence (PLIF) for Air to Fuel Ratio (AFR) and Laser Sheet Dropsizing (LSD) for droplet Sauter Mean Diameter (SMD). First, a fluorophor was selected for PLIF measurements at 248nm. Second, its concentration was calculated for PLIF signals to gain a cubic dependence with droplet diameter. Third, a calibration plate was imaged to determine Intensified Charge Coupled Device (ICCD) array pixel resolution and image manipulation factors for LSD where corresponding pixels in PLIF images are divided by those from elastically scattered Mie images. Fourth, a “flatfield” image defined the laser sheet region in PLIF and LSD measurements to give PLIF image correction factors to compensate for non-uniformities in laser sheet intensity distribution and ICCD intensifier pixel response. Finally, Phase Doppler Anemometry (PDA) measured Sauter Mean Diameter (SMD) of monodisperse droplet streams from a piezoelectric generator followed by PLIF and LSD imaging to extract transfer standards.

4.2 PLIF FLUOROPHOR

A precise quantity of fluorophor in the sprayed liquid allowed PLIF signals to gain a cubic dependence with droplet diameter. By volume, Avtur contains ~20% aromatics that absorb UV light and fluoresce to give mixed absorption and emission characteristics. Table 4.1 shows Exxsol D80 was a good surrogate to Avtur. This is hydrotreated to leave 0.3% aromatics by weight to allow seeding with a fluorophor.

Fuel Property	Avtur	Exxsol D80
Density (kg/m ³ @ 15°C)	800	796
Viscosity (m ² /s @ 15°C)	1.8E-06	1.7E-06
Surface Tension (mN/m @ 25°C)	25	26.3

Table 4.1: Properties of Avtur and Exxsol D80 (Exxon, 2002 and Goodger, 2006)

4.2.1 Fluorophor Requirements

The fluorophor for subsequent experiments must dissolve in Exxsol D80; absorb at the applicable laser excitation wavelength of 308nm or 248nm, have insensitivity to temperature and pressure; be vulnerable to oxygen quenching to detect only the liquid-phase fluorescence; avoid saturation; self-quenching and laser attenuation within fuel droplets. In contrast to the work of Réveillé (2005), the undertaken cold flow studies do not require the fluorophor to co-evaporate with the fuel. The PLIF signal, S_{PLIF} is:

$$S_{PLIF} = C_{PLIF} \sum_{i=0}^N d_i^n \quad \text{Eq. 4.1}$$

The constant, C_{PLIF} includes laser fluence and signal collection solid angle. Fluorophor concentration fixes the index of dependence, n with droplet diameter, d_i . PLIF signals gain a cubic index of dependence with diameter when light absorption remains under a certain threshold and light is uniformly distributed across the droplet width. Figure 4.1 illustrates the influence of fluorophor concentration on droplet illumination and n .

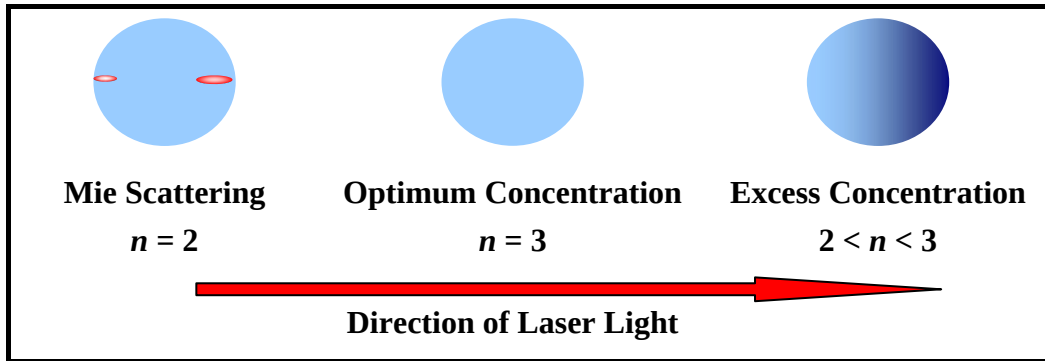


Figure 4.1: Influence of Fluorophor Concentration on n (Le Gal, 1999)

The droplet on the left hand side corresponds to low light absorption where Mie scatter is collected at the laser excitation wavelength: $n = 2$ and the PLIF contribution is surface-dependant. The central droplet represents an ideal case of equal light absorption across the droplet width: $n = 3$ and the PLIF contribution is volume-dependant. The droplet on the right hand side typifies excessive light absorption due to strong fluorophor concentration where more light absorbs on one side relative to the other. Here, n is between two and three to give weak PLIF signals that over-predict AFR and under-predict SMD. Conversely, Domann and Hardalupas (2000) reported that insufficient fluorophor concentration resulted in Amplified Stimulated Emission (ASE), where droplets behave like cavities with gains above unity to raise fluorescence signals. The Beer-Lambert Law in Eq. 4.2 describes light behaviour in an absorbing medium.

$$I = I_o e^{-\epsilon \cdot c \cdot d} \quad \text{Eq. 4.2}$$

Where I_o is initial light intensity, I is light intensity after distance d ; ϵ is molecular absorptivity or extinction coefficient and c is concentration. Eq. 4.3 linearly relates absorbance, A with concentration, c :

$$A = \log_{10} \frac{I}{I_o} = \epsilon c l \quad \text{Eq. 4.3}$$

A is also referred to as the optical density, l is path length taken as 1cm and ϵ is constant for any fluorophor concentration at all wavelengths. Eq. 4.4 relates ϵ , A and c :

$$\epsilon = \frac{A}{c} \quad \text{Eq. 4.4}$$

4.2.2 Fluorophor Selection for PLIF at 248nm

Le Gal (1999) calibrated PLIF signals at 266nm using a droplet generator; PDA; PLIF imaging and various strength solutions of P-Terphenyl dissolved in mineral spirits. Although the droplet generator had a dropsizes distribution of $50 - 180\mu\text{m}$ compared to modern high shear fuel injectors that typically yield a distribution in the order of $10 - 60\mu\text{m}$, the extracted calibration constant applied to spray measurements using the same optical configuration. An absorbance threshold limit of 2.738 gave PLIF signals a near-cubic index of dependence of 2.996 with droplet diameter and required 0.023g/l of P-Terphenyl in mineral spirits. This has significant absorbance at 266nm and fluoresced at 340nm. Harding (1996) took PLIF measurements at 308nm using mineral spirits seeded with 0.01125g/l of 2,5 Diphenyloxazole (PPO). PPO has an absorbance maximum at 302nm and fluoresces between 355 – 380nm. PPO pumped at 308nm exhibits well-separated absorption and fluorescence spectra but absorbs weakly when excited at 248nm; fluorescence first occurs at 320nm and then more profoundly at 355nm. This eliminated PPO as a candidate for PLIF imaging at 248nm for two reasons. First, the emission would occur within an absorption band. Second, the fuel spray between the excitation plane and camera would absorb most of the emitted fluorescence to significantly weaken the PLIF signals. Figure 4.2 shows the chemical structures of 1,4 Diphenylbenzene (P-Terphenyl) $\text{C}_6\text{H}_5\text{C}_6\text{H}_4\text{C}_6\text{H}_5$; 1,3 Diphenylbenzene (M-Terphenyl) $\text{C}_6\text{H}_5\text{C}_6\text{H}_4\text{C}_6\text{H}_5$; and 2,5-Diphenyloxazole (PPO), $\text{C}_{15}\text{H}_{11}\text{NO}$.

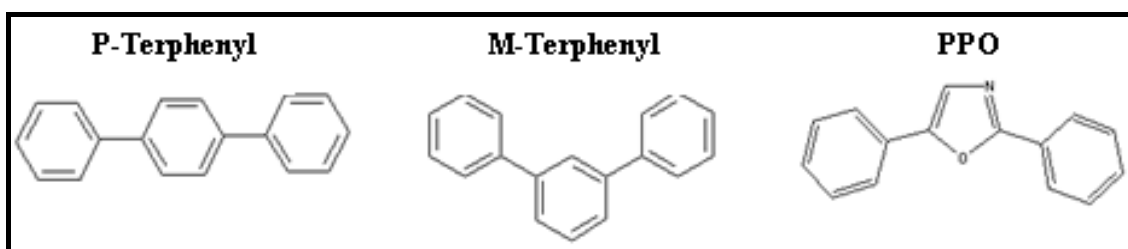


Figure 4.2: Structures of P-Terphenyl, M-Terphenyl and PPO

P-Terphenyl has aromatic rings opposite each other in the “para” formation. In M-Terphenyl the aromatic rings are displaced by one carbon atom in the “meta” formation and its molecular structure is similar to PPO where one oxygen atom separates both aromatic rings. M-Terphenyl has similar absorbance to PPO at 308nm when excited at 248nm. This suggests that the same concentration of M-Terphenyl in Exxsol D80 at 248nm as used by Harding for PPO in mineral spirits at 308nm would be suitable.

4.2.2.1 Concentration Calculation

The Relative Molecular Mass (RMM) of a compound is the sum of the Relative Atomic Mass (RAM) of the atomic species in its formula. The RMM of PPO is 221.258g. Each gram contains 0.00452 moles. 0.01125g/l of PPO in mineral spirits gives a concentration of 5.08×10^{-5} moles/litre. The RMM of M-Terphenyl is 230.3086g and each gram contains 0.00434 moles. To obtain the same absorbance as Harding requires 0.0117g/l of M-Terphenyl in Exxsol D80. This solution gives a concentration of 5.12356×10^{-5} mol/l. A slightly stronger solution of 0.0118g/l of M-Terphenyl in Exxsol D80 was prepared and its absorbance measured in a UV-Visible Cecil CE99500 spectrometer at a bandwidth of 2nm, scan speed 10nm/s and wavelength range of 200 – 900nm. Figure 4.3 below plots absorbance against wavelength. At 248nm the absorbance value is 2.72 and under the 2.738 absorbance threshold limit of Le Gal.

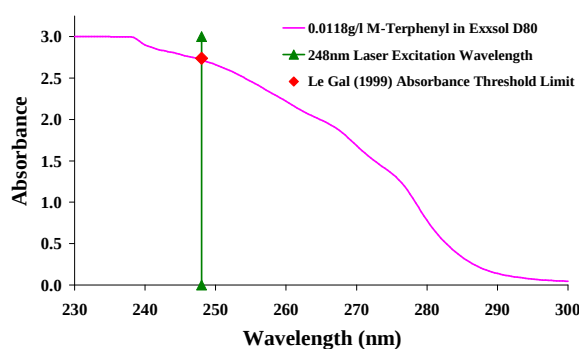


Figure 4.3: A vs λ for 0.0118g/l of M-Terphenyl in Exxsol D80

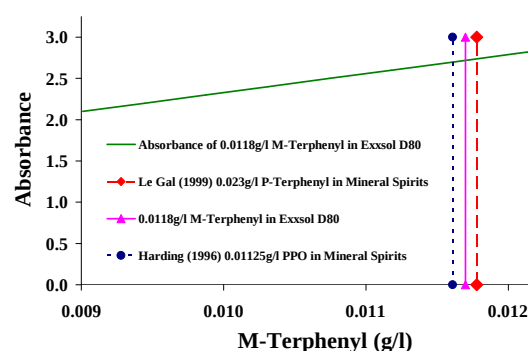


Figure 4.4: A vs M-Terphenyl Concentration

Substitution of the 2.738 absorbance threshold limit and calculated epsilon value yields a maximum M-Terphenyl concentration of 5.157×10^{-5} mol/l. Division of this concentration by the number of moles per gram in M-Terphenyl gives 0.011878g. Figure 4.4 also shown above plots absorbance against fluorophor concentration. This shows that 0.0118g/l of M-Terphenyl in Exxsol D80 rests between the equivalent concentrations used by Harding and Le Gal and is therefore suitable for PLIF at 248nm.

4.3 PLIF AND LSD IMAGE CORRECTION

The following tasks were performed before data acquisition or if the set-up changed:

- Alignment of the laser sheet
- Measurement of laser sheet thickness
- Calculation of ICCD array pixel resolution
- PLIF and Mie image manipulation factors for LSD image processing
- Determination of laser sheet region for PLIF and LSD image processing
- Measurement of laser sheet intensity and ICCD intensifier pixel response to correct anomalies in PLIF images

4.3.1 Laser Sheet alignment and Thickness Measurement

A laser sheet was introduced vertically into the Unsteady Flow Rig (UFR) through one rig access window. This sheet was located to travel through the centreline of the fuel spray and into a beam-dump to limit spurious scattering from shiny rig surfaces. Figure 4.5 shows the aluminium frame that was temporarily installed inside the UFR to align the laser sheet. The frame housed a boss and height-adjustable 1mm diameter spike that coincided with the spray centreline. The laser was switched on at a low pulse energy of 20mJ; known hereafter as “low power”. An iterative process ensued where adjustments were made to the optical rail assembly and final cylindrical converging lens of the sheet forming optics until the laser sheet vertically coincided with the spike. The spike was then lowered to ensure the sheet freely entered the beam-dump without being clipped.



Figure 4.5: Images of Aluminium Frame, Spike and Beam-dump

PLIF measurements of quantitative AFR required calculation of the Liquid Volume Fraction Calibration Constant (LVF_K). This necessitated a measurement of the laser sheet thickness, t_{sheet} at the spray measurement region using the same pulse energy as experiments. The laser was turned on at 100mJ pulse energy, referred to hereon as “high power”. A series of burn marks were acquired on fax paper and measured under magnification using a digital vernier rule. The mean t_{sheet} value was 800 μ m.

4.3.2 ICCD Array Pixel Resolution and Image Manipulation Factors

Figure 4.6 shows the image calibration chart and mean calibration images for both PLIF and LSD optical set-ups. This was an array of equidistant white crosses and four circles printed on a black background. It was attached to a flat plate and located just behind the measurement volume on the aluminium frame parallel to the direction of the laser sheet. At low power, the plate was edged forwards until the sheet clipped across its face. The ICCD camera was focussed on several crosses that were magnified on the monitor.

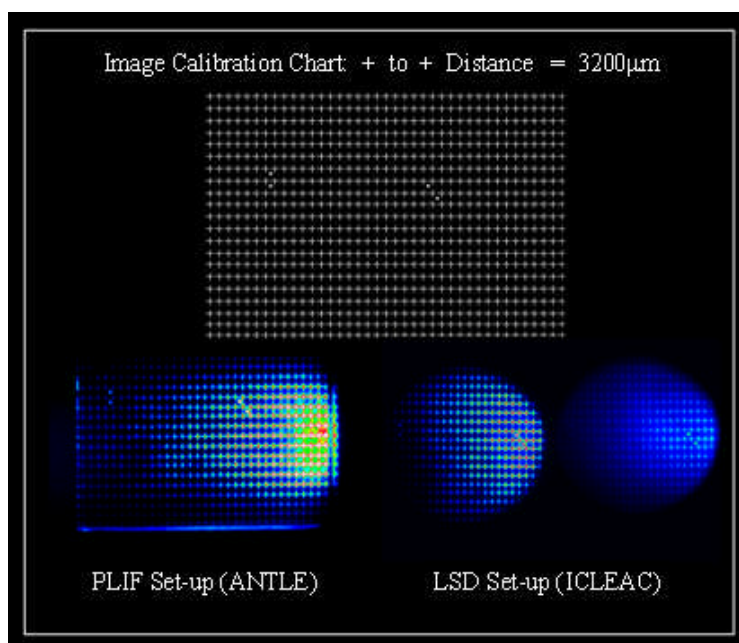


Figure 4.6: Calibration Chart and Images

In PLIF measurements pertaining to the Affordable Near Term Low Emissions Engine (ANTLE) weak modules the camera was fitted with a high aperture Nikon 50mm lens at $f/1.2$ and situated adjacent to the rig window to increase its field of view. In LSD measurements the camera lens was replaced with a Nikon 105mm UV lens at $f/4.5$ and the camera was moved back to image the PLIF and Mie images. Dual imaging mirrors were fine-tuned to separate and optimally align both images on the ICCD array. A Neutral Density (ND) filter of 1.0 in the Mie channel was used to balance the signal intensities because Mie scatter is profound at shorter wavelengths. Non-fluorescing fuel was imaged to check for Mie breakthrough in the PLIF channel. Room light was imaged to check for PLIF breakthrough in the Mie channel. Twenty images were acquired and averaged for each optical set-up. Spatial resolution in PLIF images was $246 \times 246 \times 800\mu\text{m}$ and was slightly compromised in LSD images at $267 \times 267 \times 800\mu\text{m}$ to stop the overlap of PLIF and Mie images. The calibration image optimised the optical set-up; gave the ICCD array pixel resolution to calculate LVF_K ; spray length to estimate species residence time for NO_x prediction and LSD image manipulation factors such as split line position, orientation angles and x, y shifts to perfectly divide corresponding pixels in PLIF images by those from the elastically scattered Mie images.

4.3.3 Acetone Fluorescence Flatfielding Experiment

A “flatfield” image defined the laser sheet region; measured non-uniformities in ICCD array pixel response and anomalies in laser sheet intensity distribution normal to the light sheet. The image was essentially used to correct PLIF images but proved useful in excluding the scattered signals from shiny surfaces during LSD image processing. LSD measurements were not flatfielded because the dual imaging set-up projected both PLIF and Mie images onto the same camera chip. Each image therefore had identical pixel resolutions and non-uniformities and subsequent division of corresponding PLIF and Mie pixels during LSD image processing removed all irregularities. A uniform distribution of the species under investigation gives the best flatfield image. However, Exxsol D80 vapour contains a mixture of liquids with various boiling points so a uniform concentration of acetone CH_3COCH_3 vapour was imaged. Acetone vapour absorbs between 225 – 320nm to make it suitable for excitation at 248nm and fluoresces strongly between 350 – 550nm (Thurber and Hanson, 1999). Figure 4.7 shows a schematic of the experimental configuration used to generate the acetone vapour.

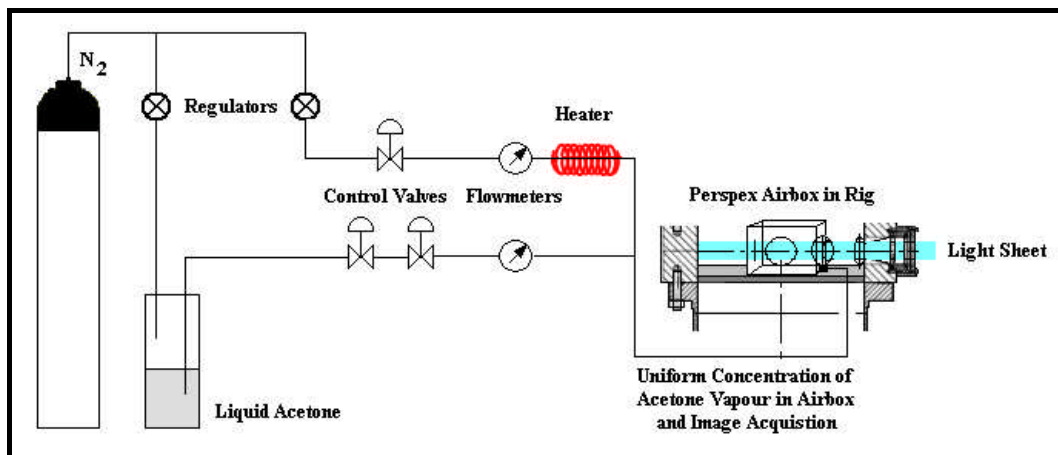


Figure 4.7: Schematic of Flatfielding Experiment

Acetone vapour was transported in a nitrogen carrier to a perspex airbox that measured 250 x 70 x 140mm with laser entry exit slots of 5 x 65mm. Figure 4.8 shows photographs of the airbox located at the spray measurement region in the UFR.

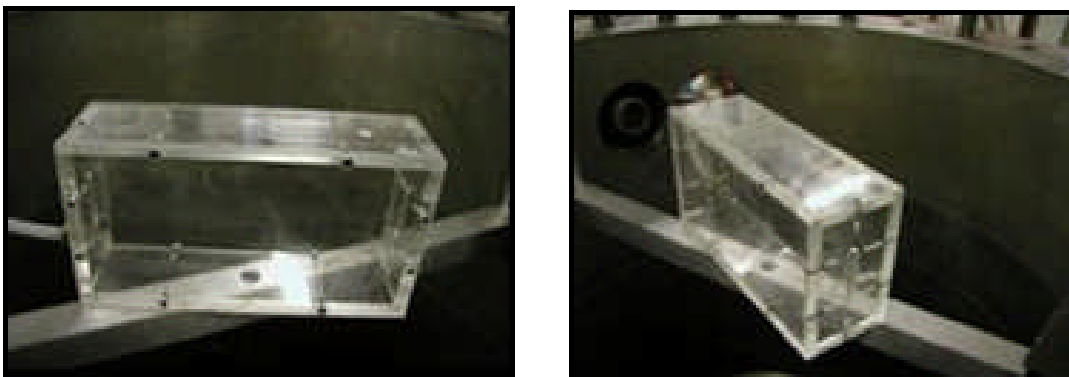


Figure 4.8: Perspex Airbox in Spray Measurement Region

The laser was switched on at low power and the sheet path was checked through the airbox into the beam-dump. At high power one hundred background images were acquired. The laser was turned off and the acetone seeder was switched on. The seeder had two nitrogen supply lines. The first line pressurised the acetone tank and the second delivered nitrogen to a heating element via a flowmeter and control valve. At $\sim 220^{\circ}\text{C}$ the nitrogen flow rate was set to $\sim 0.046\text{l/m}$ and the acetone flow rate to $\sim 0.018\text{l/m}$. This produced a weak concentration of acetone vapour and stopped excessive light absorption on the side closest to the laser. The laser was turned on at high power and seven hundred and fifty images were acquired. The seeder was shut down by turning off the acetone flow rate, the heater once it had cooled to $\sim 50^{\circ}\text{C}$ and then the nitrogen. Figure 4.9 shows the image processing routine to obtain the flatfield image.

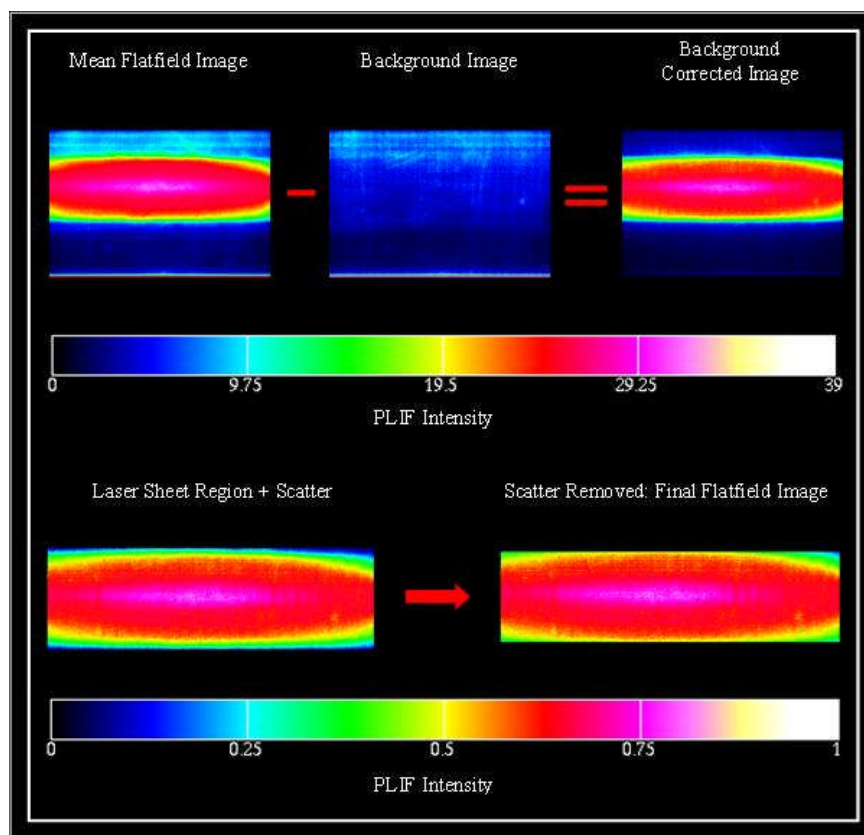


Figure 4.9: Flatfield Image Processing Routine

The routine subtracted the mean background image from the mean flatfield image; masked weakly illuminated regions outside the laser sheet region from illuminated particles inside the laser sheet and normalised the final image from zero to one. The final image provided the required image correction factors for subsequent processing.

4.4 CALCULATION OF CALIBRATION CONSTANTS

Calculation of PLIF and LSD calibration constants required either a prior knowledge of signal characteristics; a PDA measurement in the fuel spray under investigation, or PLIF and LSD measurements of a monodisperse droplet stream of a known size. With

this set-up no prior knowledge of signal characteristics existed and PDA measurements over-predict the SMD in dense sprays due to attenuation of the laser sheet and scattering of signals that leads to non-registration of weak signals from smaller droplets. The final option was taken to calculate the LVF_K and the LSD calibration constant (LSD_K). LVF_K was the number of counts that corresponded to a pixel 100% full of fuel. Application of LVF_K with air and fuel densities to PLIF images yielded quantitative AFR maps. Division of the PDA result by mean LSD intensity gave LSD_K for quantitative SMD.

4.4.1 Review of Droplet Generators and Droplet Break-Up

Ultrasonic droplet generators acoustically levitate a droplet through balancing gravitational and capillary forces of a liquid (Rajan and Pandit, 2001). Pneumatic designs use the sudden pressure of a compressed gas to force droplets through a nozzle (Cheng *et al*, 2005). Electrohydrodynamic designs employ an electric field to induce compression, expansion and jet break-up (Crowley, 1983). Piezoelectric designs, however, are mostly used given their simplicity and lower cost and have been used to study droplet evaporation and combustion (Wang *et al* 1984); droplet collision and coalescence (Jiang *et al* 1992); air-assisted liquid atomisation (Liu and Reitz, 1993); drop size and vaporisation rates (Santangelo and Kennedy, 1999); droplet impaction on solid objects (Hung and Yao, 1999); droplet splashes and dynamics (Luxford *et al*, 2004); inhalation drug therapy (Heij *et al*, 2000) and most famously for inkjet printing (Zoltan, 1972 and Darling *et al*, 1984). Originally developed by the Cranfield Icing Group in collaboration with NASA, the piezoelectric droplet generator shown in Figure 4.10 was loaned to the Optical Diagnostics Group (ODG) to calibrate the laser signals.

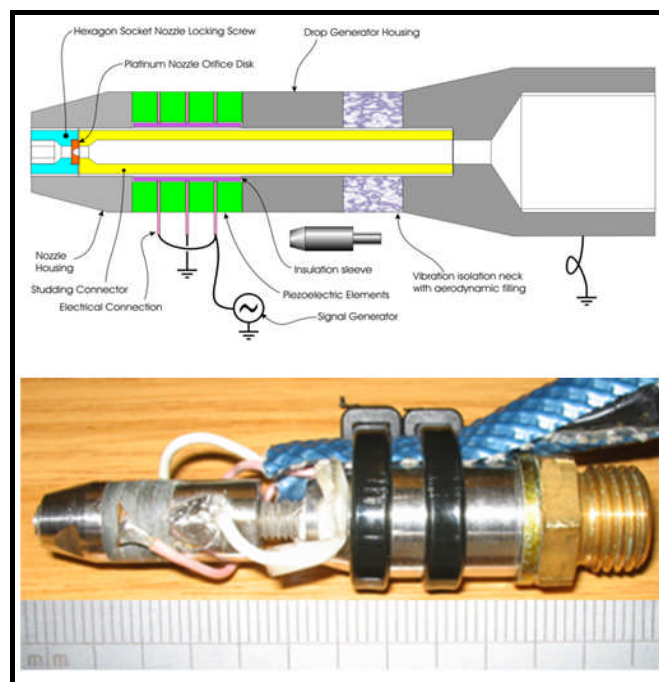


Figure 4.10: Piezoelectric Droplet Generator (Luxford, 2001)

The calibration exercise required the application of PDA, PLIF and LSD. In this device, droplet diameter is a function of orifice disk diameter, liquid injection pressure and frequency. A frequency of specific amplitude excited the concentric piezoelectric ceramic located around a capillary just upstream of the nozzle that contained the pressurised liquid. Vibrations instigated a rhythmic mechanical motion in the capillary and stimulated liquid expansion and contraction. Reforming liquid surface tension forces attempted to pull any exposed liquid back inside the nozzle. Increasing the disruption level generated pressure waves that propagated to longitudinally deform any liquid that was already outside the nozzle until it broke through surface tension forces to yield the desired monodisperse droplet stream.

Signal amplitude controlled disturbance levels and the eventual dropsize distribution. Figure 4.11 shows a monodisperse distribution of equally sized and spaced droplets.



Figure 4.11: Monodisperse Dropsizes Distribution

Figure 4.12 typifies a bimodal distribution characterised by the presence of satellite droplets. This was formed when a tail broke away from a droplet due to excess liquid deformation before it exited the nozzle. The bimodal distribution was observed in this study and signal amplitude was reduced to obtain the desired monodisperse distribution.



Figure 4.12: Bimodal Dropsizes Distribution

Figure 4.13 represents a chaotic polydisperse dropsizes distribution due to excessive signal amplitude. External disruptive forces overwhelm internal consolidating forces and different volumes of liquid break free at dissimilar rates from exiting droplets. This regime was found to give absolutely no control over the obtained droplet size.



Figure 4.13: Polydisperse Dropsizes Distribution

A perusal of the literature (Santangelo and Kennedy, 1999, Erdmann *et al*, 2000 and Feng *et al* (2003) showed SMD related to volume flow rate, Q and frequency, f through:

$$SMD = \left(\frac{6Q}{\pi f} \right)^{\frac{1}{3}} \quad \text{Eq. 4.5}$$

Brenn *et al* (1996) and Celata *et al* (2005) reported that SMD related to liquid jet velocity, U_L , orifice disk diameter, D and frequency, f by:

$$SMD = \left(\frac{3U_L D^2}{2f} \right)^{\frac{1}{3}} \quad \text{Eq. 4.6}$$

Eq. 4.7 related flow rate, Q to liquid jet velocity, U_L and orifice diameter, D :

$$Q = \left(U_L D^2 \frac{\pi}{4} \right) \quad \text{Eq. 4.7}$$

Rearrangement for $U_L D^2$ and substitution into Eq. 4.6 gave the same relationship in Eq. 4.5. Farrugia *et al* (1998) and Devarakonda and Ray (2003) related SMD to Q and f by:

$$SMD = \left(\frac{3Q}{4\pi f} \right)^{\frac{1}{3}} \quad \text{Eq. 4.8}$$

Celata *et al* (2005) reported that for non-viscous fluids such as water the optimum frequency, f for nozzle vibration was:

$$f = \frac{U}{\pi SMD \sqrt{2}} \cong 0.225 \left(\frac{U}{SMD} \right) \quad \text{Eq. 4.9}$$

At the formation point, Celata *et al* (2005) gave the SMD of a spherical droplet to be:

$$SMD \cong 1.89D \quad \text{Eq. 4.10}$$

The spike shown in Figure 4.5 located the PDA measurement volume in the middle of the vertical laser sheet. A monodisperse droplet stream was generated and PDA was applied to measure the SMD. PLIF and LSD images of the same stream were acquired with PDA beams switched off. Results were processed to extract LVF_K and LSD_K .

4.4.2 Calibration Experiment Using Piezoelectric Droplet Generator

The droplet generator was mounted on a frame that allowed axial and vertical movement. A helium pressurised tank of Exxsol D80 with 0.018g/l M-Terphenyl was connected to the droplet generator. The fuel was filtered upstream of the generator to prevent nozzle fouling. The piezoelectric crystal was driven by a digital pulse generator and a stream was generated using an arbitrary combination of frequency and pressure.

The generator was moved to locate the stream onto the spike. The laser was turned on at high power and the stream was imaged to ensure it passed through the 800 μ m wide laser sheet. Although Moukaideche (2004) provided the initial operating conditions for this study, attempts to reproduce these produced extra spectra with different peak spacings from the primary droplets to signify the presence of satellite droplets and hence bimodal drops size distributions. The desired monodisperse distribution was obtained by rewiring reversed electrical connections; driving the generator with a sine wave instead of the square pulse recommended by Brenn *et al* (1996); increasing the frequency band to 20 – 40kHz, that was incidentally much larger than the Rayleigh criteria and by using a 20V peak-to-peak signal amplitude to drive this high impedance device. A manual dial pulse generator was used instead of the digital version to improve control over the frequency range between 0.001 – 1000kHz.

First attempts using a 20 μ m nozzle failed because high surface tension forces resulted in the streams rarely lasting for more than several seconds. The 50 μ m nozzle, however, increased stream stability and gave the desired monodisperse droplet stream with SMD values comparable to those from modern high shear fuel injectors. Distance between the nozzle and measurement region was critical; if less than 20mm the droplets were not properly formed; if above 200mm aerodynamic interactions would make the droplets coalesce and the stream to oscillate in and out of the measurement region. Optimum separation was 55mm. Table 4.2 shows operating conditions for the investigated cases.

Case	Pressure (kPa)	Frequency (Hz)
dg1	441	4.65E+04
dg2	490	2.13E+02
dg3	490	5.13E+06
dg4	552	5.13E+06
dg5	552	5.13E+05
dg6	558	4.26E+03
dg7	565	-
dg8	565	-
dg9	565	3.33E+09
Dg10	565	5.26E+06

Table 4.2: Droplet Generator Operating Conditions

Eq. 4.10 was in good agreement with experiments that gave the correlation in Eq. 4.11 under various combinations of injection pressure and frequency. Although frequency had insignificant effect on SMD, it had substantial influence over the jet break up-point.

$$SMD \cong 1.86D$$

Eq. 4.11

Figure 4.14 shows a plan view of the PDA experimental set-up within the UFR.

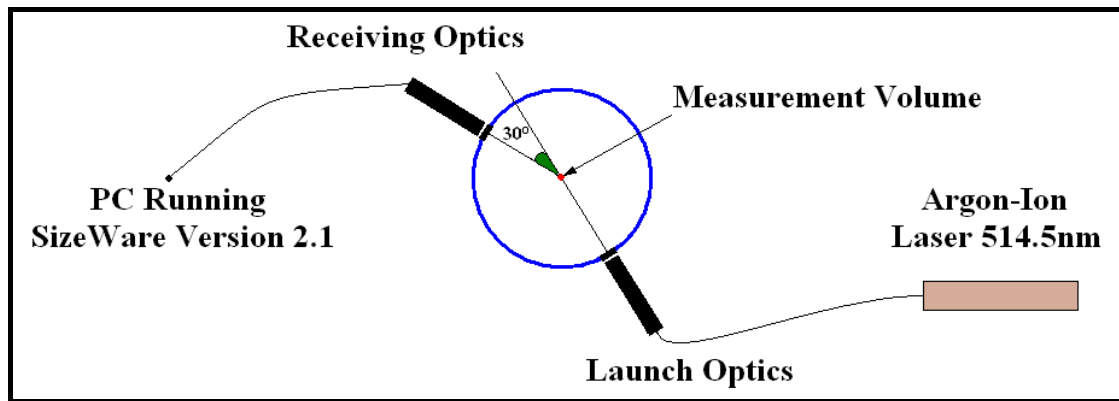


Figure 4.14: Plan View of PDA Configuration in UFR

PDA receiving optics collected intensity modulated light from droplet refraction at 30° to the measurement volume. The system was configured to measure droplet velocity and diameter in one-dimensional mode. Green light at 514.5nm from a Coherent Innova 70 5-Watt Argon-Ion laser entered a transmitter unit through a Bragg cell. This was set to 40MHz to produce frequency shifted beams that were sent via an optical cable to the transmitter head that was adjacent to an optical access window on the UFR.

Frequency-shifted beams passed through a Galilean telescope and increased in diameter to 1.4mm. For measurement accuracy the beam separation was set to 28mm. The beams travelled through a 600mm spherical lens and intersected at the lens focal point to create an interference fringe pattern near the spike. To simplify the experimental set-up the receiving lens also used a 600mm focal length lens. PDA beams were switched on and illuminated with a nebuliser of Exxsol D80. PDA launch optics were situated to locate the beam intersection point over the spike and screws in the transmitter head were used for fine adjustment. The PDA measurement volume was of the order of $1000 \times 200 \times 200 \mu\text{m}$ and had thirteen fringes, each separated by a distance of $11.028 \mu\text{m}$.

The PDA receiving optics were focussed onto the droplet stream until a high data rate was acquired. When viewed through the eyepiece the beam intersection point appeared as a black haircross. Screws in the receiver head were adjusted until the droplets were in the 7 o'clock position relative to the haircross. The PDA measurement volume was set to measure a maximum concentration of 10^5 droplets of maximum diameter of $299.92 \mu\text{m}$. The direction of fringe motion was set to positive to increase the data collection rates. Bandwidth of the signal filters was set to 40MHz for the *U* and 4MHz for the *V* channel. The velocity range was -11 to 33.08m/s. Photomultiplier tube voltages were 1100V. PDA signals were processed using a Dantec 58N20 covariance signal processor and a PC running SizeWare Version 2.1.

For the LSD calibration one hundred PLIF and Mie images were collected at high laser power with no stream running. The laser was then turned off. The first stream was set up and the PDA beams switched on to measure SMD for validated sample sizes of 20K, 50k, 100k and 200k droplets. With the stream running the PDA beams were switched off. The laser was turned on at high power and two hundred PLIF and Mie images acquired. The laser was turned off, the next stream was generated and the process was repeated. LSD_K and LVF_K were extracted using data from the largest PDA dataset because this consistently gave the narrowest drops size distributions.

Figure 4.15 plots SMD, droplet velocity and injection pressure for all investigated cases. Frequencies were not plotted because they had insignificant effect on the SMD. Eq. 4.5 and Eq. 4.10 were in good agreement with most measurements. A change in frequency changed the jet break-up point but otherwise exerted little influence over the SMD. According to the Rayleigh criteria, a 50 μm nozzle required the disturbance wavelength, λ to be greater than 157 μm to instigate jet break-up. However, monodisperse droplet streams were generated every time despite the fact that only three cases dg1, dg2, and dg6 obeyed the Rayleigh criteria. The dg3 result gave the smallest SMD and was possibly due to temporary nozzle contamination. Cases dg7 and dg8 applied a pressure of 565kPa and zero frequency but the dg7 result was comparable to other conditions and dg8 gave the best drops size distribution where $\sim 29,000$ droplets had an SMD of $\sim 77\mu\text{m}$.

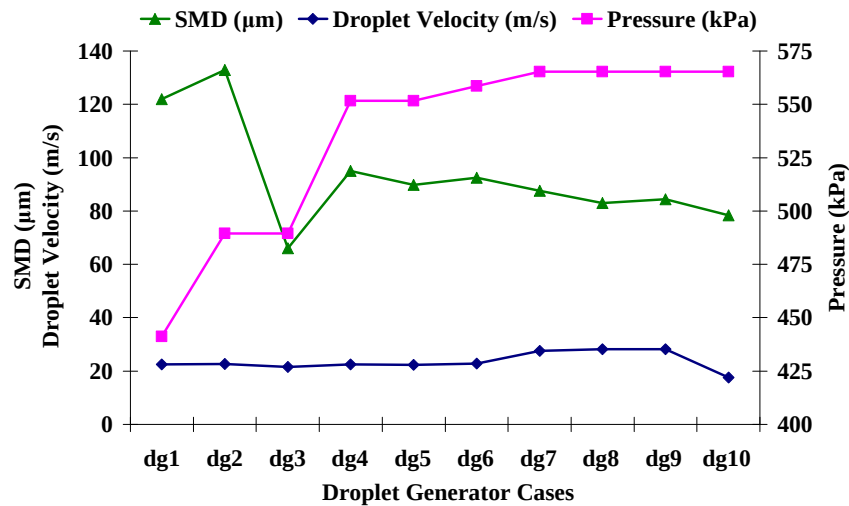


Figure 4.15: Plot of PDA Results for 200,000 Validated Samples

Jet break-up also progressed by impurities or internal pipe roughness. These amplified liquid disturbances when forced under pressure through a nozzle. This study showed:

- Steady increases in pressure reduced SMD due to its effect on flow rate
- Natural impurities and internal pipe roughness contributed to jet break-up
- Nozzle disk diameter and injection pressure significantly influenced SMD
- Frequency influenced the jet break-up point but insignificantly affected SMD

Figure 4.16 shows an individual Probability Density Function (PDF) for each of the ten investigated cases for a validated sample size of 200,000 droplets. Appendix A shows the smaller datasets.

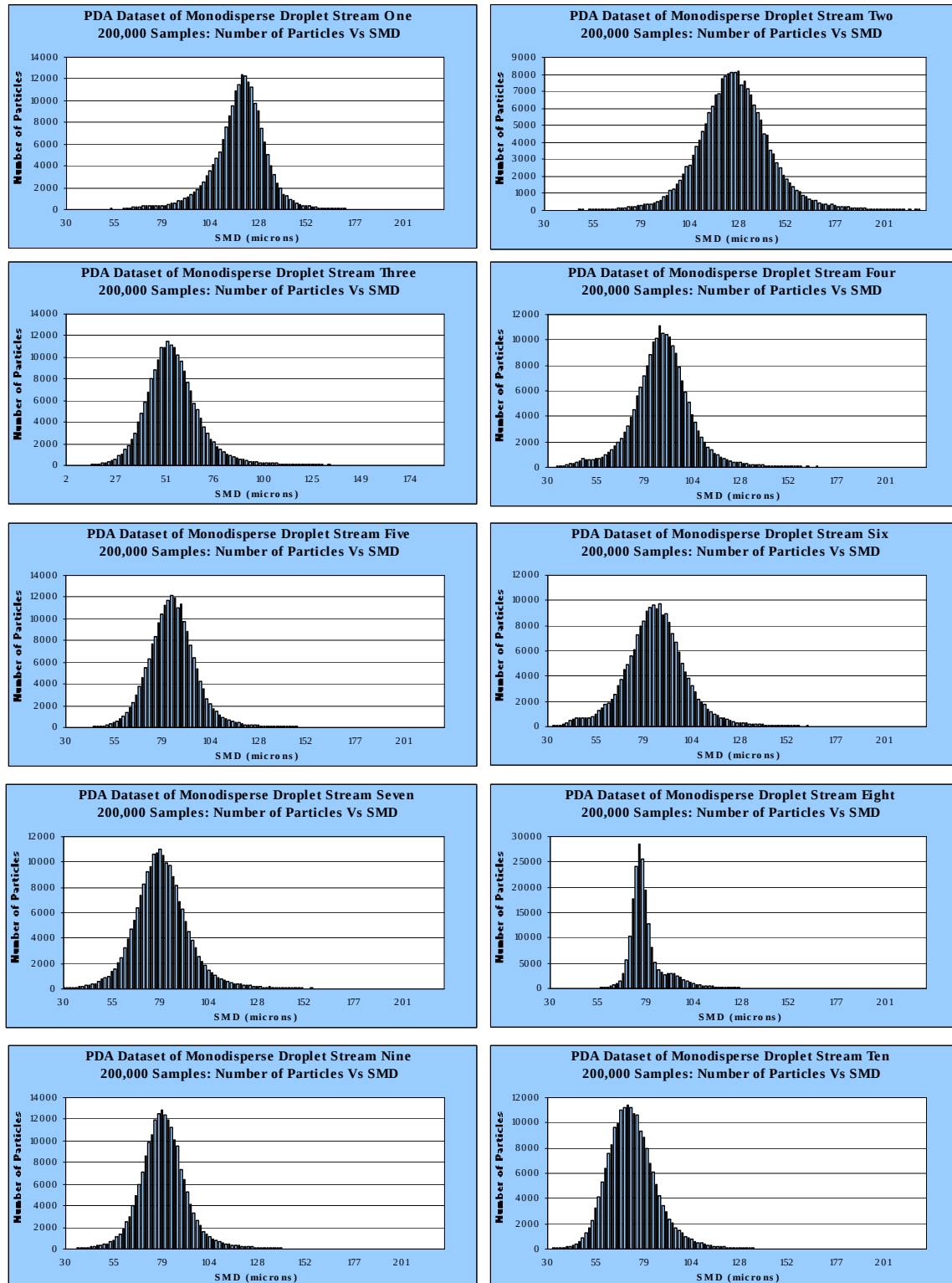


Figure 4.16: PDA Dataset for 200,000 Validated Samples

4.4.3 Calculation of LSD_K

Division of the PDA measurement by LSD intensity for a given stream yielded LSD_K . Subsequent multiplication of LSD fuel spray images by LSD_K produced quantitative two-dimensional maps of SMD measured in microns via the relationship of Eq. 4.12:

$$LSD_{Calibrated} = \frac{C_{PLIF}}{C_{Mie}} \frac{\sum_{i=0}^N d_i^3}{\sum_{i=0}^N d_i^2} = LSD_K \frac{\sum_{i=0}^N d_i^3}{\sum_{i=0}^N d_i^2} : D_{32} \text{ SMD} \quad \text{Eq. 4.12}$$

Figure 4.17 summarises the image processing routine to extract LSD_K .

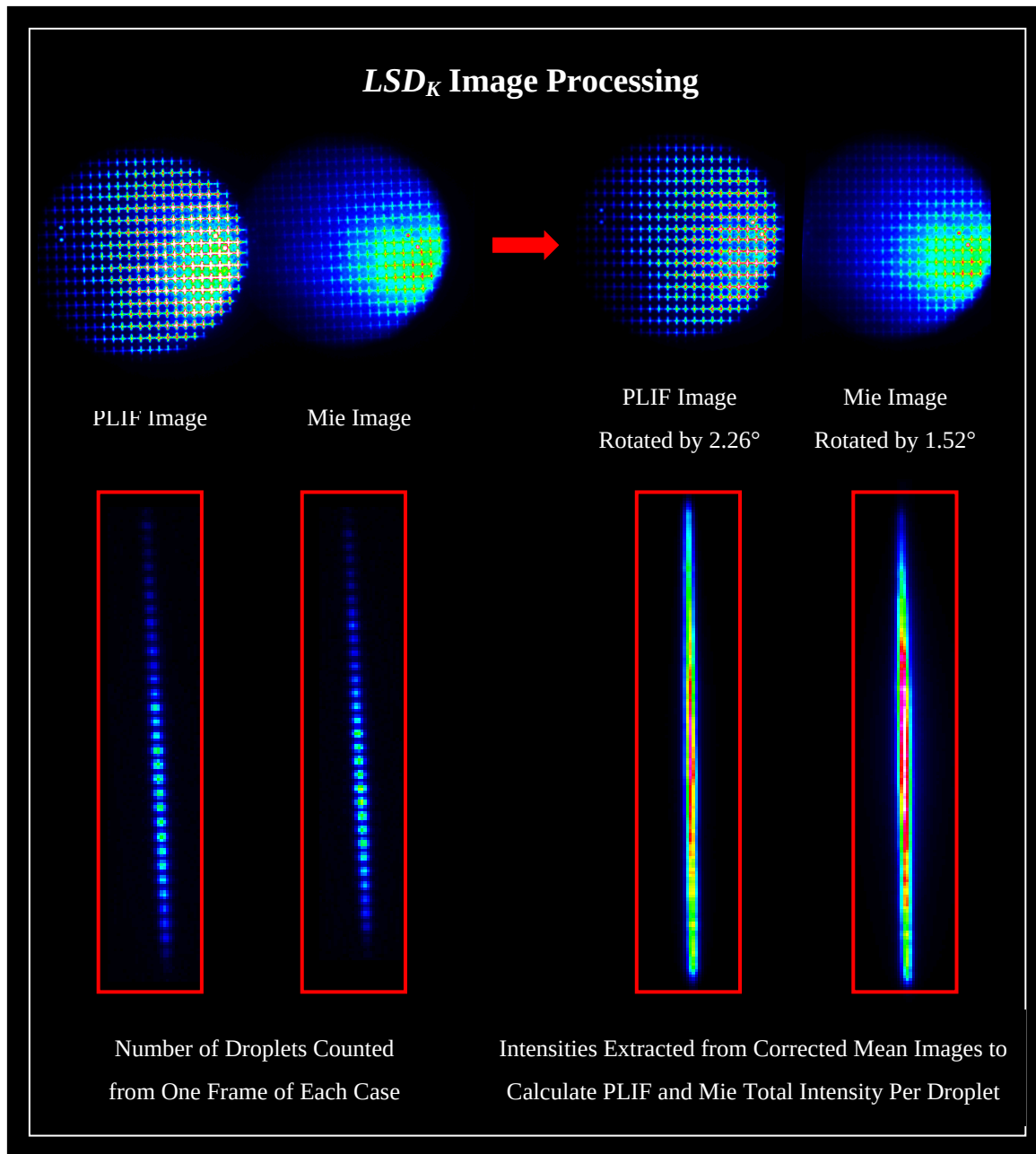


Figure 4.17: LSD_K Image Processing

All images were processed using Cranfield Laser Image Processing Software (CLIPS) that was developed by Tait (1994). The LSD image calibration chart from Section 4.3.2 provided key image manipulation factors for macros that automated image processing. The calibration chart was first processed to test macro reliability. The first macro averaged raw data and subtracted the mean background. The second macro shifted and correctly orientated the mean PLIF and Mie images for LSD division. The ND filter obstructing the Mie channel required PLIF images to be divided by ten. To define the stream region the mean background-subtracted PLIF and Mie images were saved into ASCII format. The third macro output ten raw frames in each image to allow the number of droplets to be counted. The final macro output mean PLIF and Mie intensities in specified stream regions. Although not all pixels contained fuel, all registering intensities were used in the calibration to ensure an equal treatment across cases. A given stream region has horizontal pixel intensities but excludes pixels both above and below that defined region. The vertical intensity contribution from a given droplet was unknown. Therefore, the total number of droplets in a complete stream was counted and all registered intensities were considered as LSD processing cancels the fake intensity contributions from pixels that contain no fuel. Definition of a larger stream region reduced the intensity per droplet but yielded less variation in LSD_K between cases. Eq. 4.13 shown below gave the total intensity within defined regions.

$$Total\ Intensity_{PLIF, Mie} = \overline{Intensity}_{PLIF, Mie} \left((W_{Stream_{PLIF, Mie}} + 1) \times (H_{Stream_{PLIF, Mie}} + 1) \right) \quad Eq. 4.13$$

Eq. 4.14 below gave intensity per droplet:

$$Intensity\ Per\ Droplet_{PLIF, Mie} = \frac{Total\ Intensity_{PLIF, Mie}}{Number\ of\ Droplets} \quad Eq. 4.14$$

The SMD of a given droplet stream was measured by PDA. For the same stream the total PLIF intensity per droplet was divided by the total Mie intensity per droplet. PLIF intensities were much smaller than Mie intensities at 248nm. In LSD image processing PLIF intensities were therefore multiplied by one hundred to stop truncation of LSD results upon conversion to integer format. For this reason LSD_K also multiplied PLIF intensities by the same factor. This was not accomplished for the derivation of LVF_K for application to PLIF images and hence the third macro corrected for the ND filter but did not multiply the PLIF images by ten. Eq. 4.15 shown below gave LSD_K .

$$LSD_K = \frac{D_{32_{PDA}}}{\left(\frac{100 \times Intensity\ per\ Droplet_{PLIF}}{Intensity\ per\ Droplet_{Mie}} \right)} \quad Eq. 4.15$$

For PDA measurements the manufacturer quoted an absolute uncertainty value of 4%. This study used 10% although Kershaw (2007) subsequently calculated it as 11.2%.

$$abs / ucert_{PDA} = D_{32_{PDA}} \times 0.1 \quad \text{Eq. 4.16}$$

Eq. 4.17 below estimated the absolute uncertainty in PLIF and Mie signals by counting the total number of droplets $\pm$ one droplet and then dividing by the number of droplets:

$$abs / ucert_{PLIF, Mie} = Intensity \text{ per Droplet}_{PLIF, Mie} \times \left(\frac{1}{Number \text{ of Droplets}} \right) \quad \text{Eq. 4.17}$$

Eq. 4.18 below gave the total absolute uncertainty in LSD_K , $abs / ucert_{LSD_K}$.

$$LSD_K \times \left[\left(\frac{abs / ucert_{PDA}}{D_{32_{PDA}}} \right) + \left(\frac{abs / ucert_{PLIF}}{Intensity \text{ per Droplet}_{PLIF}} \right) + \left(\frac{abs / ucert_{Mie}}{Intensity \text{ per Droplet}_{Mie}} \right) \right] \quad \text{Eq. 4.18}$$

4.4.4 Calculation of LVF_K

LVF_K transformed PLIF images into maps of Liquid Volume Fraction (LVF). LVF maps were converted into maps of quantitative Air to Fuel Ratio (AFR) with application of air and fuel densities. LVF corresponded to the intensity value of a single pixel. A pixel filled 100% with fuel yielded a maximum LVF value of unity. This assumed no attenuation of laser light through a given pixel. In reality, signal losses do exist from in-plane attenuation of light as it travels through droplets and from the multiple scattering of photons between the light sheet and imaging optics. PLIF signals were proportional to droplet volume, V_D and calculated using the SMD value from PDA measurements.

$$V_D = \left(\frac{\pi D_{32_{PDA}}^3}{6} \right) \quad \text{Eq. 4.19}$$

Eq. 4.20 found droplet spacing by dividing stream length by the number of droplets.

$$Droplet \text{ Spacing} = \left(\frac{Stream \text{ Length}}{Number \text{ of Droplets}} \right) \quad \text{Eq. 4.20}$$

Eq. 4.21 calculated LVF with information from Sections 4.3.1 and 4.3.2.

$$LVF = \left(\frac{V_D}{t_{Sheet} \times D_{32_{PDA}} \times Droplet \text{ Spacing}} \right) \quad \text{Eq. 4.21}$$

Figure 4.18 shows a theoretical LVF volume:

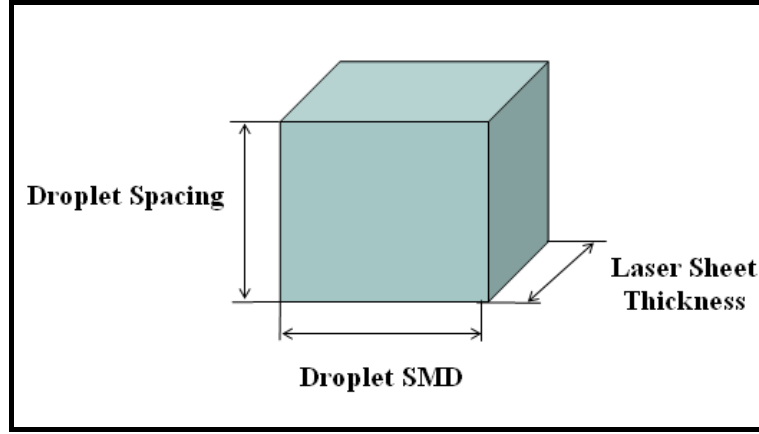


Figure 4.18: Theoretical LVF Volume

Eq. 4.22 calculated LVF_K by dividing the PLIF intensity per droplet by the volume of one droplet and multiplying by pixel volume. Eq. 4.23 calculated LVF_K uncertainty.

$$LVF_K = \left[\left(\frac{PLIF \text{ Intensity per Droplet}}{V_D} \right) \times (Pixel \text{ Length}^2 \times t_{Sheet}) \right] \quad \text{Eq. 4.22}$$

$$abs / ucrt_{LVF_K} = LVF_K \times \left[\left(\frac{3 \times V_D \times \left(\frac{0.1 \times SMD}{SMD} \right)}{V_D} \right) + \left(\frac{abs / ucrt_{Pixel \text{ Length}}}{abs / ucrt_{t_{Sheet}}} \right) + \left(\frac{2 \times Pixel \text{ Length}}{t_{Sheet}} \right) \right] \quad \text{Eq. 4.23}$$

4.4.5 Results

Figure 4.19 plots results for LSD_K and LVF_K for the LSD set-up:

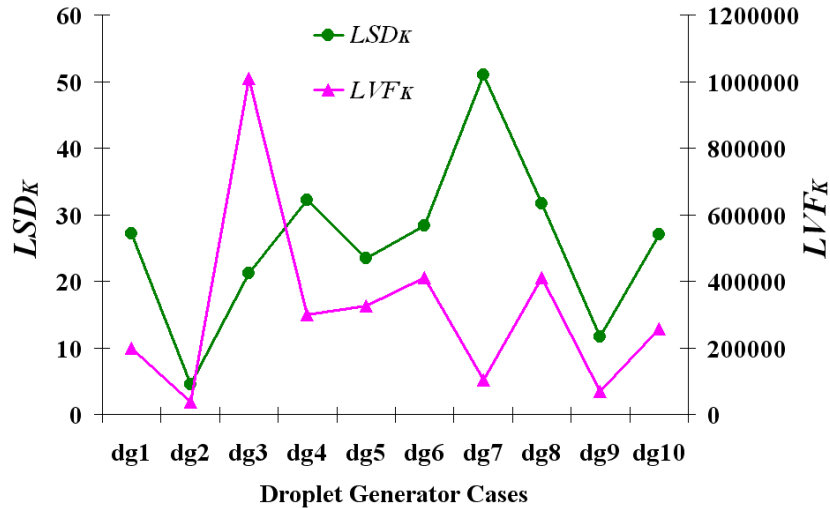


Figure 4.19: LSD Set-up Results for LSD_K and LVF_K

Figure 4.20 used six droplet generator cases to calibrate LSD spray images for the experiments described in Chapter Eight that characterised five airblast injectors, one Turbomeca Lean Module (TLM) and a pressure-swirl spray from one ANTLE weak module. Mean LSD_K and LVF_K values were 28.29 and 317,149.

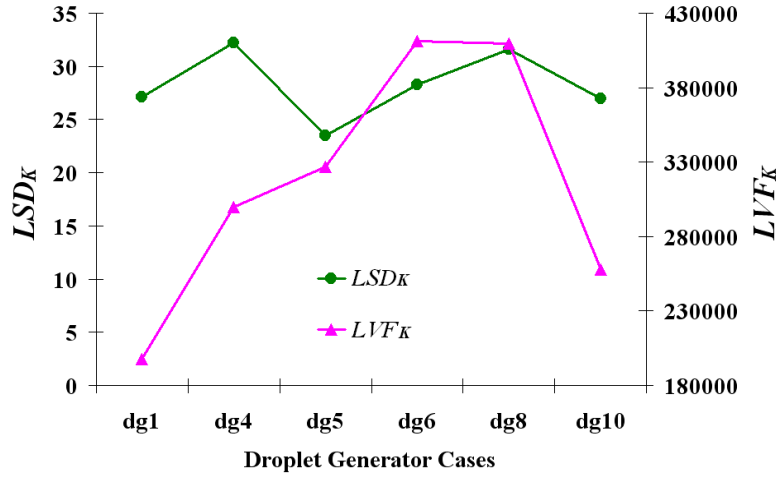


Figure 4.20: LSD Experimental Set-Up: Cases Used for LSD_K and LVF_K

Qualitative LSD measurements of a weak module fuel spray indicated the possibility of severe secondary atomisation. This prompted a swift PDA and LSD measurement campaign described in Chapter Seven on the pressure-swirl spray. PDA and LSD results closely agreed in the extremely near nozzle region to show no major step-change in SMD. However, the main spray from the airblast atomiser was clipped on each side of the pressure-swirl fuel spray. The optical set-up was then configured to increase the field of view to allow only PLIF measurements. The calibration exercise using PDA and the droplet generator was repeated using fourteen droplet streams to find LVF_K for the new set-up. Figure 4.21 shows flatfielded and unflatfielded LVF_K results.

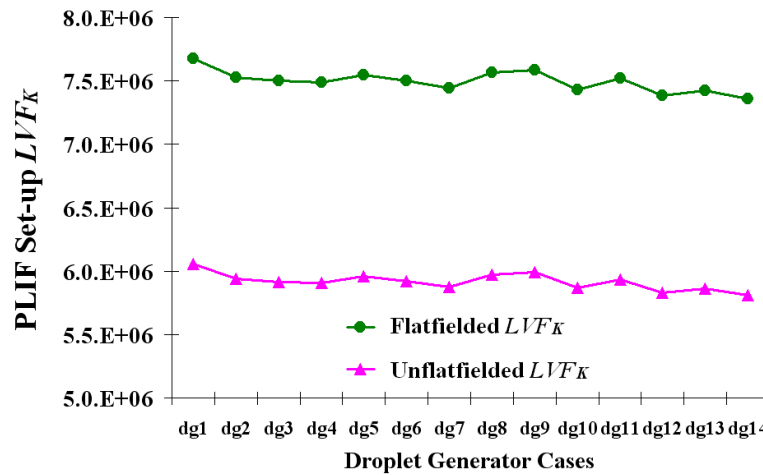


Figure 4.21: PLIF Experimental Set-Up: Flatfielded and Unflatfielded LVF_K

The mean flatfielded LVF_K value was 7,496,152 and unflatfielded LVF_K was 5,917,019. The ~27% difference crudely represented the effects of non-uniformities in laser sheet

intensity and ICCD array pixel response. Both LVF_K values were tested but resulted in dubious AFRs. As the LSD_K value used to calibrate the LSD signals yielded images that agreed well with PDA measurements, the unflatfielded LVF_K value from the LSD set-up was scaled for the PLIF set-up.

4.4.6 Scaling LSD LVF_K to PLIF LVF_K

A calibration factor was determined to scale the LSD LVF_K value into PLIF LVF_K . Both LSD and PLIF experiments used different lenses; filter efficiencies; path lengths and image accumulations. For M-Terphenyl excited at 248nm, the peak of the intensity vs wavelength plot was at 305nm. The LSD experiment used a long pass filter in the PLIF channel to exclude wavelengths below 300nm. However, this did not have a sharp cut-off point. It included some wavelengths below 300nm and excluded some above 350nm. In the PLIF alone set-up the glass lens blocked wavelengths below 350nm. Figure 4.22 shows collection efficiency is a function of the coloured areas:

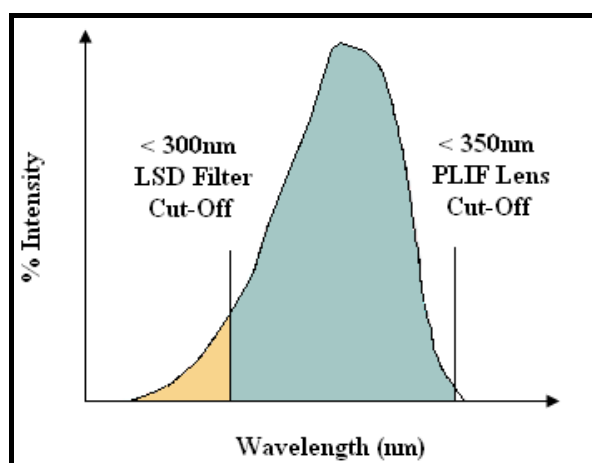


Figure 4.22: Plot of Percentage Intensity vs Wavelength

Number of counts in a theoretical pixel increases with collection efficiency. Figure 4.23 shows the emission spectrum of 1.3g/l M-Terphenyl in Cyclohexane (Berlman, 1971).

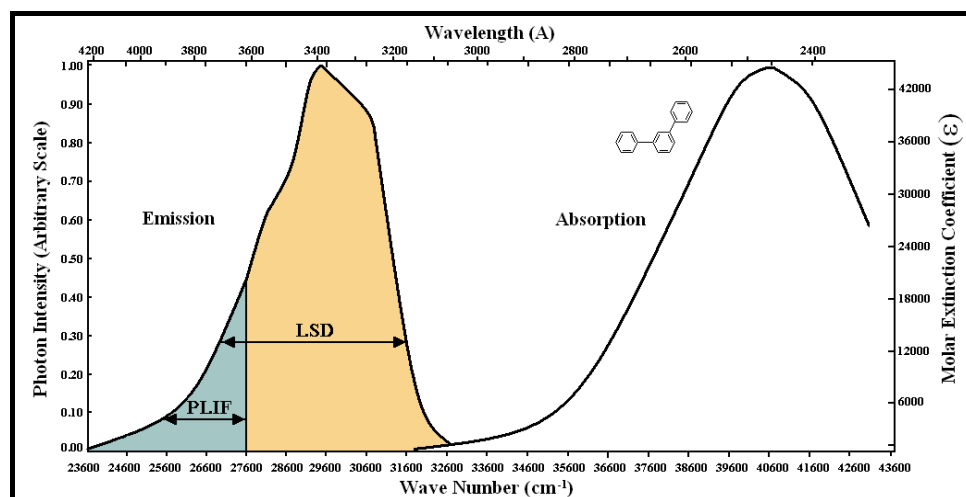


Figure 4.23: M-Terphenyl Emission Spectrum (Berlman, 1971)

The area under the emission spectrum was estimated with simple geometry to gauge the collection efficiency of the PLIF and LSD lenses. The LSD long pass filter considered the complete region under the emission curve from 300nm upwards. The PLIF set-up only took the blue region above 350nm. Please note that in Figure 4.23 wavelength decreases from left to right. Eq. 4.24 shown below estimated the change in collection efficiency between PLIF and LSD set-ups by relating LVF_K to lens focal length; path length; filter collection efficiency and to the number of image accumulations. Precise calculation was difficult because the filters did not have sharp cut-off points.

$$\left(\frac{LVF_{K_{PLIF}}}{LVF_{K_{LSD}}} \right) = \left(\frac{K_{PLIF}}{K_{LSD}} \right) = \left[\left(\frac{f_{LSD}}{f_{PLIF}} \right)^2 \times \left(\frac{r_{LSD}}{r_{PLIF}} \right)^2 \times \left(\frac{\Phi_{PLIF}}{\Phi_{LSD}} \right) \times \left(\frac{Accumulations_{PLIF}}{Accumulations_{LSD}} \right) \right] \quad \text{Eq. 4.24}$$

Substitution of the values into Eq. 4.25 yielded LVF_K .

$$LVF_{K_{PLIF}} = \left[317,149 \times \left(\frac{4.5}{1.2} \right)^2 \times \left(\frac{1.171}{0.4} \right)^2 \times \left(\frac{11}{84.6} \right) \times \left(\frac{1}{10} \right) \right] = 496,660 \quad \text{Eq. 4.25}$$

This value was used to calibrate AFR images in the PLIF set-up. The uncertainties in focal length and path length terms were very small. A larger, approximate 10% uncertainty existed in the term to approximate filter efficiency. The calibration measurement was not perfect as droplet sizes were not perfectly known, nor was the droplet spacing. There was a larger uncertainty from attenuation of the laser light sheet and from out of plane attenuation and together these amount to ~30%. Results showed that the calculated PLIF LVF_K value rendered plausible AFR. Considering all sources of uncertainty an overall error of 50% may be present in the calculated AFR.

4.5 SUMMARY

This chapter presented the method to calibrate laser signals for quantitative measurements of Planar Laser Induced Fluorescence (PLIF) for Air to Fuel Ratio (AFR) and Laser Sheet Dropsizing (LSD) for Sauter Mean Diameter (SMD). A fluorophor was selected and its concentration calculated for the PLIF signals to gain a cubic dependence with droplet diameter for measurements at 248nm. A calibration plate was imaged to determine Intensified Charge Coupled Device (ICCD) array pixel resolution and LSD image manipulation factors where corresponding pixels in PLIF and elastic Mie scattered images are divided. An acetone fluorescence flatfielding experiment defined the laser sheet region and gave image correction factors for PLIF images to compensate for non-uniformities in laser sheet intensity distribution and ICCD intensifier pixel response. A piezoelectric droplet generator was used to create a

monodisperse droplet stream for ten cases in the LSD set-up and fourteen cases in the PLIF set-up. Phase Doppler Anemometry (PDA) was applied to measure droplet SMD followed by LSD and PLIF imaging. The LSD calibration constant (LSD_K) for LSD images was 28.29 and Liquid Volume Fraction (LVF) calibration constant (LVF_K) for PLIF images was 496,660. The latter was scaled from LSD LVF_K because the calculated LVF_K values in the PLIF alone set-up yielded dubious AFRs.

CHAPTER FIVE

RIG SCALING STRATEGIES FOR LIQUID FUEL SPRAYS

5.1 INTRODUCTION

Aero fuel injectors are responsible for fuel-air mixing critical to combustion efficiency, stability and to the formation of pollutants. Computer simulation of fuel sprays is difficult in some regions of the spray due to the large number of droplets circa $>10^4 \text{ cm}^{-3}$; the broad range of droplet sizes and momenta; the complex dependence of droplet trajectory on size and airflow and of airflow on droplet dynamics. Most spray modelling therefore relies on reduced models and assumptions but all rely heavily on validation against experiments (Kuo, 1996). A typical gas turbine combustor operates at pressures and temperatures above 4MPa and 800K. Restricted access and hostile operating conditions can damage measurement probes. This makes it difficult to undertake detailed measurements of all fuel injection processes inside an operating gas turbine. Access is easier in test rigs that reproduce full engine pressure and temperature but these are extremely expensive to run and are rarely feasible to operate for more than several tests towards the end of a design process. For reasons of economy, fuel injector sprays are often characterised at lower pressures and temperatures in non-combusting test rigs using optical diagnostics. This requires engine operating conditions to be scaled down to attainable rig operating conditions in a laboratory environment.

Finding the optimum rig operating condition within the accessible range is termed the “scaling problem”. Good measurement practice demands the aspect of the two-phase flow being measured such as patternation or droplet size is similar in the test rig and engine. At lower pressure and temperature conditions many aspects of fuel spray behaviour will not be representative of the engine condition. However, it is possible to restore certain aspects of spray behaviour with judicious choice of rig air and fuel mass flow rates, pressure and temperature. A fractional deviation (Φ) was defined to quantify the success a given rig scaling strategy had in replicating key aspects of engine fuel spray behaviour. Possible rig scaling strategies were tested to quantify faithfulness of fuel patternation in airblast and hybrid atomisation for use in subsequent experiments.

5.2 PREVIOUS WORK ON FUEL INJECTOR SCALING

There is little literature on fuel injector scaling; however, Gupta and Lilley (1985) discussed the importance of different flow parameters to flow behaviour in several flow and combustion applications; Büchner *et al* (1993) considered key parameters in pulsating turbulent premixed flames and Sayre *et al* (1994) reported on parameters in

fuel sprays. More literature existed on scaling the operating conditions and physical combustor size for economical rig testing. Stewart (1952) described the pressure-scaling method, where static pressure was inversely proportional to linear scale. Both model and engine operated on identical fuels; air/fuel mass flow rate ratios (AFRs); inlet temperatures and velocities. Reynolds Number (Re) controls mixing and ensures similarity of flow patterns. Eq. 5.1 defines Re as the ratio of inertial to viscous forces that act upon an element of fluid. Treating the flow field as an ideal gas, Re is:

$$Re = \left(\frac{P_a U_a L}{RT_a \mu_a} \right) = Constant \quad \text{Eq. 5.1}$$

Matching the temperature, gas constant, and fluid viscosity this simplifies to:

$$P_a U_a L = Constant \quad \text{Eq. 5.2}$$

Reaction kinetics requires reaction time to be proportional to residence time:

$$\frac{1}{P_a} \propto \frac{L}{U_a} \quad \text{Eq. 5.3}$$

Combining Eq. 5.2 with a simplified form of Eq. 5.3 gives the pressure-scaling law:

$$P_a L = Constant \quad \text{and} \quad U_a = Constant \quad \text{Eq. 5.4}$$

Many workers reported problems with pressure-scaling. Harvey (1955) and Pauley (1956) stated that scaled-down combustors suffered from combustion oscillations as they operated at higher pressures. Lefebvre and Halls (1959) reported that scaled models were expensive, difficult to make and experienced comparatively lower metal temperatures. They suggested using a higher inlet temperature or fuels with a higher emissivity. Herbert and Bamford (1959) shared this view and stated that larger discrepancies existed in wall temperature if pressure was not exactly varied with linear scale. It was concluded that pressure-scaling was more suitable for scaling afterburners and ramjet combustion systems rather than gas turbine combustors and the latter were investigated by Stewart and Quigg (1962). Despite the satisfaction of basic similarity requirements for aerodynamic and combustion performance, pressure-scaling failed to match heat transfer and liquid atomisation criteria. The Combustion Institute recognised the need for more papers on scaling and a session on modelling principles was held at the Ninth International Symposium on Combustion in New York, 1962. Löblich (1962) stated an exact mathematical treatment of all combustion processes was impossible and supported a partial modelling approach that allowed deliberate oversight

of some similarity rules. Spalding (1962) concurred and stated that this approach brought similarity in replicating specific combustion processes. Lawhead and Combs (1962) reported that chosen rules should not accentuate or suppress processes or interactions that would otherwise occur in the full-size unit. Blevins and Coleman (1998) evaluated pressure-scaling and massflow “mA” scaling in a ramjet combustor. In pressure-scaling the mass flow was scaled to combustor length and in “mA” scaling the mass flow was scaled to combustor area. “mA” scaling aimed to reproduce the same pressure in the sub and full-scale units but both methods failed. McVey and co-workers (1989) considered scaling fuel injector operating conditions with a full size airblast injector to dispose of problems associated with geometric similarity. Lefebvre (1992) studied the injection of air into the liquid stream of a prefilming airblast atomiser and concluded that mean drop sizes depended on the ratio of the energy required to atomise the fuel and the initial kinetic energy of the atomising air. Caines *et al* (2001) investigated the performance of a full-scale airblast atomiser at sub-atmospheric conditions and agreed that the kinetic energy of the air stream was the governing factor in fuel atomisation due to its pronounced effect on the Weber number.

Löblich, Spalding, Lawhead and Combs and Priem (1962) advocated the use of Non Dimensional Parameters (NDPs) to model a physical system if only a partial knowledge of the system is available because an exact mathematical treatment of all combustion processes is impossible. This chapter used this approach to develop scaling laws that yielded flow similarity between the fuel spray in the rig and engine operating condition (Jermey, Hussain and Greenhalgh, 2003). To date, these principles have been used by Eckstein (2004) in combustion instability investigations; Secareanu *et al* (2004) in an industrial gas turbine airblast injector; Bernero (2006) in a dual fuel gas turbine burner; Lightfoot (2006) in a study on dimensional analysis and by Nakamura *et al* (2008) in work that related fuel injector performance to pollutant emissions.

5.3 NON-DIMENSIONAL ANALYSIS

Influential NDPs in liquid fuel injection are believed to be:

- Reynolds Number (Re)
- Mach Number (Ma)
- Stokes Number (Stk)
- Weber Number (We)
- Droplet Momentum (p_D)

Re , Ma , We , and Stk are considered for airblast atomisation, and also p_D for pressure-swirl atomisation. To match patternation requires the actual and modelled conditions to

have identical air streamlines and turbulence levels. This is termed dynamic similarity and necessitates the conservation of Re and Ma . Eq. 5.5 defines Re as the ratio of inertial to viscous force:

$$Re = \frac{\rho_a U_a L}{\mu_a} \quad \text{Eq. 5.5}$$

Ma is the ratio of velocity to the local sound speed:

$$Ma = \frac{U_a}{c} \quad \text{Eq. 5.6}$$

Stk describes droplet trajectory and is a measure of how faithfully a fuel droplet follows or deviates from the air streamlines. If $Stk \ll 1$, the droplet response time is shorter than the characteristic flow time and droplets will almost certainly follow the prevailing airflow. Eq. 5.7 describes Stk as the ratio of drag to inertia force:

$$Stk = \frac{\rho_L d^2 U_a}{18 \mu_a D_h} \quad \text{Eq. 5.7}$$

We determines onset of secondary atomisation and Eq. 5.8 defines it as the ratio of momentum to surface tension force:

$$We = \frac{\rho_a U_a^2 d}{\sigma_L} \quad \text{Eq. 5.8}$$

At low We , consolidating surface tension forces prevent droplet break-up. As We increases the disruptive aerodynamic forces deform a droplet into a flat disk shape. Figure 5.1 shows four deformation modes post initial distortion (Krzczkowski, 1980).

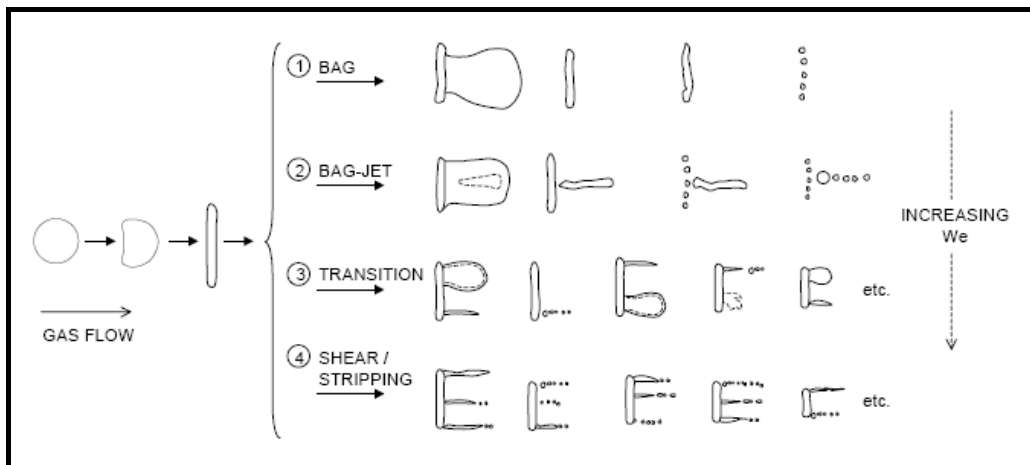


Figure 5.1: Influence of We on Droplet Stability (Krzczkowski, 1980)

Between $12 < We \leq 50$ bag break-up occurs where a thin hollow bag bursts into small droplets. Bag-jet break-up occurs at $50 < We \leq 100$ where a jet ligament forms beside the hollow bag. Between $100 < We \leq 350$ a thin sheet is drawn from the periphery of a droplet before it disintegrates. At higher We , liquid continuously strips away from a droplet to produce ligaments and smaller droplets. Ohnesorge number (Oh) describes the effect of liquid viscosity in opposing atomisation. High viscosity fluids atomise poorly. Increased temperature reduces liquid viscosity and improves atomisation to give smaller droplets. As the fractional discrepancy separately considers We and Re it omits Oh , defined in Eq. 5.9 as the ratio of liquid viscous to surface tension force:

$$Oh = \frac{\sqrt{We}}{Re} \quad \text{Eq. 5.9}$$

Although Stk considers momentum and drag, p_D is also taken into account for pressure-swirl atomisation. Eq. 5.10 defines this as the product of droplet mass and velocity:

$$p_D = M_D U_D \quad \text{Eq. 5.10}$$

Eq. 5.11 defines the mass of one droplet as:

$$M_D = \rho_D V_D \quad \text{Eq. 5.11}$$

For clarity, ρ_D is equal to ρ_L . Eq. 5.12 gives the volume of one droplet:

$$V_D = \left(\frac{\pi d^3}{6} \right) \quad \text{Eq. 5.12}$$

Substitution of Eq. 5.12 into Eq. 5.11:

$$M_D = \rho_D \left(\frac{\pi d^3}{6} \right) \quad \text{Eq. 5.13}$$

Eq. 5.14 rearranges the conservation of mass equation for droplet velocity:

$$U_D = \left(\frac{\dot{m}_D}{\rho_D A_{\text{Eff}}} \right) \quad \text{Eq. 5.14}$$

Eq. 5.15 shown overleaf substitutes Eq. 5.13 and Eq. 5.14 into Eq. 5.10:

$$p_D = \rho_D \left(\frac{\pi d^3}{6} \right) \left(\frac{\dot{m}_D}{\rho_D A_{Eff}} \right) \quad \text{Eq. 5.15}$$

Eq. 5.16 simplifies Eq. 5.15 for droplet momentum, p_D :

$$p_D = \left(\frac{\pi \times d^3}{6} \right) \left(\frac{\dot{m}_D}{A_{Eff}} \right) \quad \text{Eq. 5.16}$$

5.3.1 SMD Correlations

To conserve Stk , We and p_D requires the mean droplet sizes in the rig and engine to be known and this requires a model that predicts droplet size in both circumstances. Atomisation modelling is uncertain and perhaps the most reliable models are empirical correlations of the type discussed in Lefebvre (1989) but these are still uncertain and say little about the shape of the drops size distribution. In combustion, the most popular definition for mean droplet size is Sauter Mean Diameter (SMD). Eq. 5.17 defines it as that diameter of droplet with the same volume to surface area ratio as the entire spray.

$$SMD = \frac{\sum N_i D_i^3}{\sum N_i D_i^2} = D_{32} \quad \text{Eq. 5.17}$$

To define a scaling strategy that preserves droplet size requires a model between droplet size, operating conditions and liquid and air properties. No extra uncertainty is introduced by using the same model to predict SMD in the rig and engine conditions. However, several questions arise when correlating the spray behaviour between hot and cold conditions. Ambient air pressure and temperature changes liquid properties and the aerodynamic forces imparted to the liquid. A spray flame also changes shape with pressure. Both affect atomisation. With hot experiments the heat transfer alters the droplet size distribution through evaporation. In the absence of heat, the spatial mass distribution of fuel and shape of the spatial distribution of droplet size will differ. However, the disparity is considered as minor in the near-nozzle region. Therefore, all cold experiments characterise sprays to a length of only 42mm from the injector exit.

5.3.1.1 *Airblast Atomisation*

The correlation of El-Shanawany and Lefebvre (1980) shown overleaf in Eq. 5.18 was used to calculate the SMD in airblast atomisation. This is dimensionally correct and based on light scattering measurements using three nozzles flowing water, kerosene and some higher viscosity liquids over a wide range of air velocities.

$$SMD = D_h \left(1 + \frac{1}{AFR} \right) \left[0.33 \left(\frac{\sigma_f}{\rho_a U_a^2 D_p} \right)^{0.6} \left(\frac{\rho_f}{\rho_a} \right)^{0.1} + 0.068 \left(\frac{\mu_f^2}{\rho_f \sigma_L D_p} \right)^{0.5} \right] \quad \text{Eq. 5.18}$$

For airblast injectors, fuel pattenation is a weak function of the initial momentum imparted to the fuel droplets by the fuel pressure drop. As this momentum is small and Stk is also small, the initial velocity is rapidly washed out by the airflow. However, if there are multiple distinct air streams close together at the injection point, the initial momentum may determine the particular stream a given droplet joins and travels with. Forthcoming calculations therefore ignore initial momentum for the airblast atomiser.

5.3.1.2 Pressure-Swirl Atomisation

For pressure-swirl injectors, pattenation is a much stronger function of the initial momentum imparted to the fuel droplet by the fuel pressure drop. The initial liquid velocity decreases over time due to aerodynamic drag until it matches the air velocity. Although the literature contains a large body of empirical data for pressure-swirl atomisation, most SMD correlations contain numerous discrepancies between SMD and liquid properties such as surface tension and viscosity; and air properties such as pressure and temperature, injection pressure and nozzle dimensions. A second correlation proposed by Lefebvre (1983) was used to calculate the SMD for pressure-swirl atomisation. Eq. 5.19 gathered experimental results from many workers and considered jet disintegration in terms of aerodynamic forces and turbulence levels.

$$SMD = 2.25 \sigma_L^{0.25} \mu_L^{0.25} \dot{m}_L^{0.25} \Delta P_L^{-0.5} \rho_A^{-0.25} \quad \text{Eq. 5.19}$$

All terms were now available barring the liquid injection pressure differential across the nozzle, (ΔP_L) . This was calculated using effective nozzle area, A_{Nozzle} . Fuel flow rate, (Q) and corresponding ΔP_L were recorded with the injector installed in the test rig. For clarity, $\dot{m}_L = \dot{m}_D$.

$$\dot{m}_L = \left(\frac{Q}{1000 \times 60} \right) \rho_L \quad \text{Eq. 5.20}$$

Eq. 5.21 shows the simplified Bernoulli equation for incompressible flow that was used to calculate liquid velocity:

$$U_L = \sqrt{\frac{2 \Delta P_L}{\rho_L}} \quad \text{Eq. 5.21}$$

Overleaf, Eq. 5.22 substitutes Eq. 5.21 into the conservation of mass equation:

$$\dot{m}_L = \rho_L A_{Eff} \sqrt{\frac{2\Delta P_L}{\rho_L}} \quad \text{Eq. 5.22}$$

Eq. 5.23 calculates A_{Eff} from $\dot{m}_L$ and ΔP_L :

$$A_{Eff} = \frac{\dot{m}_L}{\sqrt{2\rho_L \Delta P_L}} \quad \text{Eq. 5.23}$$

The result also equals:

$$A_{Eff} = C_d A_{Nozzle} \quad \text{Eq. 5.24}$$

It was assumed that initial droplet velocity equalled liquid velocity so the discharge coefficient $C_d < 1$. Having determined A_{Eff} , the conservation of mass equation was used to find ΔP_L for various fuel mass flow rates and Eq. 5.25 rearranged for liquid velocity:

$$U_L = \frac{\dot{m}_L}{\rho_L A_{Eff}} \quad \text{Eq. 5.25}$$

Eq. 5.26 substitutes Eq. 5.20 into Eq. 5.25 to calculate the liquid velocity:

$$U_L = \frac{\left(\frac{Q}{1000 \times 60}\right) \rho_L}{\rho_L A_{Eff}} \quad \text{Eq. 5.26}$$

From Eq. 5.21 the liquid injection pressure differential across the nozzle is:

$$\Delta P_L = \frac{1}{2} \rho_L U_L^2 \quad \text{Eq. 5.27}$$

Eq. 5.28 substituted Eq. 5.26 into Eq. 5.27 to calculate liquid velocity:

$$\Delta P_L = \frac{1}{2} \rho_L \left[\frac{\left(\frac{Q}{1000 \times 60}\right) \rho_L}{\rho_L A_{Eff}} \right]^2 \quad \text{Eq. 5.28}$$

Eq. 5.29 overleaf simplifies Eq. 5.28:

$$\Delta P_L = \frac{1}{2} \rho_L \left[\frac{\left(\frac{Q}{1000 \times 60} \right)}{A_{Eff}} \right]^2 \quad \text{Eq. 5.29}$$

All terms were now available to calculate the SMD for pressure-swirl atomisation and Eq. 5.19 was subsequently used to calculate the quantities Stk , We and p_D .

5.3.2 Available Rig Scaling Strategies

The rig scaling strategy calculates four rig quantities from the target engine operating condition: rig air and fuel mass flow rates, pressure and temperature. The scaling strategy also has four constraints that are fixed or required. An example of a constraint is rig inlet air temperature that was set by the available compressor. A particular requirement can be conservation of Air to Fuel Ratio (AFR) between the engine and rig conditions. The following rig scaling strategies fix the rig temperature and pressure and are believed to be in current use for full size fuel injectors. They conserve:

- Global Air Velocity and AFR
- Global Air Velocity and Air/Fuel Momentum Flux Ratio
- Relative Pressure Drop and AFR
- Relative Pressure Drop and Air/Fuel Momentum Flux Ratio
- $M\sqrt{T}/AP$. This only has three constraints to leave fuel flow rate undetermined. It is also equivalent to preserving the relative pressure drop. Conserving the relative pressure drop is the same as conserving Ma

Other possible strategies preserve:

- Re , Ma and Stk number, fix temperature
- Re and AFR, fix pressure and temperature
- Re , Ma and Air/Fuel momentum flux ratio, fix temperature
- Re , Ma and AFR, fix temperature
- Re , AFR, Air/Fuel momentum flux ratio and Air/Fuel kinetic energy flux ratio, fix temperature (AFR, momentum and kinetic energy flux ratios together yield only two constraints)
- Re and AFR, set $Ma = 0.3$ and fix temperature. Ma is set to 0.3 to keep air velocity as high as possible without introducing compressibility effects
- Re , set $Ma = 0.3$, fix temperature and AFR for acceptable fuel flow rate and Stk
- Re and conserve Ma , fix temperature and AFR, again the AFR is chosen to yield a practical fuel flow and acceptable Stk

Table 5.1 defines the quantities preserved by the chosen rig scaling strategies:

Quantity	Definition	Equation	Symbol
Global Air Velocity	Average velocity magnitude through a constriction such as an injector	$\sqrt{\frac{2\Delta P}{\rho_a}}$	U
Air/Fuel Momentum Flux Ratio	Ratio of the momentum flux in the air stream to momentum flux in fuel stream	$\frac{M'_a U_a}{M'_f U_f}$	$\frac{P_a}{P_f}$
Relative Pressure Drop	Air pressure drop across the injector divided by the absolute air pressure	$\frac{\Delta P}{P_{up}}$	
AFR	Ratio of air mass flux to fuel mass flux	$\frac{M'_a}{M'_f}$	AFR
$M\sqrt{T}/AP$	Air mass flux times sq. rt. temp. divided by effective area of injector air passages times absolute upstream air pressure	$\frac{M'_a \sqrt{T}}{A_e P_{up}}$	
Air/Fuel Kinetic Energy Flux Ratio	Ratio of kinetic energy flux in air stream to kinetic energy flux in fuel stream	$\frac{M'_a U_a^2}{M'_f U_f^2}$	
Reynolds Number	Ratio of inertial force to viscous forces	$\frac{\rho_a U_a L}{\mu_a}$	Re
Mach Number	Ratio of velocity to local sound speed	$\frac{U_a}{c}$	Ma
Weber Number	Ratio of inertial to surface tension forces	$\frac{\rho_a U_a^2 SMD}{\sigma_L}$	We
Stokes Number	Ratio of particle stopping distance to radius of curvature of streamlines $Cc \sim 1$	$\frac{\rho_f SMD^2 U_a Cc}{18\mu_a R}$	Stk
Droplet Momentum	Droplet mass times droplet velocity	$M_D U_D$	p_D
Sauter Mean Diameter	Ratio of average volume to average surface area for an ensemble of droplets	$\frac{\sum_i n_i d_i^3}{\sum_i n_i d_i^2}$	SMD

Table 5.1: Definition of Preserved Quantities

5.3.3 Quality of Rig Scaling Strategies

The ideal rig scaling strategy would preserve all the mentioned quantities including mean droplet size and all the relevant non-dimensional groups such as Re , Ma , We , Stk and p_D that are also defined in Table 5.1 in the rig to the same level of precision as in the engine. Given the restricted pressures and temperatures available in a low-cost rig this is rarely, if ever possible, especially under non-combusting conditions. A strategy was selected from a range of imperfect but possible strategies according to the spray feature under investigation. Spray behaviour varies strongly with position in the mixing field. Behaviours include patternation – the spatial distribution of fuel; air–fuel mixing; fuel droplet size and evaporation rate. Φ was used to rank strategy performance. This used non-dimensional analysis to judge the performance of each strategy according to how well it conserved engine quantities Re , Ma , We , Stk and p_D , or a subset of these quantities most relevant to the spray process of interest. Φ is a weighted addition of individual discrepancies and Φ_X is a sensitivity measure for quantity X and takes a value between zero and one. All strategies were given sensitivities of unity to compute how well each approached the ideal value of zero. Eq. 5.30 defines Φ for airblast atomisation and considers Re , Ma , Stk and We :

$$\Phi_{Airblast} = \sqrt{\Phi_{Re} \left(\frac{Re_{Rig} - Re_{Eng}}{Re_{Eng}} \right)^2 + \Phi_{Ma} \left(\frac{Ma_{Rig} - Ma_{Eng}}{Ma_{Eng}} \right)^2 + \Phi_{Stk} \left(\frac{Stk_{Rig} - Stk_{Eng}}{Stk_{Eng}} \right)^2 + \Phi_{We} \left(\frac{We_{Rig} - We_{Eng}}{We_{Eng}} \right)^2} \quad \text{Eq. 5.30}$$

Eq. 5.31 defines Φ for pressure-swirl atomisation and also includes p_D :

$$\Phi_{PS} = \sqrt{\Phi_{Re} \left(\frac{Re_{Rig} - Re_{Eng}}{Re_{Eng}} \right)^2 + \Phi_{Ma} \left(\frac{Ma_{Rig} - Ma_{Eng}}{Ma_{Eng}} \right)^2 + \Phi_{Stk} \left(\frac{Stk_{Rig} - Stk_{Eng}}{Stk_{Eng}} \right)^2 + \Phi_{We} \left(\frac{We_{Rig} - We_{Eng}}{We_{Eng}} \right)^2 + \Phi_{p_D} \left(\frac{p_{D_{Rig}} - p_{D_{Eng}}}{p_{D_{Eng}}} \right)^2} \quad \text{Eq. 5.31}$$

Eq. 5.32 gives the total fractional deviation for hybrid atomisation where both airblast and pressure-swirl atomisers operate in tandem:

$$\Phi_{Hybrid} = \sqrt{(\Phi_{Airblast})^2 + (\Phi_{PS})^2} \quad \text{Eq. 5.32}$$

To validate the scaling method required a comparison between experimental and actual results. RR provided engine emissions data. PLIF spray measurements of AFR in this

study and their subsequent transformation into two-dimensional Nitric Oxide (NO) maps showed good agreement with RR measurements. This validated the scaling and image processing methods for LSD and PLIF spray measurements of SMD and AFR.

5.3.4 Investigated Strategies

Investigated strategies fell into two categories: free-pressure and pressure-determining. Table 5.2 listed the first group where upstream rig pressure was a free parameter.

Free-Pressure Strategies
Conserve Momentum Flux Ratio and Relative Pressure Drop
Conserve AFR and Relative Pressure Drop
Conserve Momentum Flux Ratio and Global Air Velocity
Conserve AFR and Global Air Velocity
Conserve Re and AFR Conserved, Free Pressure

Table 5.2: Free-Pressure Strategies

Table 5.3 lists strategies where upstream rig pressure was fixed by conserved quantities.

Pressure-Determining Strategies
Re , Ma and Momentum Flux Ratio
Re , Ma and AFR
Re , AFR, Momentum Flux Ratio and Kinetic Energy Ratio
Re and AFR Conserved, $Ma = 0.3$
Re Conserved, $Ma = 0.3$, AFR as a Free Parameter
Re and Ma Conserved, AFR as a Free Parameter

Table 5.3: Pressure-Determining Strategies

5.4 CALCULATIONS

The fractional deviation, Φ is weighted to estimate the faithfulness of patternation for airblast and hybrid atomisation. All calculations assume:

- The same fuel injector is used in the rig and engine for geometric similarity
- Fuel is incompressible and unheated since leaving the tank
- Engine fuel is of density 790kg/m^3 ; surface tension 0.028N/m and absolute viscosity $1.68 \times 10^{-3} \text{Ns/m}^2$ at 25°C . Rig fuel is of density 806kg/m^3 ; surface tension 0.028N/m and absolute viscosity $1.68 \times 10^{-3} \text{Ns/m}^2$ at 25°C
- Ratio of specific heats, γ is 1.4. Gas constant of air, R is 287J/kg/K
- SMD is used as the droplet diameter to calculate We , Stk and p_D

Eq. 5.33 shows air density calculations use the density upstream of the injector:

$$\rho_a = \frac{P_{Up}}{RT_{Eng}} \quad \text{Eq. 5.33}$$

Eq. 5.34 defines ΔP as the product of injector pressure drop and upstream air pressure:

$$\Delta P = \left(\frac{\Delta P}{P} \right) P_{Up} \quad \text{Eq. 5.34}$$

Eq. 5.35 shows global air velocity, U is calculated using the Bernoulli equation for incompressible flow since all strategies that gave $Ma > 0.3$ were discarded. U was used to find Re , We and Stk . Strictly the lower slip velocity should be used but in airblast atomisation the initial liquid velocity is small and rapidly washed out by the airflow.

$$U_a = \sqrt{\frac{2\Delta P}{\rho_a}} \quad \text{Eq. 5.35}$$

Eq. 5.36 shows the hydraulic diameter, D_h is assumed to equal the diameter of a circle with an area equal to the effective area of the injector. This was the characteristic length dimension used to calculate Re and as the streamline radius of curvature in Stk .

$$D_h = \sqrt{\left(\frac{4A_{Eff}}{\pi} \right)} \quad \text{Eq. 5.36}$$

For air viscosity calculations, Figure 5.2 fitted an eleventh order polynomial to the temperature and air absolute viscosity data of Pofel and Svelha (1973):

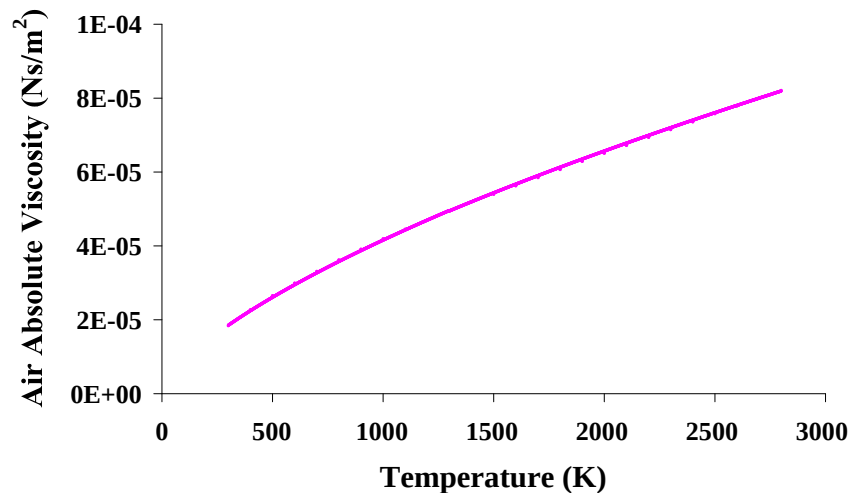


Figure 5.2: Plot of Air Absolute Viscosity vs Air Temperature

Eq. 5.37 shows the relationship to calculate air mass flow rate:

$$\dot{m}_a = \frac{\rho_a A_{\text{Eff}}}{1000} \quad \text{Eq. 5.37}$$

Eq. 5.38 calculates fuel mass flow rate by dividing air mass flow rate by injector AFR:

$$\dot{m}_f = \frac{\dot{m}_a}{AFR_{\text{Inj}}} \quad \text{Eq. 5.38}$$

Eq. 5.39 converted Eq. 5.38 into volumetric flow rate by dividing by the fuel density:

$$Q = \frac{60\dot{m}_f}{\rho_f} \quad \text{Eq. 5.39}$$

Φ ratios NDP values in the rig to the engine. As identical assumptions were used in their derivation any flaws arising from assumptions cancel out. Rig air temperature was a “free” parameter: in practice this was fixed by the available compressor. Φ was calculated at 323 and 373K for pressure-determining strategies and 323 and 373K every 101kPa between 100 and 1000kPa absolute for the free-pressure strategies. For free-pressure strategies the rig input pressure was optimised to minimise Φ . This gave the pressure difference between the rig and airbox and determined required fuel flow rates.

5.4.1 Airblast Calculation

Table 5.4 shows two engine operating conditions for a typical airblast injector taken from the ICLEAC engine programme. Condition A was a high pressure and high temperature engine operating condition and Condition B a lower pressure and temperature case. Condition B was the actual condition scaled in Chapter Eight to investigate the response of fuel sprays to acoustic forcing; selected because it had the largest dataset and displayed the most contrast with engine rumble intensity data.

Quantity	ICLEAC Condition A	ICLEAC Condition B
Upstream Pressure Absolute (kPa)	2,000	317
Air Temperature (K)	800	380
Injector Effective Area (mm ²)	230	230
Injector AFR	10	10.11
$\Delta P/P$ (%)	4	4

Table 5.4: ICLEAC Engine Operating Conditions A and B

To estimate the faithfulness of patternation, Φ_{Re} and Φ_{Stk} were given sensitivities of 1 and Φ_{Ma} and Φ_{We} sensitivities of zero. $Ma_{Eng} = 0.24$ so strategies that gave $Ma_{Rig} > 0.3$ were discarded. Separate contributions of the Re and Stk on Φ were calculated for strategies that did not directly conserve Re by recalculating Φ : firstly, with Φ_{Re} having a sensitivity unity and all others zero and secondly, with Φ_{Stk} having a sensitivity of unity and all others zero.

5.4.1.1 Condition A at 323K

Figure 5.3 plots $\Phi_{Airblast}$ with Φ_{Re} and Φ_{Stk} assigned with sensitivities of unity against downstream rig pressure at a rig air inlet temperature of 323K. If $\Phi_{Airblast}$ was equal to unity it signified a deviation of 100% from the engine condition. The following strategies gave Ma_{Rig} above 0.3 and were therefore excluded from the chart:

- AFR and Global Air Velocity
- Re and AFR, Free Pressure up to 600kPa
- Momentum Flux Ratio and Global Air Velocity

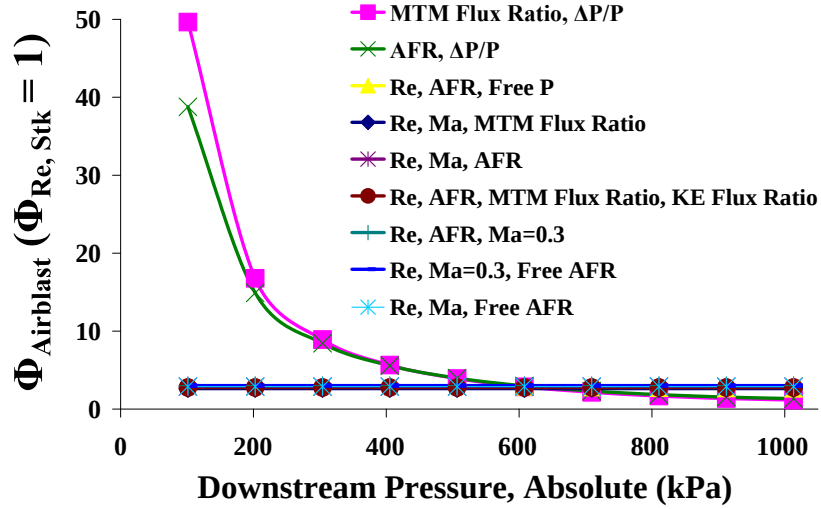


Figure 5.3: Cond. A – Plot of $\Phi_{Airblast} (\Phi_{Re}, \Phi_{Stk} = 1)$ vs Rig Pressure at 323K

Pressure-determining strategies naturally had no pressure dependence so were plotted as horizontal lines for comparison against free-pressure strategies. Pressure-determining strategies were slightly, but insignificantly worse than variable-pressure strategies above 600kPa. The tested pressure-determining strategies had the potential advantage that Re was correct and that all of the compromise was in Stk . Both free-pressure strategies that preserved relative pressure drop improved rapidly as rig pressure increased to 600kPa. Overleaf, Figure 5.4 shows the required upstream rig pressures for optimum scaling. Although the Unsteady Flow Rig (UFR) was commissioned to operate up to 700kPa, Figure 5.4 also shows that a hypothetical increase in rig pressure to ~1200kPa improved $\Phi_{Airblast}$ by ~60% for both strategies that conserved the relative pressure drop.

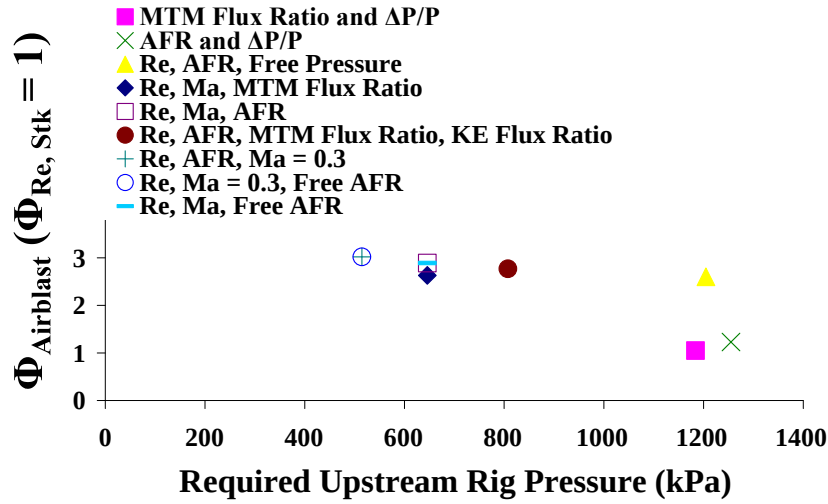


Figure 5.4: Cond. A – Plot of $\Phi_{Airblast}$ ($\Phi_{Re, Stk} = 1$) vs Rig Pressure at 323K

$\Phi_{Airblast}$ was similar for all pressure-determining strategies and for the free-pressure strategy that conserved Re shown above in yellow. $\Phi_{Airblast}$ was smaller and therefore better for the free-pressure strategies. $\Phi_{Airblast}$ was mostly due to the discrepancy in Stk and was $\sim 260\%$ for pressure-determining strategies. Figure 5.5 plot AFR against We at the optimum rig pressures for each strategy to minimise $\Phi_{Airblast}$. We_{Eng} was 114 and mean values for free-pressure and pressure-determining strategies were 71 and 66. This was 37% and 42% shy of We_{Eng} . Exclusion of the free-pressure strategy that conserved Re from the free-pressure strategies reduced the difference to within 26% of We_{Eng} .

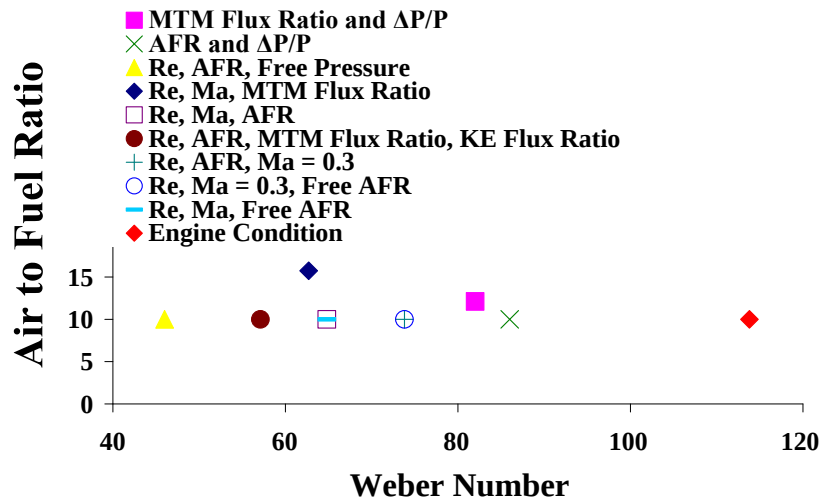


Figure 5.5: Cond. A – Plot of AFR vs We at 323K

Both free-pressure strategies that conserved relative pressure drop yielded similar $\Phi_{Airblast}$ and AFR. Compared to every other strategy they had the best match with We_{Eng} . Overleaf, Figure 5.6 and Figure 5.7 show the effect of varying AFR on We and $\Phi_{Airblast}$ for the two pressure-determining strategies that left AFR as a free parameter.

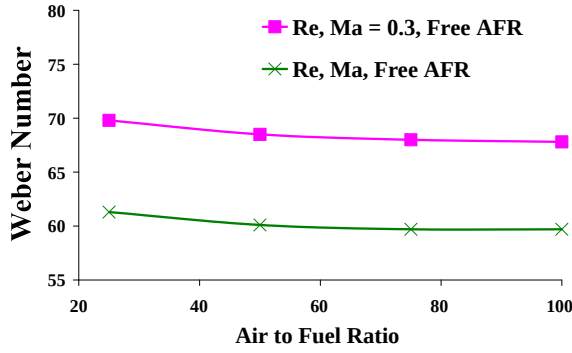


Figure 5.6: Cond. A – Plot of AFR vs We , Free AFR

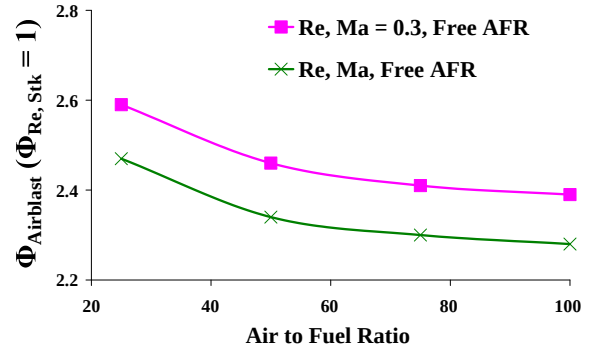


Figure 5.7: Cond. A – Plot of AFR vs $\Phi_{Airblast} (\Phi_{Re} = 1)$ vs at 323K

A low AFR spray, i.e. one that is rich improved the match with We_{Eng} whereas a high AFR leaner spray benefitted $\Phi_{Airblast}$. Although little difference existed between both, the strategy that conserved Re , Ma , Free AFR gave lower $\Phi_{Airblast}$ values but a worse match with We_{Eng} . The opposite was true for the other strategy. Figure 5.8 and Figure 5.9 shown below plot the separate contributions of Re and Stk against $\Phi_{Airblast}$ for the two best strategies. Both strategies conserved injector pressure drop.

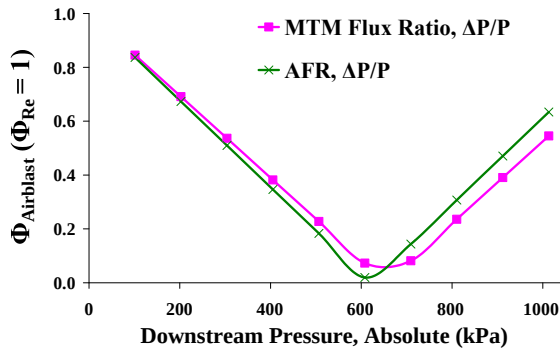


Figure 5.8: Cond. A – Plot of $\Phi_{Airblast} (\Phi_{Re} = 1)$ vs Rig Pressure at 323K

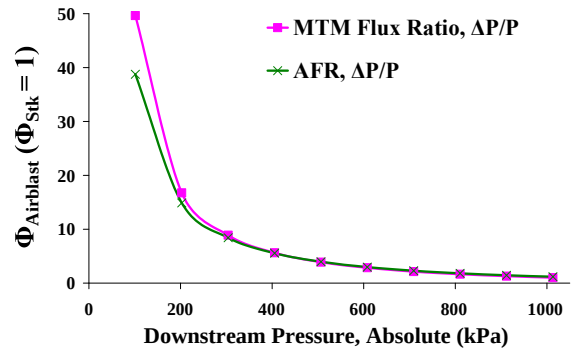


Figure 5.9: Cond. A – Plot of $\Phi_{Airblast} (\Phi_{Stk} = 1)$ vs Rig Pressure at 323K

Figure 5.8 confirmed that the fractional deviation in Re was below 100% and actually conserved at ~ 600 kPa for the strategy that conserved AFR and injector pressure drop. Figure 5.9 showed the fractional deviation in Stk dominated to follow the trend of Figure 5.3; improving slowly as rig pressure increased.

5.4.1.2 Condition A at 373K

Figure 5.10 shows equivalent results for a rig inlet temperature of 373K:

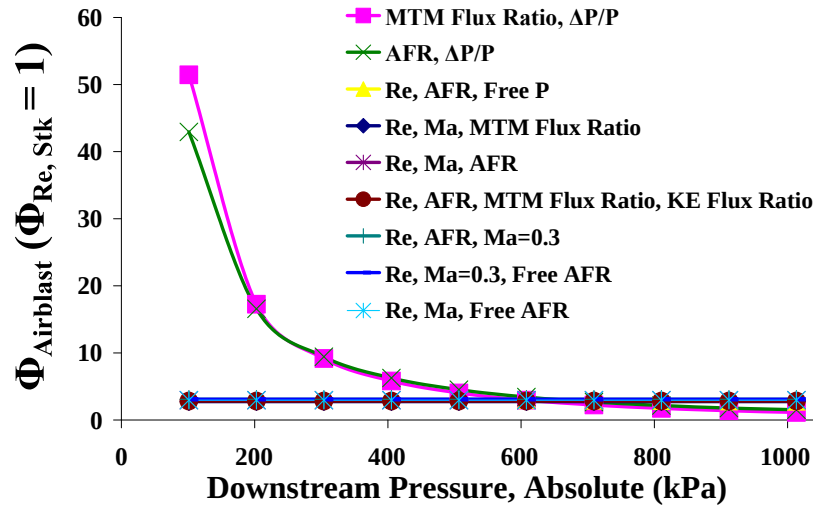


Figure 5.10: Cond. A – Plot of $\Phi_{Airblast} (\Phi_{Re, Stk} = 1)$ vs Rig Pressure at 373K

Figure 5.11 shows upstream rig pressures required to attain minimum $\Phi_{Airblast}$ for each strategy at the higher 373K temperature. The strategy that conserved momentum flux ratio and injector pressure drop improved $\Phi_{Airblast}$ by 20% at 373K over 323K. At the higher temperature all other strategies performed insignificantly worse. This difference was trivial except at atmospheric pressure. More significant is the fact that all strategies demanded higher pressures at higher temperatures. A 50K temperature rise increased liquid viscosity and evaporation rates to improve atomisation and yield smaller droplets.

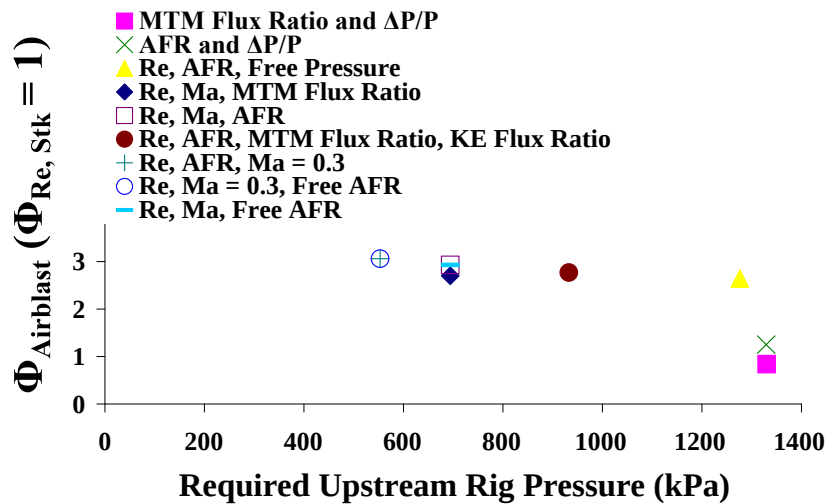


Figure 5.11: Cond. A – Required Upstream Rig Pressures vs $\Phi_{Airblast}$ at 373K

The effect of AFR variation on $\Phi_{Airblast}$ for both pressure-determining strategies that left AFR as a free parameter was similar to 323K where a higher AFR improved $\Phi_{Airblast}$.

The rig scaling strategy was selected if the demanded rig pressure and AFR were attainable and convenient. The AFR may be inconvenient for one of two reasons:

- Increasing AFR improved the fractional deviation in Stk but to make a significant improvement required an unrealistically high AFR: the fuel would be sparse and the aerodynamic blockage caused by the fuel unrealistically low
- Secondly, low AFR leads to dense sprays that are difficult to measure with optical diagnostics. It is advisable to keep the AFR as close as possible to that of the engine condition to gain similar blockage effects

To match patternation required conservation of Re , Ma and Stk . Figure 5.12 shows the plot is nearly identical to that shown in Figure 5.10 where the fractional deviation in Stk dominates. Incidentally, the same plot for 323K is similar to Figure 5.3.

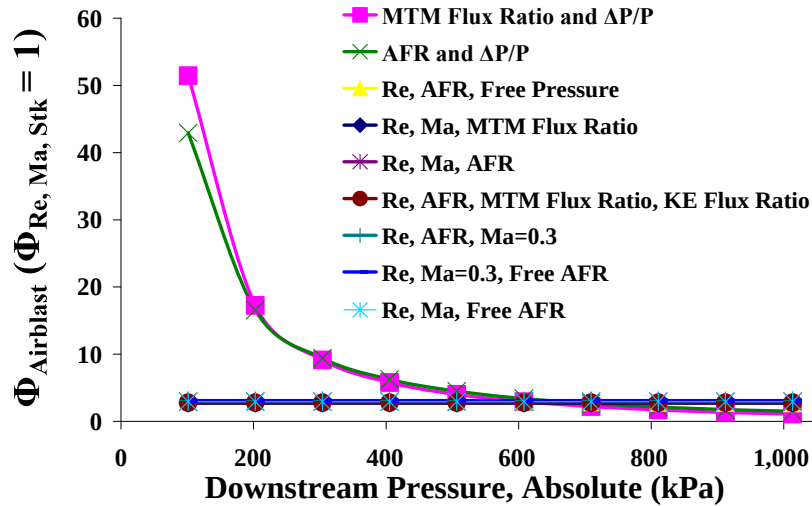


Figure 5.12: Cond. A – Plot of $\Phi_{Airblast} (\Phi_{Re, Ma, Stk} = 1)$ vs Rig Pressure at 373K

To only preserve Re and Stk and keep Ma below 0.3 required the SMD to be smaller in the rig than in the engine. The smaller SMD was also to be achieved at lower air densities and velocities. Increasing the air velocity increases Ma but this must be retained under 0.3 to avoid compressibility effects. Secondly, increasing the air velocity required air density to decrease if Re was conserved because the product of air velocity and density must remain constant and this limited the reduction in SMD. The SMD correlation required a negative AFR to attain the required SMD. Variation of the air density to within 10% of the target value did not achieve an SMD value within 10% of the target. The Re and Stk may be matched if a different fuel with a lower surface tension and viscosity is used but this would also entail adaptation of the test rig to facilitate increased air temperatures.

5.4.1.3 Condition B at 323K

Condition B was a lower temperature and pressure engine condition. Figure 5.13 plots $\Phi_{Airblast}$ against upstream rig pressure for a rig air temperature of 323K. No strategies gave Ma above 0.3 so all were plotted.

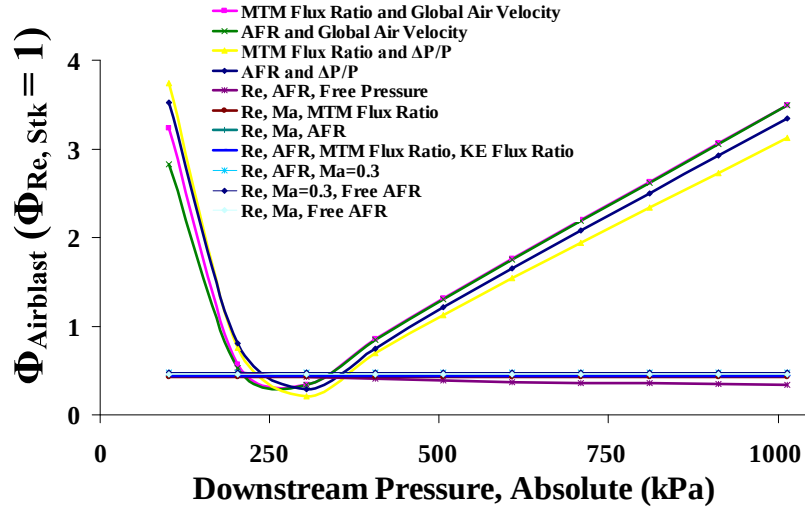


Figure 5.13: Cond. B – Plot of $\Phi_{Airblast}$ ($\Phi_{Re, Stk} = 1$) vs Rig Pressure at 323K

Free-pressure strategies performed better than pressure-determining strategies between 200 and 350kPa and at 300kPa displayed a significant 60% advantage. Strategies that conserved global air velocity had identical $\Phi_{Airblast}$ and We . Those that preserved injector pressure drop also had similar values. In free-pressure strategies, $\Phi_{Airblast}$ rose linearly after 300kPa. Above 350kPa the pressure-determining strategies reclaimed their initial advantage. Effect of increasing AFR in both pressure-determining strategies that kept AFR as a free parameter was a small decrease in $\Phi_{Airblast}$. Figure 5.14 shows the required upstream rig pressures and $\Phi_{Airblast}$ for all strategies.

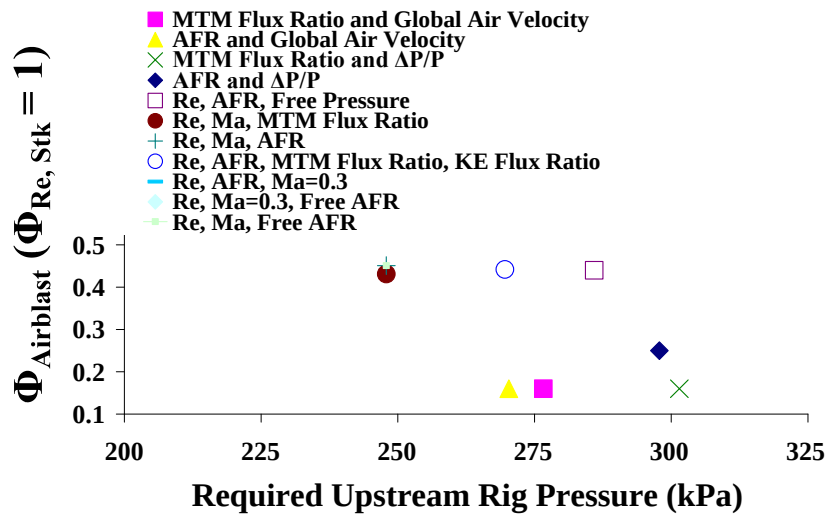


Figure 5.14: Cond. B – Required Upstream Rig Pressures vs $\Phi_{Airblast}$ at 323K

Little difference existed between $\Phi_{Airblast}$ for the six pressure-determining strategies and for the strategy Re , AFR, free pressure. As all conserved Re , $\Phi_{Airblast}$ was wholly due to the discrepancy in Stk . This was $\sim 45\%$ for all but the value was $\sim 83\%$ less than for Condition A. Figure 5.15 plots AFR against We at the ideal rig pressures demanded by each strategy to optimise $\Phi_{Airblast}$. We_{Eng} was 50 and the mean We_{Rig} for all strategies was 47. This was 6% smaller than We_{Eng} . If the strategy Re , AFR, free-pressure was removed the mean We_{Rig} deviated from We_{Eng} by only 1%.

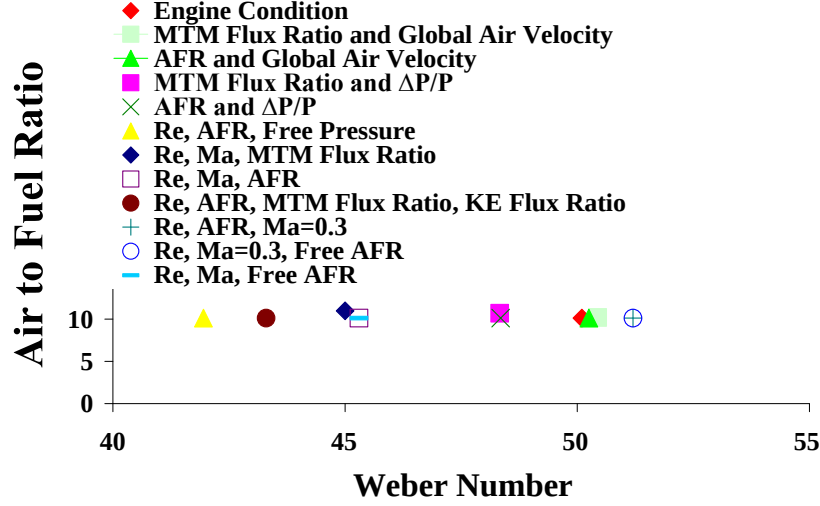


Figure 5.15: Cond. B – Plot of AFR vs We at 323K

Figure 5.16 and Figure 5.17 illustrated the effect of varying AFR on We and $\Phi_{Airblast}$ for both pressure-determining strategies that retained AFR as a free parameter.

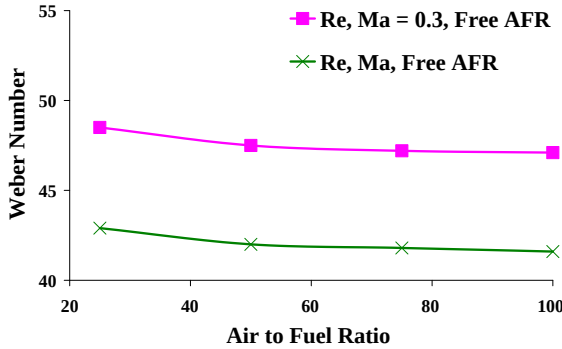


Figure 5.16: Cond. B – Plot of AFR vs We , Free AFR

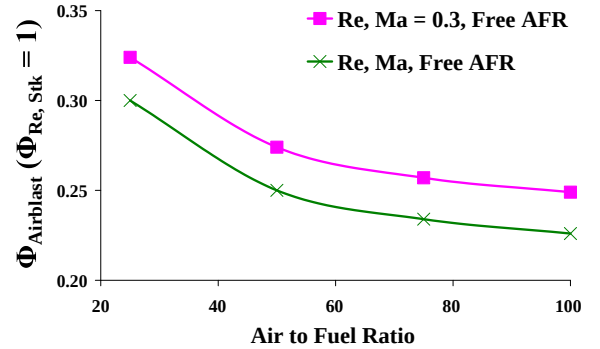


Figure 5.17: Cond. B – Plot of AFR vs $\Phi_{Airblast}$ (Φ_{Re} , $Stk = 1$) at 323K

Scaling to a lower temperature and pressure engine condition improved the match with We and helped capture the physics of secondary atomisation. This may be of significant importance to droplet clustering studies. The above analysis showed that strategies conserving global air velocity were better than those that maintained the injector pressure drop.

Figure 5.18 and Figure 5.19 plot the discrete contributions of Re and Stk to $\Phi_{Airblast}$.

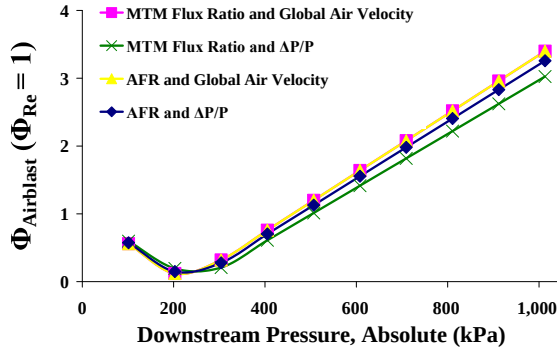


Figure 5.18: Cond. B – Plot of $\Phi_{Airblast} (\Phi_{Re} = 1)$ vs Rig Pressure at 323K

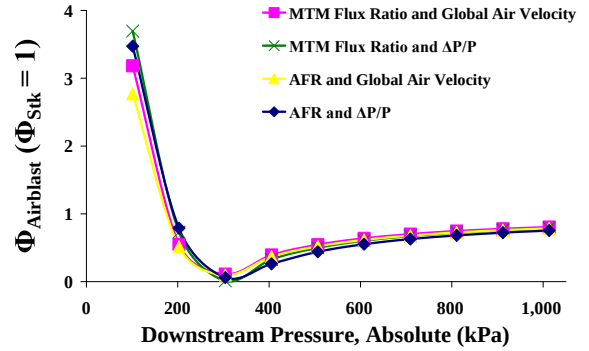


Figure 5.19: Cond. B – Plot of $\Phi_{Airblast} (\Phi_{Stk} = 1)$ vs Rig Pressure at 323K

Again, the fractional deviation in Re was much smaller than in Stk but this did rise above 100% as the rig pressure increased beyond the optimum value. Re was preserved at 300kPa for both strategies that conserved global air velocity and at slightly higher pressures for those that conserved injector pressure drop. Importantly, the fractional deviation in Stk governed and pursued the trend of Figure 5.13 but importantly, was of a smaller magnitude than for Condition A at lower rig pressures.

5.4.1.4 Condition B at 373K

Figure 5.20 plots $\Phi_{Airblast}$ against rig pressure for a rig inlet temperature of 373K.

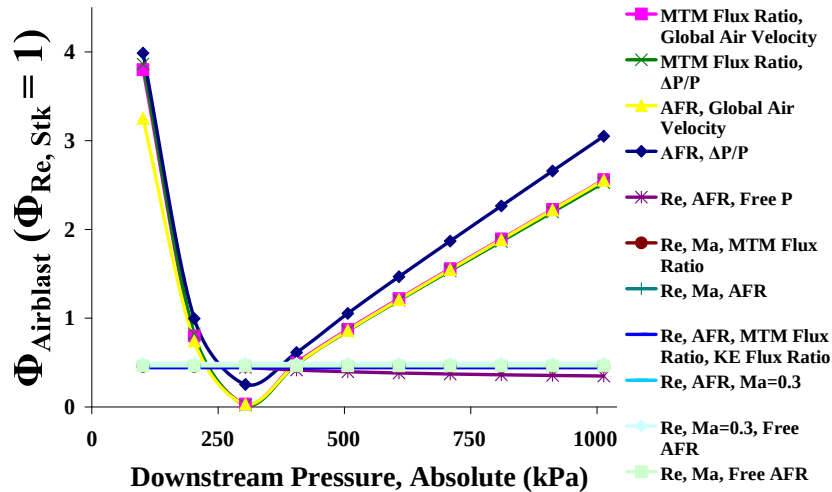


Figure 5.20: Cond. B – Plot of $\Phi_{Airblast} (\Phi_{Re, Stk} = 1)$ vs Rig Pressure at 373K

Pressure-determining strategies performed marginally worse at higher temperatures. Free-pressure strategies that conserved global air velocity and the strategy that conserved momentum flux ratio and injector pressure drop improved $\Phi_{Airblast}$ by ~90%

at 373K over 323K. Other free-pressure strategies that conserved AFR and injector pressure drop and Re , AFR, free pressure were unchanged from 323K. Figure 5.21 shows the 50K temperature rise weakened $\Phi_{Airblast}$ in both pressure-determining strategies that left AFR free.

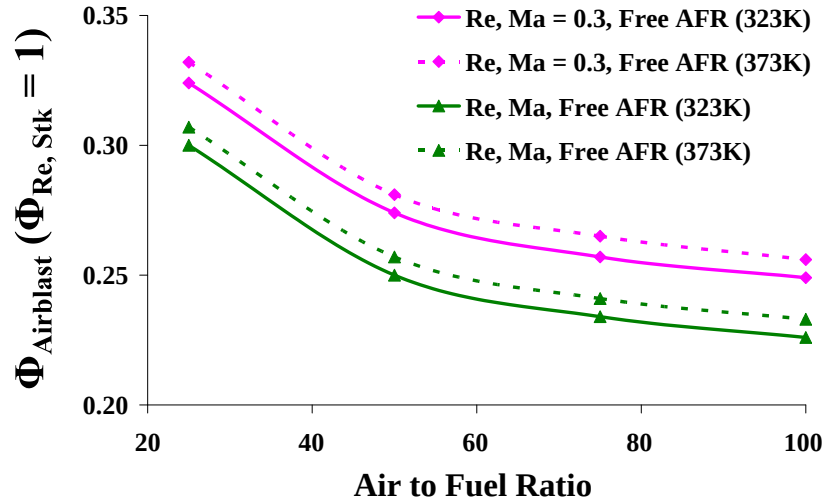


Figure 5.21: Cond. B – Comparison Plot $\Phi_{Airblast}$ vs AFR at 323K and 373K

At 373K We_{Eng} was $\sim 2.5\%$ larger than We_{Rig} for free-pressure strategies. Excluding the strategy Re , AFR, free-pressure from this group contracted We_{Rig} to within 0.5% of We_{Eng} . Figure 5.22 shows the required upstream rig pressures and $\Phi_{Airblast}$ at 373K.

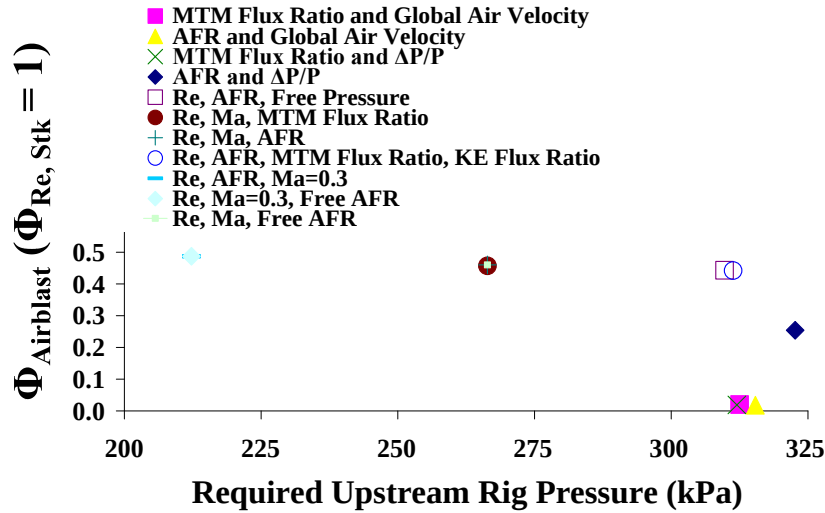


Figure 5.22: Cond. B – Required Upstream Rig Pressures vs $\Phi_{Airblast}$ at 373K

Overleaf, Figure 5.23 shows the patternation match is much better for Condition B than for Condition A at 373K and did not require a fuel of lower viscosity and surface tension.

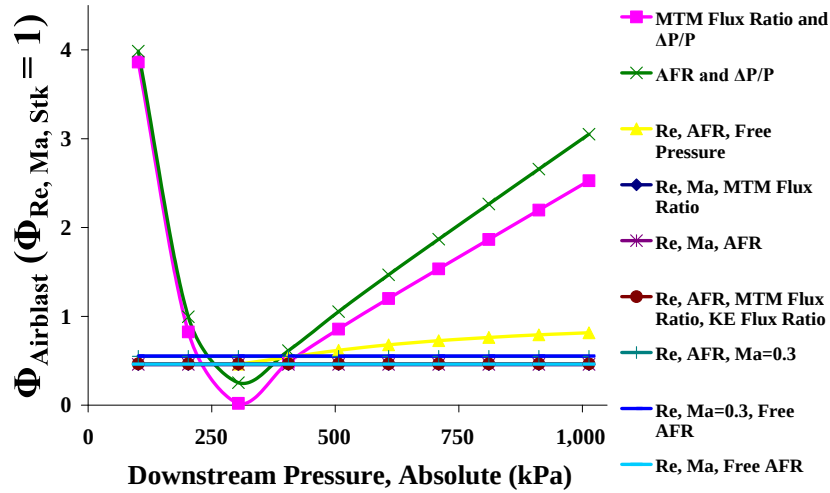


Figure 5.23: Cond. B – Plot of $\Phi_{Airblast}(\Phi_{Re, Ma, Stk} = 1)$ vs Rig Pressure at 373K

Properties of critical relevance to study combustion oscillations for ICLEAC were:

- Preserve air/fuel momentum flux ratio to preserve fuel patterning
- Preserve air velocity through the injector due to its affect on acoustic impedance

Given the above requirements, Table 5.5 scaled the ICLEAC engine operating condition using one of five potential strategies. Requirements were met with conservation of the air to fuel momentum flux ratio and global air velocity since these properties were of principal interest and to be conserved at the expense of other flow descriptors. The selected strategy offered a good match with Re , Ma , We and a reasonable one with Stk .

Optimum Strategies	$\Phi_{Re, Stk}$	P_{up} (kPa)	P_{Gauge} (kPa)	$\Delta P/P$ (%)	Q (l/m)	Q (g/s)
MTM Flux Ratio and U	0.020	172	12.9	4.7	0.46	6.23
AFR and U	0.018	200	12.1	4.0	0.45	6.02
MTM Flux Ratio and $\Delta P/P$	0.019	169	12.7	4.7	0.46	6.20
AFR and $\Delta P/P$	0.254	196	11.9	4.0	0.47	6.29
Re , AFR, Free-Pressure	0.443	185	8.6	3.01	0.39	5.24

Table 5.5: Cond. B – Potential ICLEAC Rig Operating Conditions at 323K

5.4.2 Hybrid Calculation

Hybrid weak module fuel injectors were described in Chapter Three. These were supplied by RR under the ANTLE programme. In brief, the design incorporated both an airblast and pressure-swirl atomiser. Overleaf, Table 5.6 shows the ANTLE “climb” engine operating point. Conditions C and D correspond to RR “18 Rig” and “5 Cell” test conditions. Calculations showed that scaling to the lower pressure 5 Cell conditions

yielded economical fuel flow rates and attainable rig pressures at very little detriment to the fractional deviation, Φ . Therefore, all rig operating conditions were scaled to the more convenient 5 Cell conditions.

Quantity	18 Rig ANTLE Condition C	5 Cell ANTLE Condition D
Upstream Pressure Absolute (kPa)	2,172	345
Air Temperature (K)	800	800
Injector Effective Area (mm ²)	1363	1363
Injector AFR	25.4	25.2
$\Delta P/P$ (%)	4	4

Table 5.6: 18 Rig and 5 Cell Climb Cycle Operating Condition

The ANTLE measurement campaign gathered PLIF fuel placement data for injectors that had undergone RR NO_x tests. The principal objective of this study was to develop a tool that predicted NO emissions from sprays data. In hybrid atomisation, the rig scaling strategy was optimised with respect to the atomiser that used the most fuel. Table 5.7 shows fuel split ratios between the pressure-swirl and airblast atomisers. The pressure-swirl atomiser operated alone at 7% Ground Idle and 24% Approach. Both atomisers operated at the 30% Approach, Cruise, Climb and Take-Off conditions.

Engine Operating Condition	Fuel Split (Pressure-Swirl : Airblast)
7% Ground Idle	100:0
24% Approach	100:0
30% Approach	30:70
Cruise	10:90
Climb	10:90
Take-Off	10:90

Table 5.7: ANTLE Weak Module Fuel Split Ratios

5.4.2.1 Condition C at 319K

The ANTLE rig scaling strategy was selected from the free-pressure strategies. A sensitivity of unity was given to all NDPs. Although this worsened Φ , it increased the overall similarity of the fuel spray between the rig and target engine conditions. Overleaf, Figure 5.24 plots $\Phi_{Airblast}$ against rig pressure at a rig air temperature of 319K.

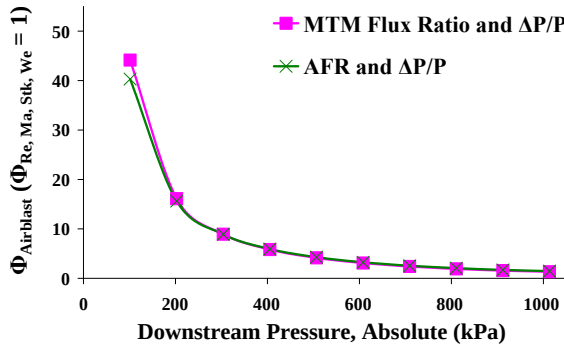


Figure 5.24: Cond. C – Plot of $\Phi_{Airblast} (\Phi_{Re, Ma, Stk, We} = 1)$ vs Rig Pressure at 319K

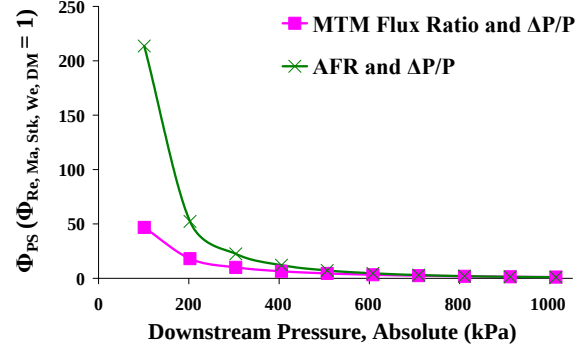


Figure 5.25: Cond. C – Plot of $\Phi_{PS} (\Phi_{Re, Ma, Stk, We, pD} = 1)$ vs Rig Pressure at 319K

The excluded strategies conserved U because these yielded $Ma > 0.3$ and also the strategy Re , AFR, free-pressure because it strongly deviated from We_{Eng} . Again, separate contributions of Re and Stk were examined. The fractional discrepancy in Re was always under 100%. At 675kPa the strategy that conserved air to fuel momentum flux ratio and injector pressure drop preserved Re but gave a large deviation in Stk .

To conserve patterning in pressure-swirl atomisation required conservation of Re , Ma , Stk and p_D . Figure 5.25 shown above plot Φ_{PS} against rig pressure. Both strategies yielded similar fractional discrepancies above 600kPa. Separate contributions of Re , Stk and p_D were tested and results matched Re at 725kPa but this led to a large deviation in Stk and p_D at atmospheric pressure. Figure 5.26 plots the total deviation for hybrid atomisation:

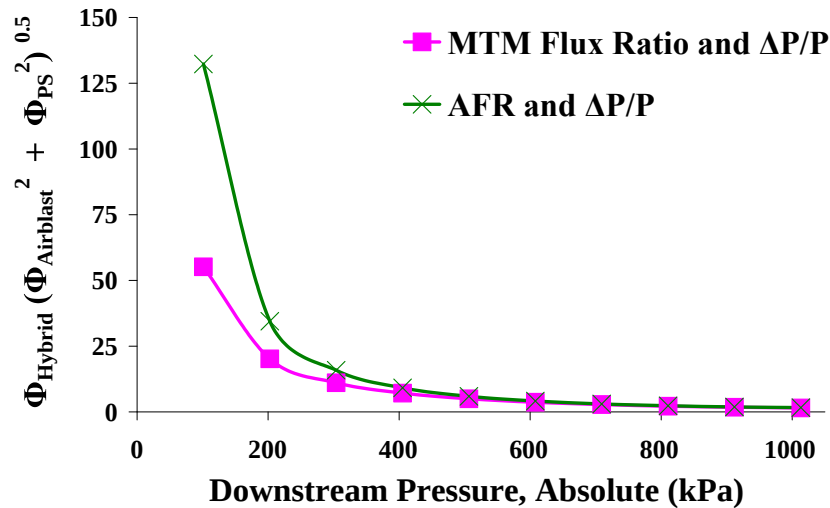


Figure 5.26: Cond. C – Plot of $\Phi_{Hybrid} (\Phi_{Airblast}^2 + \Phi_{PS}^2)^{0.5}$ vs Rig Pressure at 319K

5.4.2.2 Condition D at 319K

Similarly for Condition D, Figure 5.27 and Figure 5.28 below plot $\Phi_{Airblast}$ and Φ_{PS} against rig pressure at a rig air temperature of 319K.

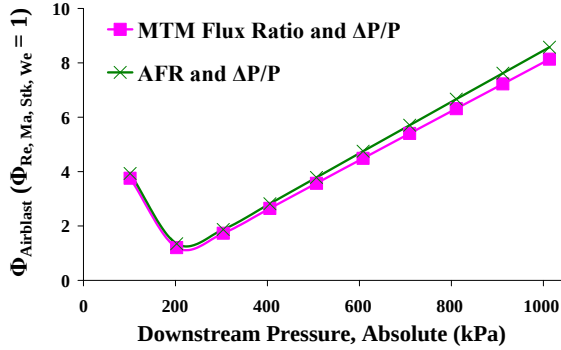


Figure 5.27: Cond. D – Plot of $\Phi_{Airblast}$ ($\Phi_{Re, Ma, Stk, We} = 1$) vs Rig Pressure at 319K

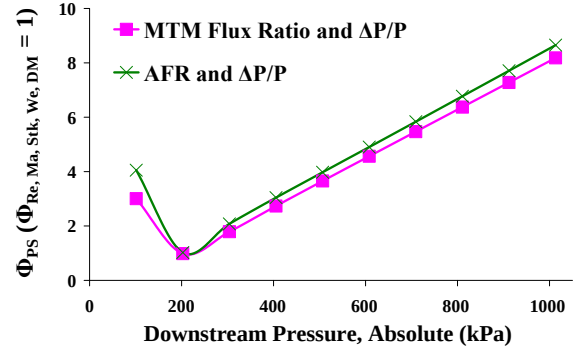


Figure 5.28: Cond. D – Plot of Φ_{PS} ($\Phi_{Re, Ma, Stk, We, pD} = 1$) vs Rig Pressure at 319K

Figure 5.29 plots Φ_{Hybrid} against rig pressure. The total fractional deviation for Condition D was similar to Condition C but met at a lower rig pressure. Figure 5.30 plots fuel flow rate against rig pressure for Conditions C and D. This showed that an approximate 60% fuel saving occurred if rig operating conditions were scaled to a lower pressure and temperature engine condition at no detriment to the fractional discrepancy.

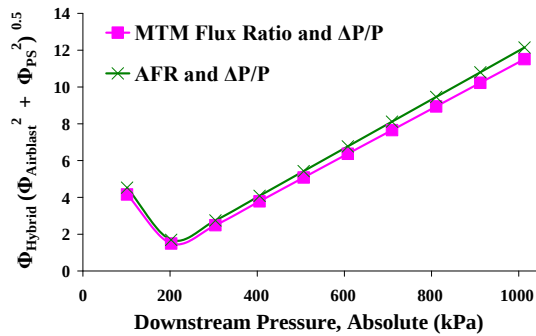


Figure 5.29: Cond. D – Plot of Φ_{Hybrid} ($\Phi_{Airblast}^2 + \Phi_{PS}^2$)^{0.5} vs Rig Pressure at 319K

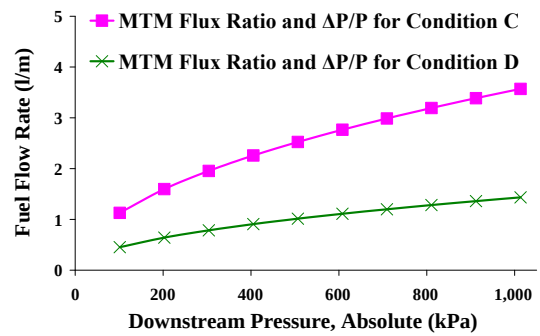


Figure 5.30: Cond. C and D – Plot of Fuel Flow Rate vs Rig Pressure at 319K

Therefore, the ANTLE engine operating conditions were scaled from RR 5 Cell scaled engine operating conditions according to the rig scaling strategy that preserved air to fuel momentum flux ratio and injector pressure drop.

5.5 TESTING SCHEDULE

Table 5.8 summarises the undertaken measurement campaign. In all cases, scaled rig operating conditions were adjusted for atmospheric pressure on the days of testing.

Main Sprays Rig (MSR) Atmospheric Pressure Experiments				
Fuel Injector	Experiment	Scaling Strategy		
21 AFR	LSD	MFR, $\Delta P/P$	AFR, $\Delta P/P$	
ANTLE Build 34	PLIF, LSD	AFR, $\Delta P/P$	AFR, U	
ANTLE Build 34C	PLIF	AFR, U		
ANTLE Build 43	PLIF	AFR, U		
ANTLE Build 45	PLIF	AFR, U		
Unsteady Flow Rig (UFR) Elevated Pressure Experiments				
Fuel Injector	Experiment	Static	Oscillating	Scaling Strategy
ANTLE Build 34	PLIF	✓		MFR, $\Delta P/P$
ANTLE Build 43	PLIF	✓		MFR, $\Delta P/P$
ANTLE Build 61	LSD, PLIF, PDA	✓	✓	MFR, $\Delta P/P$ MFR, U
ICLEAC 71257	LSD	✓	✓	MFR, U
ICLEAC 73030	LSD	✓	✓	MFR, U
ICLEAC 73630	LSD	✓	✓	MFR, U
ICLEAC 73685	LSD	✓	✓	MFR, U
ICLEAC 73686	LSD	✓	✓	MFR, U
TM Lean Module	LSD	✓	✓	MFR, U

Table 5.8: Fuel Injector Testing Schedule

5.6 SUMMARY

Credible fuel spray measurements demand scaled rig operating conditions that force a similarity in the two-phase flow with engine operating conditions. This chapter described several rig scaling strategies to find optimum rig operating conditions from engine operating conditions. Some determined rig pressure and others left it as a free parameter. All were based on conservation of one or more flow quantities or Non

Dimensional Parameters (NDPs). It was impossible to replicate every NDP in a low cost, low-pressure non-combusting test rig to the same level of precision as the engine condition but acceptable compromises were found. A fractional deviation was used to judge the performance of each rig scaling strategy in giving rig operating conditions that encouraged similarity between fuel spray behaviour in the rig and engine. Similarity laws considered the engine condition to be scaled; fuel injector geometry; atomisation mechanism(s) and most critically, spray properties of particular interest. To preserve patternation and acoustic impedance in ICLEAC airblast injector sprays the air to fuel momentum flux ratio and global air velocity were conserved. To preserve patternation and render economical fuel flow rates in ANTLE hybrid fuel injectors sprays the air to fuel momentum flux ratio and injector pressure drop were maintained. Selected strategies offered the best similarity with Re and Ma to determine airflow patterns and Stk that gauged how closely droplets followed airflows.

Pressure-determining strategies were attractive and performed well at low rig pressures, conserved Re and had all the compromises in Stk . Free-pressure strategies improved as rig pressure increased. Gains were small beyond a certain pressure and could be counter-productive if scaling to low pressure and temperature engine conditions. On average, the free pressure-strategies performed ~60% better than pressure-determining strategies. The strategies that conserved global air velocity gave a more truthful match with Re_{Eng} and We_{Eng} compared to those that preserved injector pressure drop.

All strategies demanded higher pressures at increased rig temperatures and the pressure-determining strategies performing insignificantly worse compared to free-pressure strategies. Condition A showed that for scaling to a high temperature and pressure engine condition, the strategy that conserved momentum flux ratio and injector pressure drop improved $\Phi_{Airblast}$ by ~20% at 373K over 323K. For Condition B this strategy and those that conserved global air velocity improved $\Phi_{Airblast}$ by ~90% at 373K over 323K. This demonstrated that no clear cut rule existed in choosing a rig scaling strategy and that each engine operating condition to be scaled must be evaluated separately. Important things to be considered are the required AFR, rig pressure and fuel flow rate. It was entirely possible that the optimum rig scaling strategy failed in one of these regards. This chapter described a method to determine a set of rig operating conditions from engine operating conditions. It conveyed the optimum compromise on all considered NDPs. To optimise any strategy, Φ was calculated over a two-, three-, or four-dimensional space depending on how many of the four operating conditions: pressure; temperature; fuel and air mass flow rates were left free. Use of different rig scaling strategies demonstrated the importance of choosing the most applicable strategy in evaluations of fuel spray performance and to the measurements that inform low emissions and instability-free fuel injector design.

CHAPTER SIX

ATMOSPHERIC PRESSURE EXPERIMENTS

6.1 INTRODUCTION

Given the diminishing relevance of empirical design correlations based on experimental data from non-premixed fuel injection strategies, the definition, design and verification of low emissions combustors demands new experiments and computational studies. Combined with the strategic need to improve engine performance and fuel economy, the introduction of lean burn fuel injectors is plagued by problems of flame instability and uncertainties in fuel and air mixing effectiveness that lead to combustion instability and pollutant formation. Application of optical diagnostics to measure key spray properties such as fuel patterning and droplet distribution at representative engine operating conditions can improve knowledge on atomisation, reduce empiricism, cut uncertainties and the overall technical and financial risks in low emissions combustion system design. Results also provide boundary conditions and validation data for two-phase computational spray models that predict spray properties at less cost, effort and environmental impact for intermediaries between the tested builds. The main objective of this study is to obtain patterning and droplet data for a range of fuel injectors and to identify design features that yield desirable spray patterns, conducive to low NO_x and high combustion stability as a part of two RR engine demonstrator programmes:

- Affordable Near Term Low Emissions Engine (ANTLE)
- Instability Control of Low Emission Aero-Engine Combustors (ICLEAC)

This chapter applied Laser Sheet Dropsizing (LSD) to acquire qualitative droplet Sauter Mean Diameter (SMD) data and Planar Laser Induced Fluorescence (PLIF) to measure fuel placement and Air to Fuel Ratio (AFR) in the sprays from five hybrid fuel injectors. These were characterised in the Main Sprays Rig (MSR) under non-combusting, isothermal, near atmospheric pressure conditions. First, LSD was applied to characterise the RR “21 AFR” injector and ANTLE Build 34 to determine the influence of rig scaling strategies on spray structure. This was the sole purpose of 21 AFR in this research due to a shift in RR strategy. Second, PLIF images from ANTLE Builds 34, 34C, 43 and 45 were used to develop the methodology that correlated fuel placement and hence AFR data with NO formation using GASEQ (Morley, 1995) to calculate local adiabatic flame temperatures and HOMREA (Warnatz, 2002). Third, the experimental method was improved before the elevated pressure measurements reported in Chapter Seven, where according to Chapter Five the fractional discrepancies between the aspects of two-phase flow in the engine and rig minimise as the rig pressure is increased.

6.2 MAIN SPRAYS RIG

Figure 6.1 shows a photograph and schematic of the Main Sprays Rig (MSR). This was used in this study to characterise fuel sprays from RR 21 AFR and ANTLE Builds 34, 34C, 43 and 45 under non-combusting, isothermal atmospheric pressure conditions.

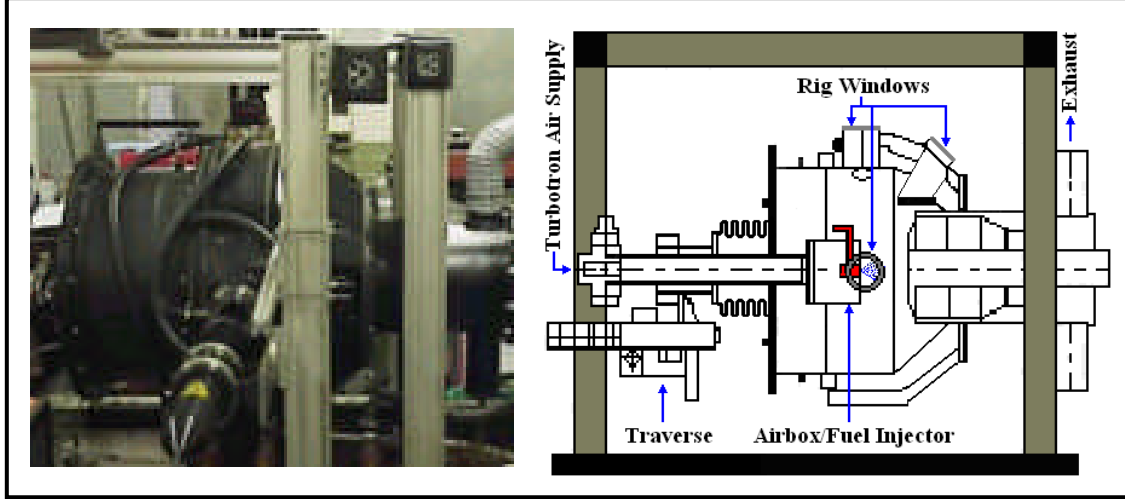


Figure 6.1: Photograph and Schematic of the MSR

The MSR was commissioned in 1997 to characterise full-size aero engine fuel sprays (Greenhalgh *et al*, 1998 and Le Gal, 1999). It is a tapered lightweight aluminium drum of 0.6m diameter and 1m length with fittings for air and fuel supplies; optical access windows; airbox that holds the fuel injector; traverse control and exhaust systems. The MSR is closed using twelve bolts and it slides apart on rails to access the airbox and fuel injector. Signal collection optics and Intensified Charge Coupled Device (ICCD) camera are located in a scaffold over the rig in a fixed position relative to the fuel spray.

6.2.1 Air Supply

A Turbotron compressor delivered air at a maximum rate of 0.12kg/s to the fuel injector, rig access windows and optional air purge along inner walls to preserve spray AFR. A differential pressure gauge measured the pressure drop between the airbox and rig and another measured the difference between airbox and ambient pressure. Injector pressure drop was set to within $\pm 0.5\text{mbar}$. With all air purges off, Eq. 6.1 was used to find air mass flow rate. To account for losses A_{Eff} is 99% of the bellmouth area, ΔP was Turbotron pressure differential and ρ_{air} is air density. Eq. 6.2 calculated effective injector area, where ΔP was the pressure difference between airbox interior and drum.

$$\dot{m} = A_{\text{Eff}} \sqrt{2\rho_{\text{air}}\Delta p} \quad \text{Eq. 6.1}$$

$$A_{\text{Eff}} = \frac{\dot{m}}{\sqrt{2\rho\Delta p}} \quad \text{Eq. 6.2}$$

6.2.2 Fuel Supply

The fuel supply to the hybrid ANTLE weak modules arrived from two sources. A fifty-litre capacity tank stored fuel for the airblast atomiser (main) and a ten-litre tank held fuel for the pressure-swirl atomiser (pilot). Both tanks were drained, washed and dried to avoid contamination from previous experiments. This study used fresh fuel for each measurement to preserve the cubic dependence, n of PLIF signals with droplet diameter. PLIF measurements at 308nm used Exxsol D80 seeded with 0.1125g/l of 2,5 Diphenyloxazole (PPO). Fuel to the injector was delivered through a rear bulkhead via flexible pipes under a helium butt pressure of 400 – 800kPa and was metered through two rotameters. Each was calibrated by recording the time to collect 500ml of fuel at various valve settings. Figure 6.2 shows the calibration plot for the pilot fuel supply.

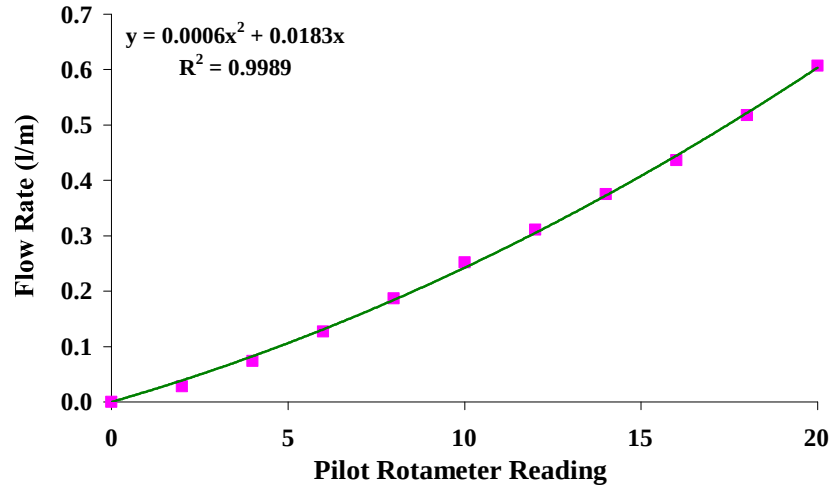


Figure 6.2: Plot of Fuel Flow Rate vs Pilot Rotameter Reading

Similarly, Eq. 6.3 set the main rotameter reading for the required fuel flow rate.

$$Reading_{Main} = \frac{Flow\ Rate + 0.013}{0.0196} \quad \text{Eq. 6.3}$$

6.2.3 Windows

Windows were made from fused silica to allow ultraviolet (UV) illumination. These were located in several ports around the MSR circumference. Each had a separate air-purge system with tangential and radial components to prevent the congregation of fuel droplets on inner surfaces that would then obscure the laser sheet access. The tangential component accelerated a solid body of rotating air along a convergent duct towards the rig axis to entrain the bulk of stray fuel droplets. The radial component guided stray droplets away from close proximity to the inner surfaces. Additionally, electric heater elements around each window evaporated any residual moisture in the air supply lines.

6.2.4 Airbox

Figure 6.3 below shows the custom-made perspex airbox that was used to mount the RR 21 AFR injector. Simulated primary zone combustor walls mimicked the confinement of an actual combustor. Each wall measured 226.5 x 75.5mm and featured a 50 x 10mm machined slot for optical access to the geometrical injector centreline. The airbox had fittings for the fuel and air supplies, pressure transducers and thermocouple. With the primary fuel supply blanked off, fuel was only delivered to the secondary feed.

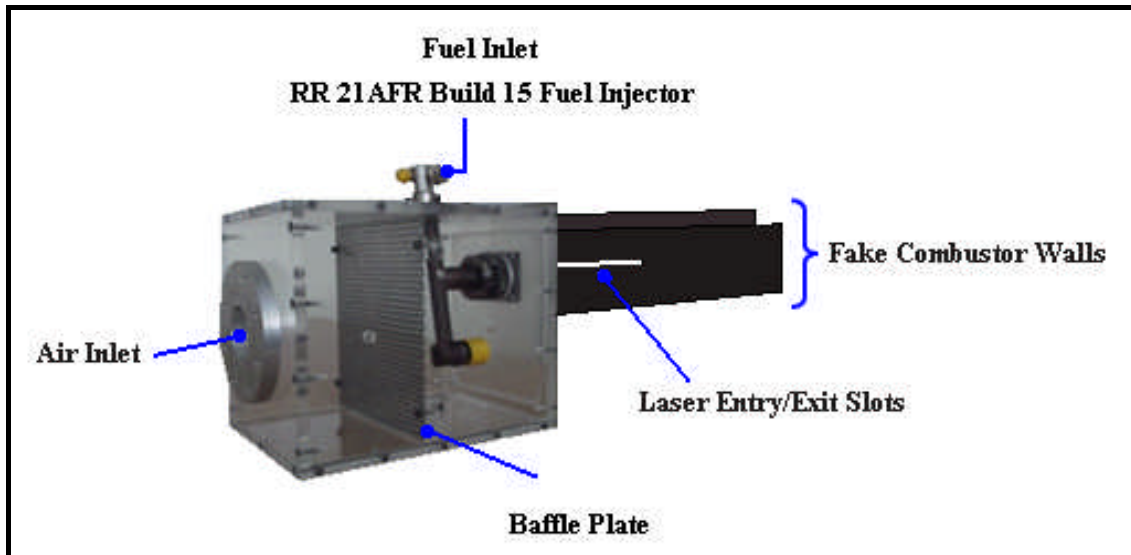


Figure 6.3: Perspex Airbox Mounting RR 21 AFR Injector

6.2.5 Traverse

The MSR airbox was linked to a computer controlled traverse for positional adjustment in one rotational and three translational degrees of freedom. Its principal use was for mapping sprays in point-wise PDA measurements. In this study it was only used to rotate the airbox through 180° for the acquisition of an additional dataset with the laser propagating from an opposite direction whilst the MSR was running. Subsequent image processing macros combined the 0° and 180° images to correct for the effects of laser attenuation through the spray. Although PLIF measurements of LVF and consequently AFR must be attenuation-corrected, LSD, by virtue of the technique did not require such a correction. However, if performed it improved signal to noise ratios and was therefore at no detriment to the LSD method where PLIF and Mie signals are divided.

6.3 LSD AND PLIF EXPERIMENTAL CONFIGURATION

Overleaf, Figure 6.4 shows a schematic of the experimental configuration for LSD and PLIF measurements. This shows the MSR; excimer laser; sheet forming optics;

instrumentation to synchronise the laser pulse with the camera shutter; dual imaging optics and ICCD camera in a fixed position above the MSR relative to the fuel spray.

The laser was a Lambda Physik EMG-150 pulsed excimer with an oscillator-amplifier and unstable resonator configuration. It was operated at 25.8kV in broadband mode with Helium (He) as the buffer gas, Xenon (Xe) as the rare gas and Hydrogen Chloride (HCl) as the halogen carrier gas. Gas composition was ~99% He, ~1% Xe, and ~0.1% HCl. Passage of an electrical discharge through the mixture produced light at 308nm that was emitted during the electronic transition of molecules from an associative upper bound state to the dissociative ground state where constituent atoms repel and separate.

Appendix B gives more detail on excimers and shows three reaction sequences for Xe and Cl atoms or ions. As mentioned, PLIF at 308nm used Exxsol D80 seeded with 0.1125g/l of 2,5 Diphenyloxazole (PPO) for optimum UV absorbance across the droplet with. Images datasets were corrected for background signals and attenuation but were not flatfielded or calibrated as qualitative results were sufficient to gauge the effect of different scaling strategies on spray structure, develop the NO_x correlation and improve the entire experimental and analysis methods before sprays work at elevated pressures.

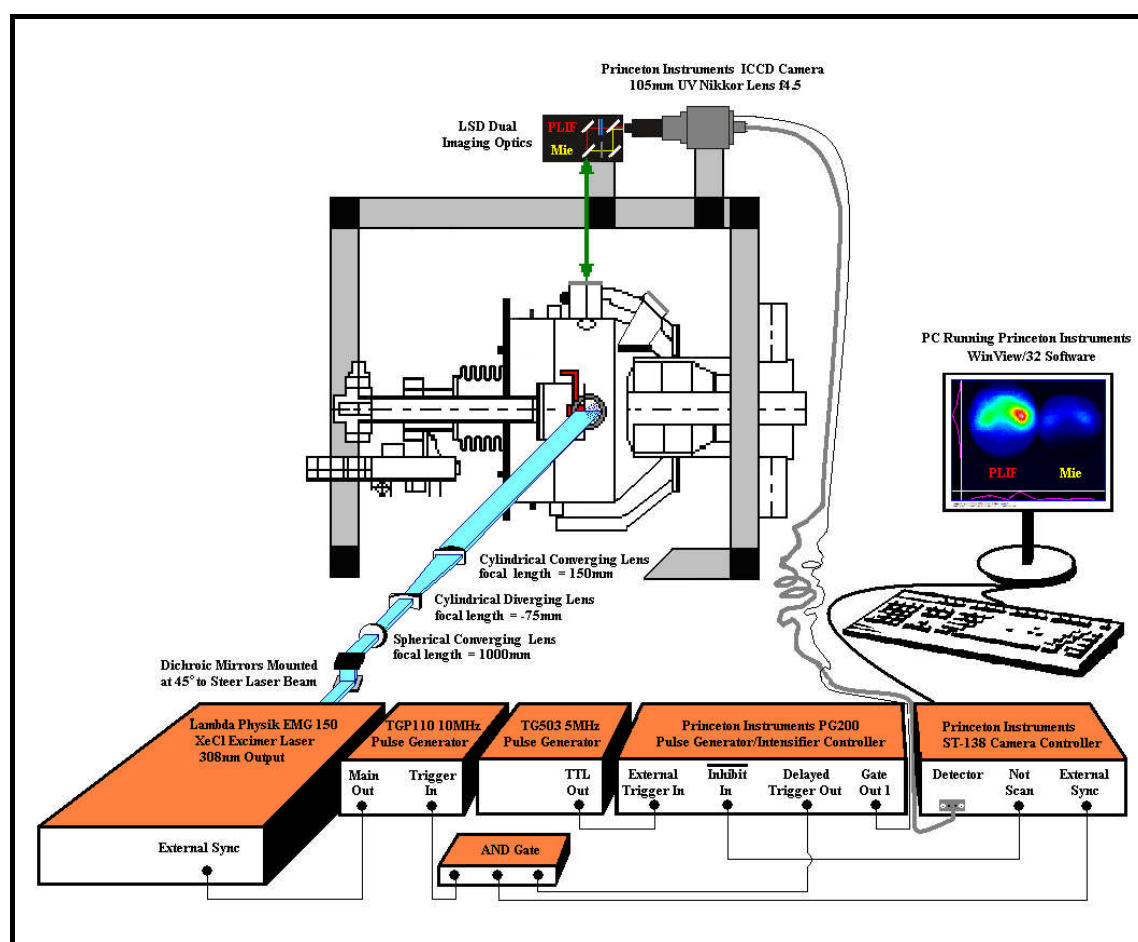


Figure 6.4: General Schematic of LSD and PLIF Measurements in the MSR

6.3.1 Instrument Synchronisation

Figure 6.5 shows the instrumentation timing sequence. A Thurlby Thandar TGP503 5MHz pulse generator triggered the PG200 pulse generator and intensifier controller. The PG200 unit monitored the ST-138 camera controller via ‘Inhibit In’ from ‘Not Scan’. When the camera was ready to acquire an image, ‘Not Scan’ went low and the PG200 unit immediately sent a pulse to the intensifier with no delay via ‘Gate Out 1’. ‘Gate Width’ was set to give a 200ns camera exposure time via ‘Gate Out 1’ to centre on a 25ns laser pulse. The PG200 unit also sent a delayed pulse to the laser, triggered by a Thurlby Thandar TGP110 10MHz pulse generator via ‘Delayed Trigger Out’ at a delay of 50ns set by ‘Gate Delay’. The laser repetition rate was $\sim 2\text{Hz}$. The laser ‘Gate Delay’ ensured it operated when the logical AND operation was true and camera shutter was open. When the camera shutter closed, ‘Not Scan’ went high until the camera loaded the image from the chip to the camera controller. This was transferred to a PC running WinView/32 Software. The camera cleaned the chip and set ‘Not Scan’ to low to indicate its ability to acquire another image. Timing was iteratively optimised to bracket the laser sheet with incremental reductions in the ‘Gate Delay’ and increases in ‘Gate Width’. The PG200 intensifier operated at 700V with the following settings: Gate Delay of 50ns; Gate Width of 200ns; Trig Level of 4.12 and Delayed Trig of 267ns.

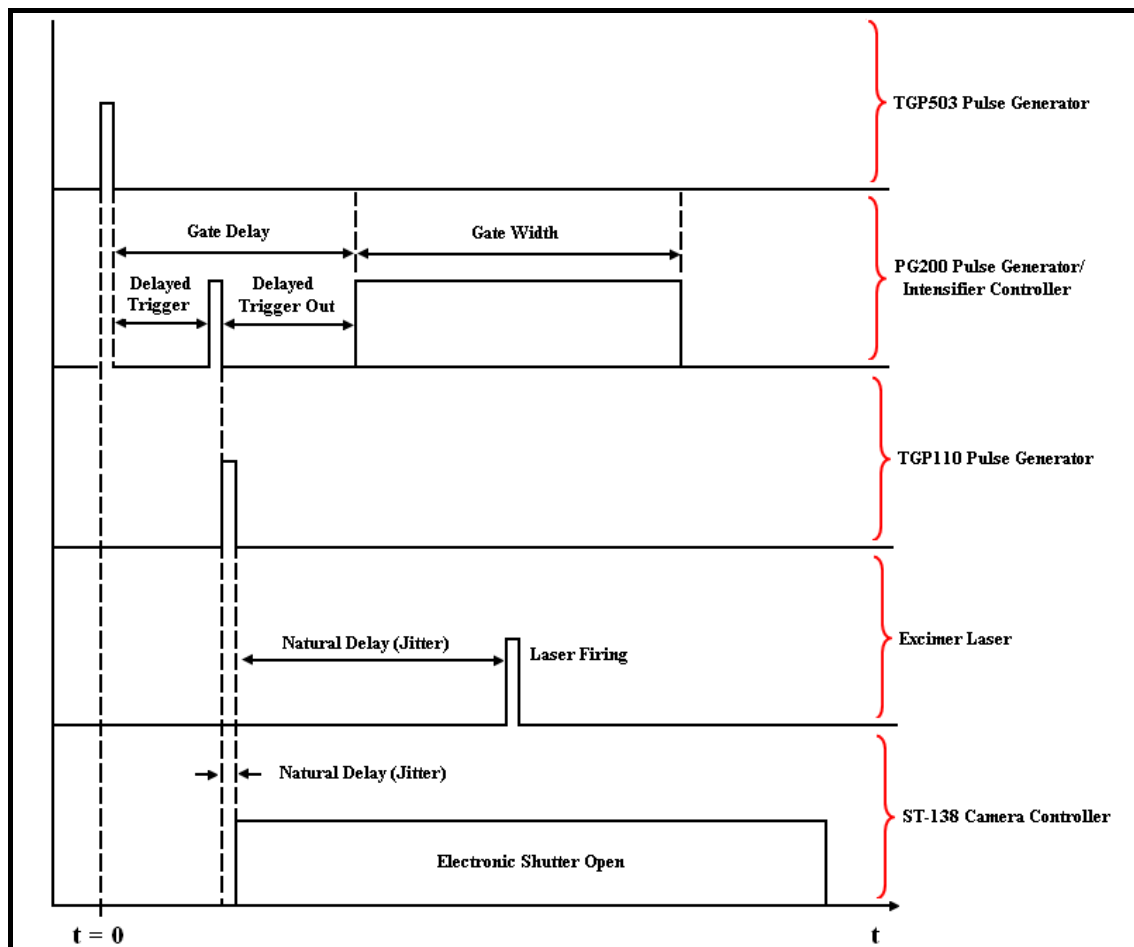


Figure 6.5: MSR Instrumentation Timing for LSD and PLIF Measurements

6.3.2 Sheet Forming Optics

Figure 6.6 shows the planar sheet forming optics used to convert the rectangular block of laser output light into a thin collimated sheet at the geometric fuel injector centreline. Appendix B also gives equations to calculate theoretical sheet dimensions (Buchave, 1994). Dichroic mirrors at incidence angles of 45° steered the laser output beam up and across towards the MSR laser access window. A spherical lens of focal length 1000mm focussed the beam down to a waist of $\sim 500\mu\text{m}$. Two cylindrical lenses with focal lengths of -75mm and 150mm formed a Galilean telescope and spread the beam out into a thin collimated sheet that measured $\sim 0.5 \times \sim 50\text{mm}$ at the geometric fuel injector centreline. White paper was used to check the light path through each optic, the laser access window and both slots in the fake combustor walls. Masking tape placed on each side of the laser access window helped to obscure the wings of the laser sheet and thereby achieve a monotonous light intensity distribution in the measurement region.

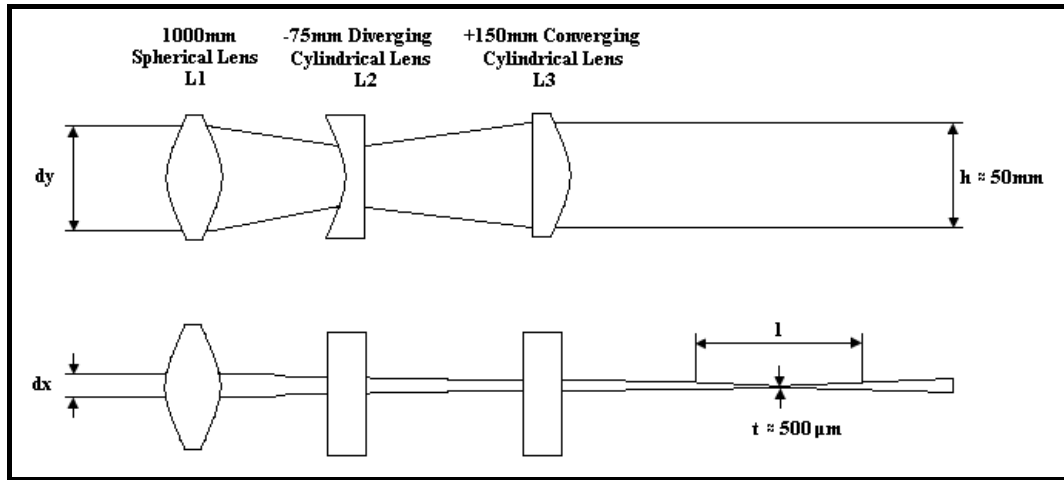


Figure 6.6: Planar Sheet Forming Optics

6.3.3 Signal Collection

Overleaf, Figure 6.7 and Figure 6.8 show a schematic and photographs of the LSD dual imaging optics and ICCD camera. Signal collection optics separated the volume-dependent PLIF and area-dependent Mie signals into near-parallel paths for collection by a Princeton Instruments ICCD camera. Fluorescence emission typically occurred around 350 – 500nm and peaked at $\sim 430\text{nm}$ (Greenhalgh, 2000). The PLIF channel was filtered with a Schott WG360 blue glass filter to transmit fluorescence above 320nm. The elastic Mie scatter channel was obstructed with an interference band pass filter that was centred on the laser excitation wavelength of 308nm. This Mie channel was blocked with a ND filter of 1.0 to reduce intensities by a factor of ten to balance with the PLIF intensities on the same ICCD chip. Use of the ND filter in the Mie path was subsequently accounted for during or after LSD image processing.

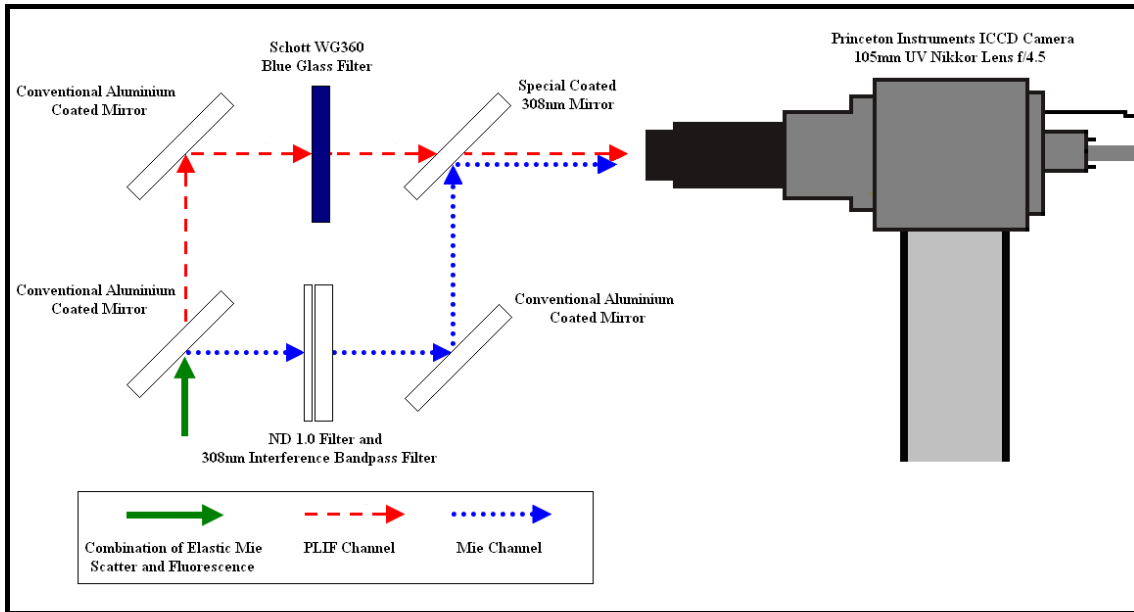


Figure 6.7: Schematic of LSD Dual Imaging Optics and ICCD Camera

PLIF and Mie images were viewed on a monitor while dual imaging mirrors were adjusted to separate and align each image next to each other on the ICCD chip. Both images were perfectly vertical with no overlap. Experiments used the calibration chart discussed in Section 4.3.2 to align images to significantly ease LSD image processing.

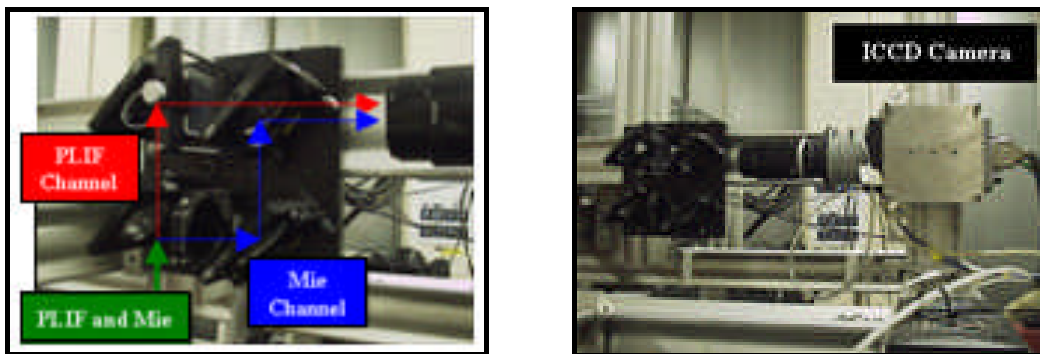


Figure 6.8: Photograph of LSD Dual Imaging Optics and ICCD Camera

The ICCD camera was positioned 90° to and 1320mm above the laser sheet in the same plane as the dual imaging optics. The camera was thermoelectrically cooled to limit thermal signals and obtain a large dynamic range. It used a Nikon 105mm UV lens with an aperture of f/5.6 and managed by a PC that controlled the ST-138 camera controller. The ICCD array had 576×384 pixels and a 15-bit grey-scale resolution, hence 221,184 measurement points. The laser sheet typically occupied 30 – 40% of this array. Spatial resolution is the pixel area multiplied by sheet thickness. For LSD images of the RR 21AFR injector the spatial resolution was $264 \times 264 \times 500\mu\text{m}$. It was slightly compromised in Builds 34, 34C, 43 and 45 at $295 \times 295 \times 500\mu\text{m}$ to visualise the much larger fuel spray system that consisted of a central pressure-swirl spray bordered by a large airblast atomiser spray.

6.4 WEAK MODULE DESIGN PHILOSOPHY

Weak modules were designed to reduce combustor gas temperatures that are a function of combustor inlet temperature and local AFR. Operation at high AFR reduces peak combustion temperatures and appreciably cuts NO_x production rates due to their exponential dependence on flame temperature and near-linear dependence with residence time. Figure 6.9 shows NO_x formation peaks just lean of the stoichiometric condition. However, Figure 6.10 shows the prime dilemma in low NO_x combustor design – combustion is very stable around the stoichiometric condition.

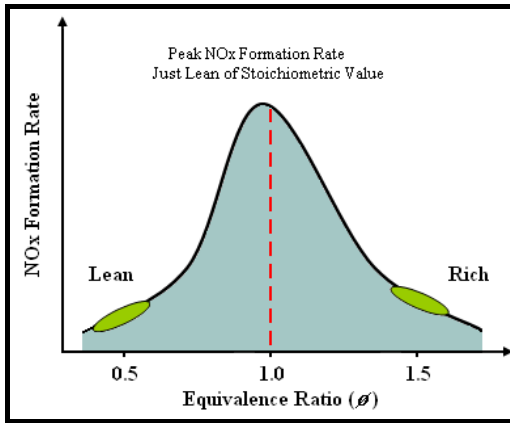


Figure 6.9: NO_x Formation vs ϕ (Lee, 1995)

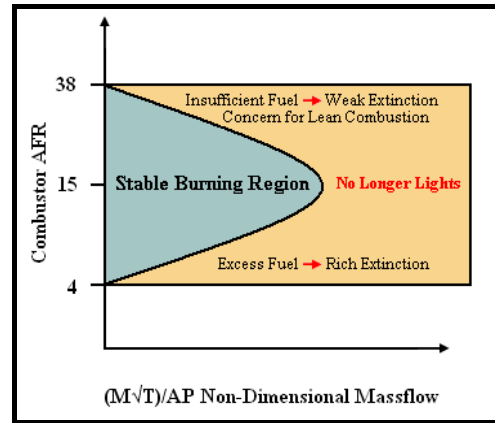


Figure 6.10: Stability Loop (Singh, 2009)

Eq. 6.4 defines the equivalence ratio, ϕ : Rich and weak extinction limits border the combustion stability loop and both steadily converge as air mass flow rates increase. It is worth noting that the limit values alter with fuel type. A key difficulty emphasised throughout the literature with any low emissions system is that combustion must be lean-premixed to necessitate the complete evaporation and mixing of fuel and air. At the high temperatures and pressures necessary to reduce fuel burn and CO₂, a competition results between the times needed for autoignition and evaporation because optimum levels lead to autoignition before evaporation. Chapter Three discussed conflicting combustor design requirements and compromises in combustor design. For combustion stability, traditional “RR Phase 5” fuel injectors operate between an AFR of 4.5 and 38. Combustion therefore occurs through the stoichiometric condition at an AFR of 14.7 where NO_x formation rates are greatest. The ANTLE weak modules investigated in this study used approximately five times more air than in Phase 5 designs to avoid regions of stoichiometric combustion. Inevitably, even with lean concepts perfect mixing does not always occur and locally stoichiometric regions are produced despite the overall lean AFR. However, poor mixing can lead to richer local zones that can support combustion and help steady the more marginalised lean flame.

$$\phi = \frac{1}{\lambda} \text{ where } \lambda = \frac{AFR_{Local}}{AFR_{Stoichiometric}} \quad \text{Eq. 6.4}$$

6.4.1 21 AFR Injector

Table 6.1 gives technical specifications for 21 AFR. Figure 6.11 shows a schematic and Figure 6.12 shows the device installed in a RR 6B Double Annular Combustor (DAC).

1° Swirler	2° Swirler	Flow Split	Prefilmer Radius	Prefilmer Profile
-60°	-50°	40:60	11mm	25°

Table 6.1: 21 AFR Technical Specifications (Gallimore, 1996)

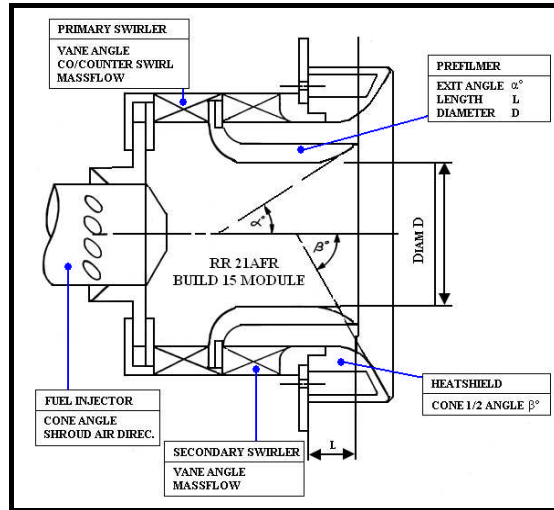


Figure 6.11: 21 AFR (Gallimore, 1996)

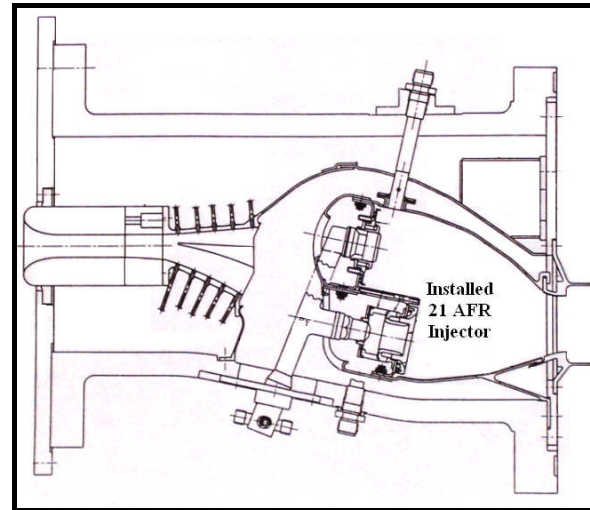


Figure 6.12: 21 AFR in RR 6BDAC (RR, 2004)

The 21 AFR injector consisted of a pressure-jet fuel injector with a duplex tip design and two co-rotating radial air swirlers separated by a prefilmer. It admitted two fuel sprays via concentrically arranged orifices onto a prefilmer. Each channel had different cross-sectional areas, flow numbers and spray cone angles. The primary channel operated at low powers and yielded sprays with a narrow cone angle. At a predetermined pressure a valve opens and fuel is supplied to the main secondary channel. Once this occurs fuel “dribbles” out of the nozzle as shown earlier in Figure 3.10 on page 57 until the channel pressure is sufficient enough to increase the pressure drop across the nozzle for the flow to develop into a spray. Both primary and secondary sprays coalesce a short distance downstream to generate a relatively rich recirculation zone that can anchor a flame and prevent weak extinction. Smaller droplets tended to follow the prevailing airflow directly into the combustor whilst larger droplets were directed by the primary radial swirling airflow onto the prefilmer surface to form a liquid sheet that was subsequently dragged downstream. The sheet was sandwiched between the primary and secondary airflows to undergo secondary atomisation. Hongyu and co-workers (1994) investigated droplet behaviour in the GE CFM56 engine combustor swirl cup. Overleaf, Figure 6.13 shows the injector was similar to 21 AFR. Primary swirler airflow rotated clockwise and secondary swirl airflow anti-clockwise.

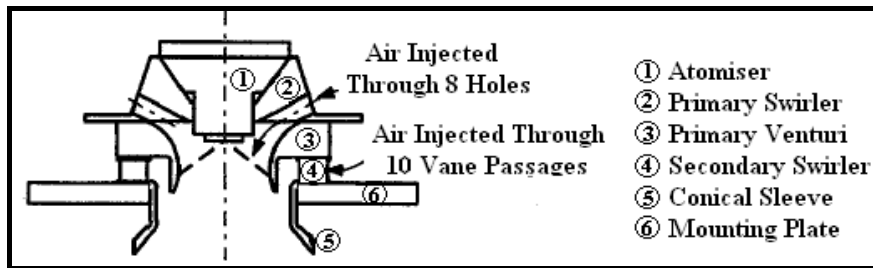


Figure 6.13: GE CFM 56 Combustor Swirl-Cup (Hongyu *et al*, 1994)

Becker and Hassa (2004) investigated internal fuel and air mixing behaviour in a similar design to 21 AFR and Figure 6.14 shows a sketch of their design. This had two radial air swirlers in a swirl cup arrangement. In comparison to 21 AFR the injector was closer to the prefilmer to increase spray interaction with the primary swirling airflow. Since an increase in pressure collapses the spray cone angle, Becker and Hassa studied the tangential momentum transfer from the swirling airflow into the spray as this was likely to induce centrifugal forces to counter the contraction and re-open the spray after overcoming aerodynamic resistance. Experiments used a smaller injector to magnify this effect and excluded the outer swirler as this only contributed slightly to the internal flowfield and more to the setting up of a recirculation zone downstream of the injector.

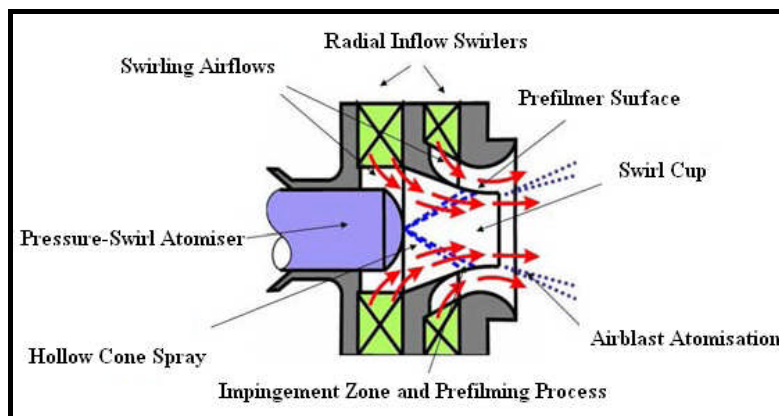


Figure 6.14: Pressure-Swirl Injector with Swirl-Cup (Becker and Hassa, 2004)

By and large, radial or axial swirlers and diverging secondary passage on the prefilmer lip serve two purposes. First, the swirlers shatter the liquid sheet to yield droplet sizes dependant on the energies imparted into the liquid sheet characterised by the Weber Number. Second, the swirlers and secondary passage actually manage the pattern of the airflow. This forces the general spray out into a wider direction that curves out to 180° and beyond very rapidly. As the amount of energy applied across the liquid sheet is relatively low, say in comparison to diesel fuel injectors, spray atomisation quality becomes a function of the liquid sheet velocity as it leaves the prefilmer lip and the magnitude of its rapid divergence that is dependent on the angle of the secondary passage. Chapter Three discussed swirl in more detail. Some literature (Lefebvre, 2000 and Ahmad and Andrews, 1986) preferred co-swirl, whereas others (Halpin, 1993, Gupta *et al* 1992 and Chin and co-workers, 2000) argued the opposite case.

6.4.2 ANTLE Weak Modules

A form of weak module is thought to exist on competitor GE90 and CFM56 engines. However, this is incorporated into a more complex dual annular combustor. The RR design featured a central pressure-swirl atomiser surrounded by a large airblast atomiser and axial air swirler system. Each atomiser had an independent fuel supply to allow fuel staging at the nozzle. Greenhalgh *et al* (2004) reported that a capability to deliver a prescribed fuel and air mixture pattern in a small volume was critical to cut NO_x emissions. This hybrid device offers such a flexibility. Low (2004) stated that these RR designs suited installation in a single annular combustor and claimed superiority over the GE90 staged design in terms of cost and simplicity. Table 6.2 gives the technical specifications of the five ANTLE weak modules characterised in this research. Figure 6.15 is a labelled schematic of a typical design and Figure 6.16 shown overleaf is a labelled image of Build 61.

Build	Swirler 1	Swirler 2	Swirler 3	Effective Area (mm ²)
34	30°	45°	55°	1460
34C	30°	45°	65°	1286
43	30°	45°	-55°	1530
45	40°	45°	-55°	1521
61	-35°	50°	55°	1363

Table 6.2: Specifications for B34, 43, 45 and 61 (Gill, 2002)

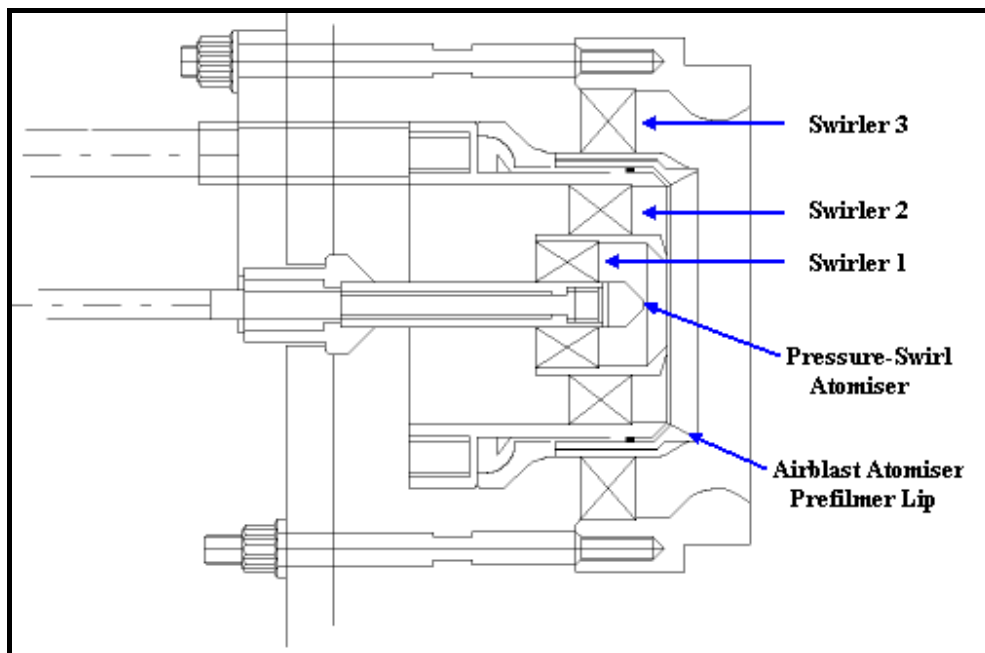


Figure 6.15: Schematic of ANTLE Weak Module B61

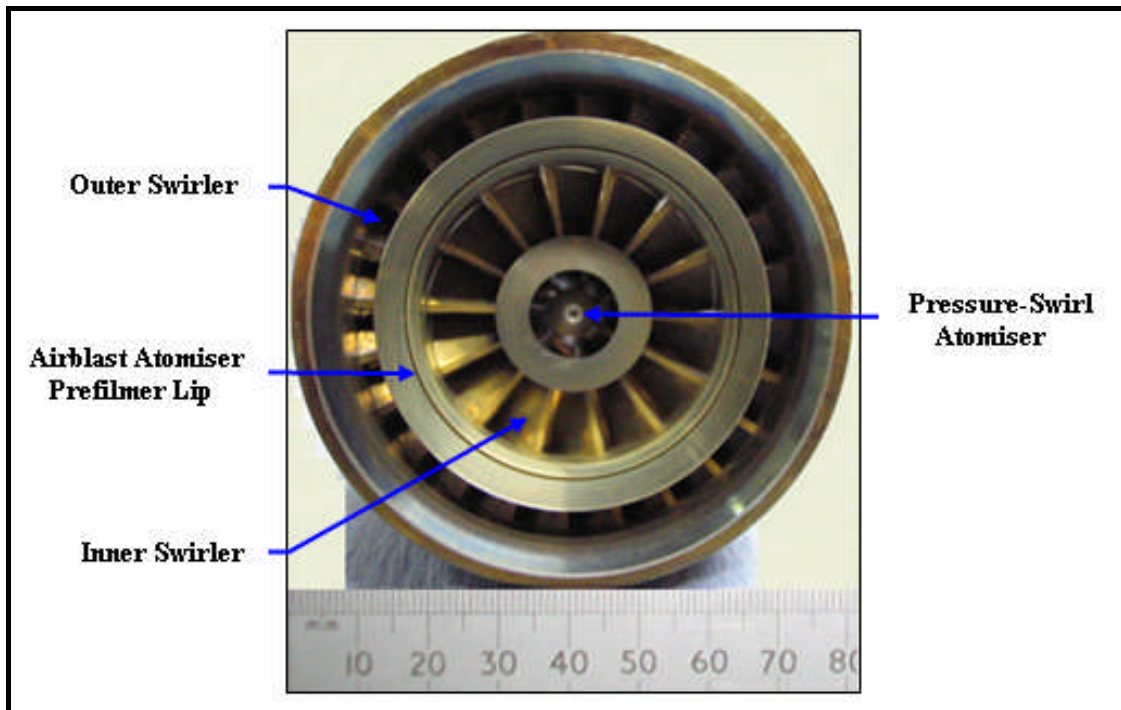


Figure 6.16: Image of ANTLE Weak Module B61

6.5 LSD AND PLIF CHARACTERISATION OF FUEL SPRAYS

This section essentially describes a visualisation technique to aid the filtering of design options with more sophistication than Lefebvre-style profiles of droplet size using PDA alone. Appendix C shows RR 5 Cell scaled engine operating conditions and Appendix D gives MSR operating conditions that were corrected for atmospheric pressure on the days of testing. LSD and PLIF techniques were applied to measure droplet SMD and AFR in the fuel sprays from 21 AFR and ANTLE Weak Module Builds 34, 34C, 43 and 45. Due to the qualitative nature of this study all results are presented in arbitrary units. Although signal calibration would have instilled a degree of measurement precision, the experimental configuration remained constant between measurements to permit some degree of a comparative analysis of spray atomisation quality and structure as a function of injector design and rig operating conditions. Measurements in this chapter served two purposes.

First, LSD was applied to obtain qualitative SMD information to gauge the effect, if any, of separate rig scaling strategies on spray atomisation quality and structure. Second, PLIF images were used to develop the NO prediction method for use in the quantitative spray studies described in Chapter Seven. Spreadsheets and image processing macros were written and tested to extract local AFR from PLIF images. Local adiabatic flame temperatures were calculated using GASEQ. Spray length divided by the global air velocity gave an estimate of the species residence times. Both flame temperature and residence time were used in HOMREA to calculate NO

formation for a given engine running condition. As the calibration of PLIF images into quantitative AFR using mass flux and entrained velocity information shown in Appendix F failed to yield plausible AFR, it prompted the laser signal calibration method described in Chapter Four for application in the experiments reported in Chapters Seven and Eight. The 21 AFR dataset consisted of 250 images acquired at 0°. Images were averaged and background-subtracted but not flatfielded or corrected for the effects of laser attenuation. Each ANTLE dataset contained 200 images. Each dataset was background-subtracted and 0° and 180° images were combined to compensate for the effects of laser attenuation through the spray with the method of Talley *et al* (1996). Images were not, however, flatfielded. In hindsight, a 180° dataset for 21 AFR should have been acquired in addition to a flatfielding experiment to assist image processing.

6.5.1 LSD Results and Discussion for 21 AFR Injector

LSD was applied to acquire droplet SMD at three simulated engine operating conditions using two rig scaling strategies. Strategy (a) preserved injector pressure drop ($\Delta P/P$) and AFR and strategy (b) conserved $\Delta P/P$ and air to fuel momentum flux ratio. Acquisition of the 0° data coincided with a shift in RR strategy and suspension of further work on this injector as RR CFD analysis and rig tests suggested the adoption of a single annular combustor and staged weak modules. A similar study was therefore conducted using Build 34. Overleaf, Figure 6.17 shows PLIF and SMD images on a false colour scale with the fuel flow rates presented under each image. As the images were not fully calibrated or flatfielded, all datasets were normalised to give the same maximum intensity and ease interpretation of results. Images measured 160 x 384 pixels to give a spray size of 42 x 101mm. PLIF images are shown to help visualise the spray structure. Essentially, strategy (a) required half the fuel flow rate of (b). As expected, this affected spray atomisation quality, fuel distribution, spray cone angle, radial and axial spray penetration. Very low fuel flow rates of 1.1 – 1.63 g/s gave an insufficient pressure drop across the injector for the flow to develop. The tulip opened a little but not enough to escape the “dribble” or “distorted pencil” flow regimes described in Figure 3.10 on page 57. In strategy (a) the fuel had low momentum and was asymmetrically distributed. Horizontal alignment of the injector may also have caused a minor gravity affect that increased at very low fuel flow rates to ease dribble into one airflow and result in poorer fuel and air mixing. On the other hand, strategy (b) used a larger fuel flow rate to yield a more developed spray that entrained more successfully in both radial air swirler flows onto the prefilmer surface to improve secondary atomisation. Appendix E shows the basic LSD image processing routine used for this injector. Figure 6.18, Figure 6.19 and Figure 6.20 on page 132 consider the Take-off (1) cases and plot droplet SMD values across three radial planes perpendicular to the injector centreline in the very near nozzle region at $X = 25\%$

(10.5mm); near nozzle region at $X = 50\%$ (21.1mm) and further downstream at $X = 75\%$ (31.68mm). Figure 6.21 overleaf plots SMD values along the injector centreline to show the expected decline in droplet SMD with downstream distance. Measurement of spray properties in these regions is critical to inform CFD boundary conditions.

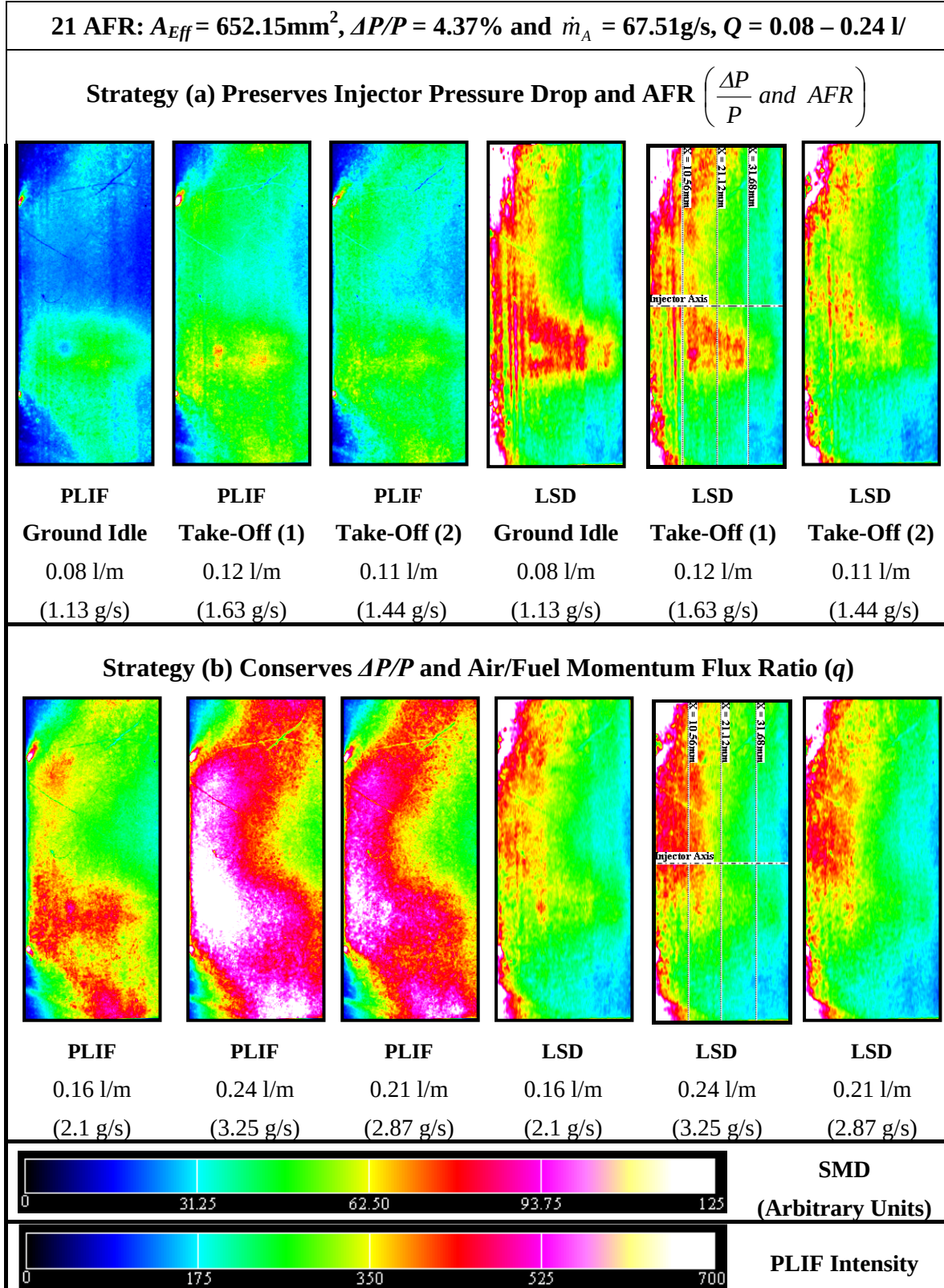


Figure 6.17: PLIF and SMD Images in Arbitrary Units for 21 AFR Injector

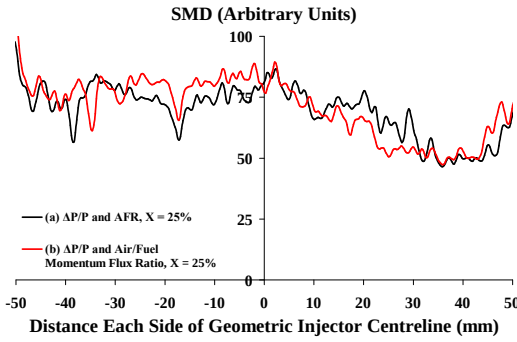
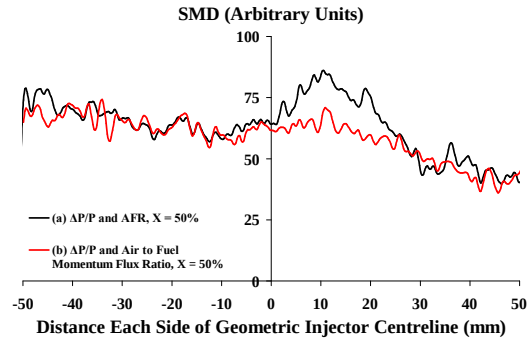
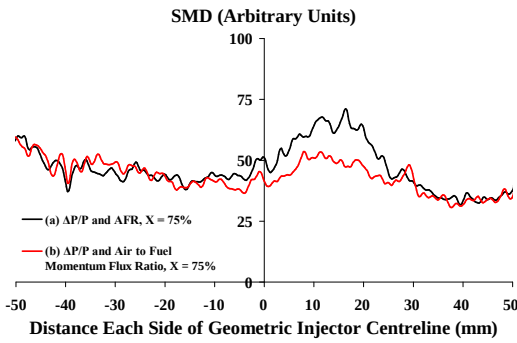
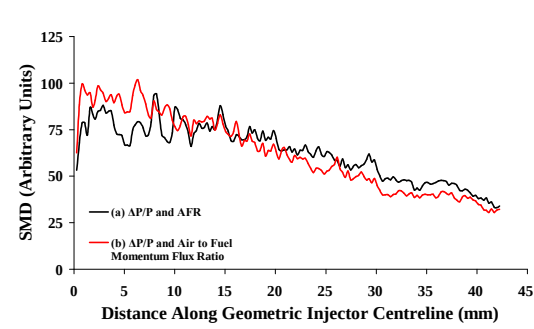

 Figure 6.18: SMD in Arbitrary Units, $X = 25\%$

 Figure 6.19: SMD in Arbitrary Units, $X = 50\%$

 Figure 6.20: SMD in Arbitrary Units, $X = 75\%$


Figure 6.21: SMD in Arbitrary Units Along CL

Figure 6.18 pertained to the very near nozzle region and showed that different rig scaling strategies produced sprays with similar SMD values, axial and radial penetrations. Strategy (a), however, yielded a spray with larger SMD values relative to (b) and more axial spray penetration in a $\sim 25\text{mm}$ region to the right of the injector centreline, although the spray aerodynamic centre may not have coincided perfectly with the geometric injector centreline.

It was not possible to correct for light attenuation through the spray because a dataset was not acquired with the injector rotated through 180° due to the mentioned change in RR strategy. Therefore, the spray asymmetry could not be confirmed. However, the asymmetry in strategy (a) was most likely due to the extremely modest fuel flow rates. Strategy (b) gave lower SMD values over (a) in central regions to a downstream distance of $\sim 17\text{mm}$. Figure 6.22 overleaf shows the fractional discrepancy for pressure-swirl atomisation, based on $\Phi_{PS} = Re, Ma, Stk, We, p_D = 1$. On average, strategy (b) outperformed (a) by $\sim 63\%$ in its ability to replicate key spray properties of genuine practical interest such as dropsizes and fuel patternation in atmospheric pressure tests. Higher fuel flow rates in (b) reduced the discrepancies in Stk, We and p_D between the rig and engine operating conditions. The fractional discrepancy doubled as the fuel flow rate was increased by 50% in both strategies.

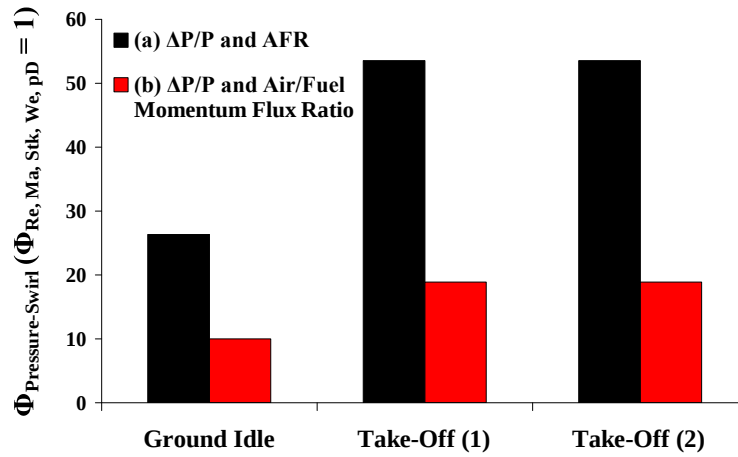


Figure 6.22: 21 AFR Injector: $\Phi_{PS} (\Phi_{Re, Ma, Stk, We, pD} = 1)$

6.5.2 LSD and PLIF Results and Discussion for Build 34

LSD and PLIF were applied to acquire droplet SMD and AFR in Build 34 with rig scaling strategies that conserved (a) U and AFR to reproduce droplet SMD and (b) $\Delta P/P$ and AFR for patternation. Since the images were partially calibrated and not flatfielded, all datasets were normalised to yield the same maximum intensity to simplify interpretation of the results. Figure 6.23 overleaf shows LSD images of droplet SMD. Hot colours indicate high SMD values. The spray direction is from left to right. Images measured 104×329 pixels and represent a spray size of 30.7×97.2 mm. Fuel flow rates and fuel split ratios between the pressure-swirl (pilot) and airblast (main) atomisers are shown as (pilot:main). To maintain $\Delta P/P$ at 3.3% in both datasets strategy (a) varied the air mass flow rate ($\dot{m}_A$) between 176 – 217 g/s and U through the injector between 103 – 123 m/s. In strategy (b) both $\dot{m}_A$ and U were held constant at 130 g/s and 74 m/s.

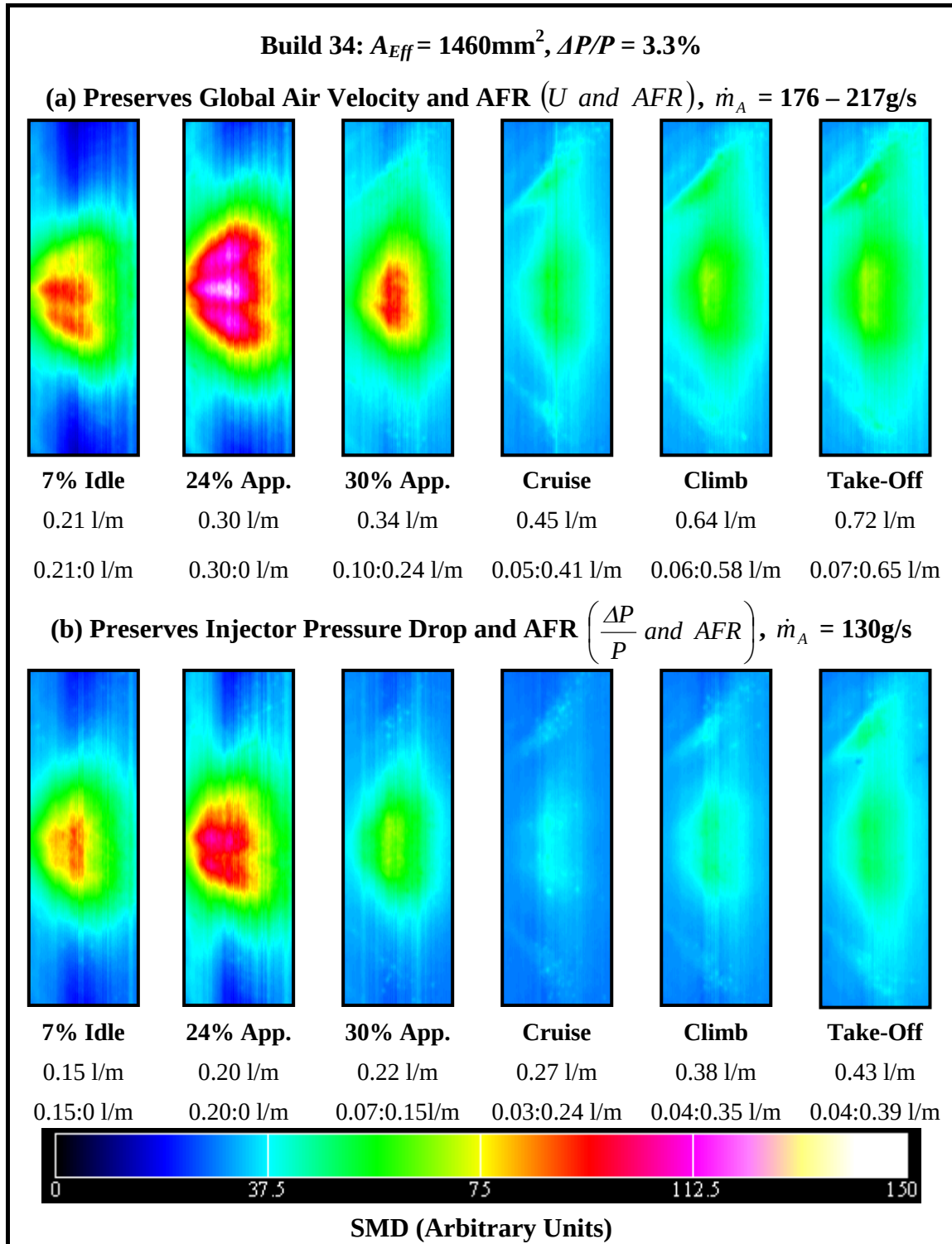


Figure 6.23: SMD Images in Arbitrary Units for B34

The six charts shown overleaf between Figure 6.24 and Figure 6.29 plot droplet SMD in three radial planes perpendicular to the injector centreline at downstream distances of $X = 25\%$ (7.7mm), 50% (15.4mm) and 75% (23mm). In the very near and near nozzle regions, the sprays were dominated by injector design characteristics; air and fuel velocities and momentum. Further downstream the spray becomes less sensitive to the coupling effects with the surrounding airflow because all air goes through the injector.

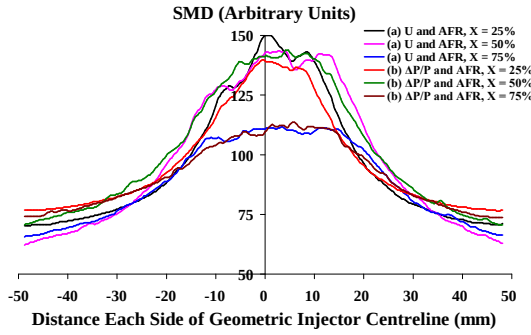


Figure 6.24: B34: 7% Idle: (a) $U = 103$ m/s, $\dot{m}_A = 176$ g/s, $Q = 0.21$ l/m (0.21:0 l/m), (b) $Q = 0.15$ l/m (0.15:0 l/m)

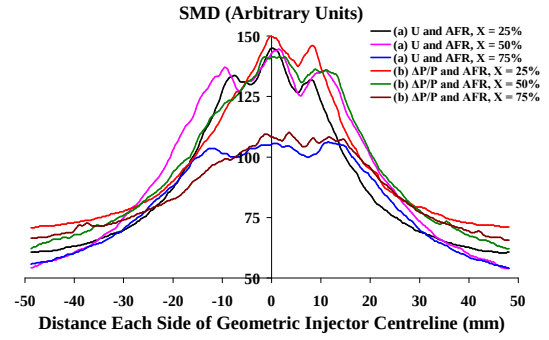


Figure 6.25: B34: 24% App.: (a) $U = 112$ m/s, $\dot{m}_A = 195$ g/s, $Q = 0.30$ l/m (0.30:0 l/m), (b) $Q = 0.20$ l/m (0.20:0 l/m)

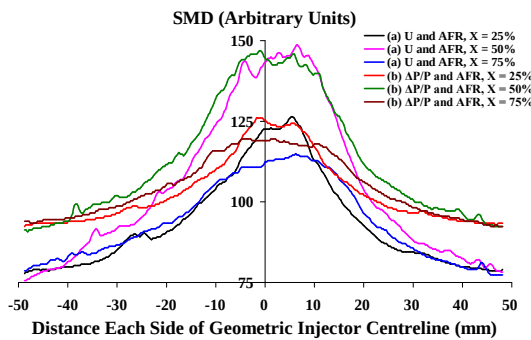


Figure 6.26: B34 : 30% App.: (a) $U = 114$ m/s, $\dot{m}_A = 199$ g/s, $Q = 0.34$ l/m (0.10:0.24 l/m), (b) $Q = 0.22$ l/m (0.07:0.15 l/m)

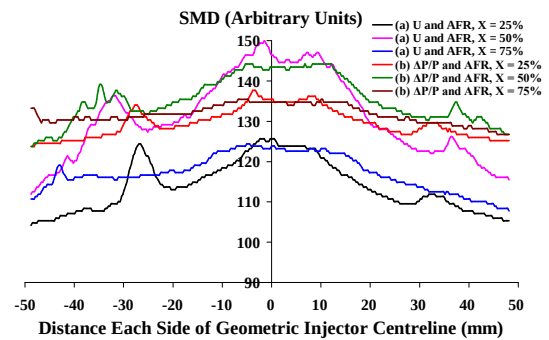


Figure 6.27: B34: Cruise: (a) $U = 123$ m/s, $\dot{m}_A = 217$ g/s, $Q = 0.45$ l/m (0.05:0.41 l/m), (b) $Q = 0.27$ l/m (0.03:0.24 l/m)

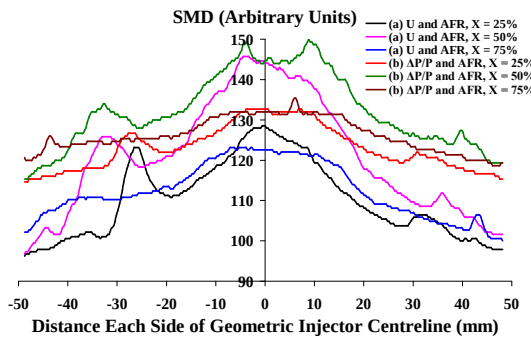


Figure 6.28: B34: Climb: $U = 123$ m/s, $\dot{m}_A = 217$ g/s, $Q = 0.64$ l/m (0.06:0.58 l/m), (b) $Q = 0.38$ l/m (0.04:0.34 l/m)

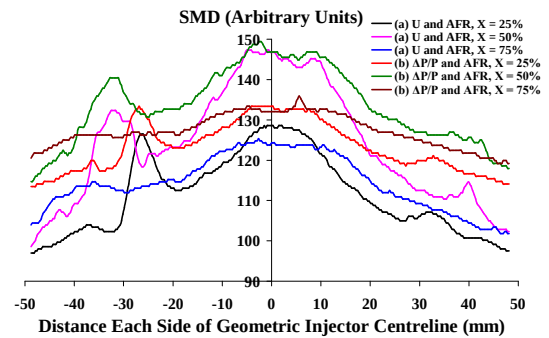


Figure 6.29: B34: Take-Off: $U = 123$ m/s, $\dot{m}_A = 217$ g/s, $Q = 0.72$ l/m (0.07:0.65 l/m), (b) $Q = 0.43$ l/m (0.04:0.39 l/m)

Overleaf, Figure 6.30 shows fractional discrepancies, Φ_{Hybrid} based on $\Phi_{Airblast} = Re, Ma, Stk, We = 1$ and $\Phi_{PS} = Re, Ma, Stk, We, p_D = 1$. Strategy (a) outperformed (b) by $\sim 50\%$, principally because larger fuel flow rates broadened the spray cone angles (Jasuja, 1997). This aided secondary atomisation to give smaller droplets that followed swirling airflows to reduce fractional discrepancies in the considered non-dimensional groups, especially Stk as smaller droplets entrained better than larger droplets in air streamlines.

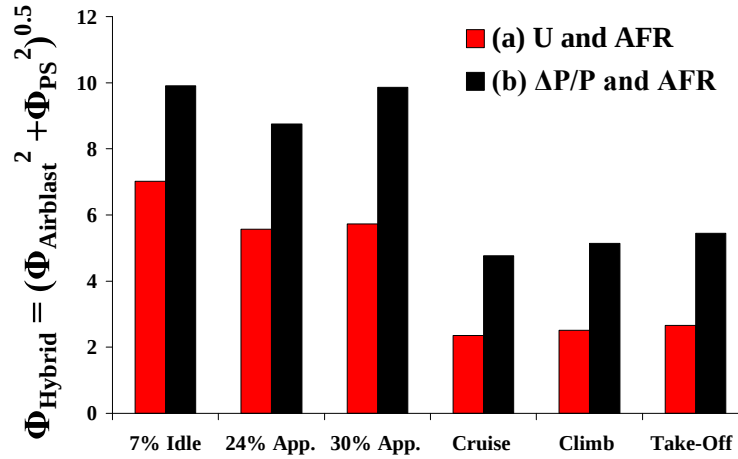
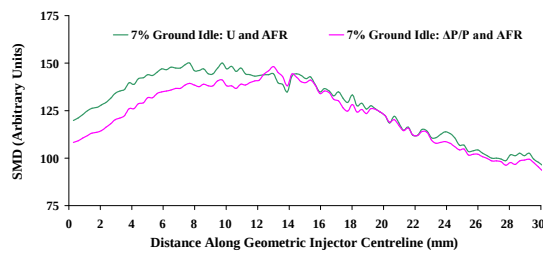


Figure 6.30: B34: $\Phi_{Hybrid} (\Phi_{Airblast}^2 + \Phi_{PS}^2)^{0.5}$

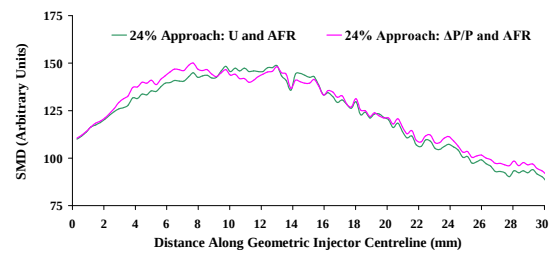
At 7% Ground Idle and $X = 25\%$, droplet SMD was larger in (a) along with spray asymmetry in central spray regions in comparison to (b). At $X = 50\%$, the droplet SMD reduced and was less in (a) than (b) although spray asymmetry persisted in (a). At $X = 75\%$ spray asymmetry diminished in (a) and droplet SMD values were comparable in both strategies and much smaller compared to the very near nozzle region. Droplet SMD values in the very near nozzle region, near nozzle region and further downstream region were smaller in the outer spray regions in (a) than (b). At 24%, Approach in the very near nozzle region (a) showed less asymmetry and gave smaller droplet SMD values than (b). In the near nozzle region at $X = 50\%$ spray cone angles increased for (a) and (b). However, in (a) droplet SMD values increased in central spray regions but declined in outer spray regions compared to the very near nozzle region because of a greater interaction with swirling airflows that improved secondary atomisation. Droplet SMD values were smaller for (b) in central and outer regions and were principally due to lower fuel flow rates that contracted spray cone angles, limited secondary atomisation and the ability of swirlers to manage fuel and air patternation. Further downstream at $X = 75\%$ the droplet SMD values significantly reduced in (a) and (b) in comparison to the very near nozzle region. In each plane (a) yielded smaller SMDs in outer spray regions.

At 30% Approach, the fuel split ratio between the pilot and main was (30:70) but the pilot spray remained dominant. In the very near nozzle region at $X = 25\%$ the droplet SMD values were smaller in (a) than (b). In the near nozzle region at $X = 50\%$ the droplet SMD values increased but (a) yielded smaller droplet SMD values in central and outer regions in comparison to (b). Further downstream at $X = 75\%$ the droplet SMD values declined in (a) but increased $\sim 10\text{mm}$ each side of the geometric injector centreline and decreased in central regions for (b). At the Cruise condition, in the very near nozzle region at $X = 25\%$ both (a) and (b) exhibited similar profiles but (a) had smaller droplet SMD values and a larger degree of asymmetry on the left of the geometric injector centreline. In the near nozzle region at $X = 50\%$ the asymmetry

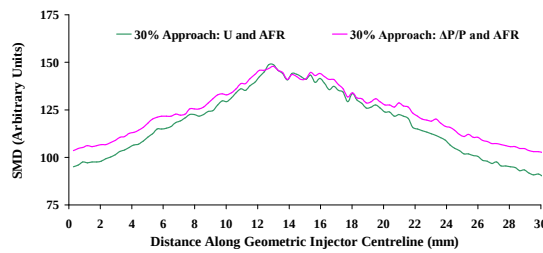
travelled leftwards. Droplet SMD values increased in (a) and (b) relative to the very near nozzle regions. The droplet SMD values increased in central regions but decreased in outer zones in (a). Further downstream at $X = 75\%$ the droplet SMD reduced below the values in the near nozzle region but remained larger compared to the very near nozzle region. As expected, spray asymmetry decreased with downstream distance. At the Climb and Take-Off cases, the asymmetry remained in (a). In the very near nozzle region at $X = 25\%$ the droplet SMD values were smaller in (a) than (b). In the near nozzle region at $X = 50\%$ the asymmetry travelled leftwards once again and droplet SMD values rose in (a) over (b) compared to the very near nozzle region. Further downstream, at $X = 75\%$ and similar to the Cruise case, the asymmetry diminished and droplet SMD values fell below values in the near nozzle region but were larger than at the very near nozzle region. Figure 6.31 to Figure 6.36 plot droplet SMD values along the geometric injector centreline for all cases for each rig scaling strategy.



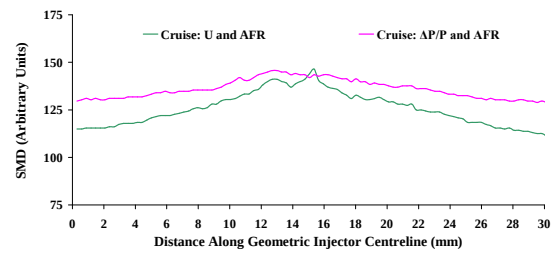
**Figure 6.31: SMD in Arbitrary Units Along B34
CL – 7% Ground Idle**



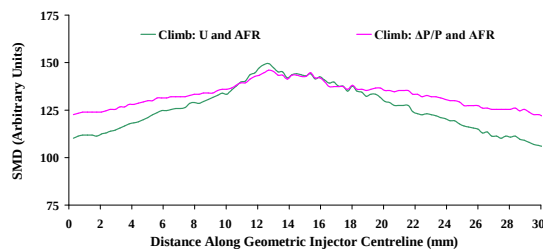
**Figure 6.32: SMD in Arbitrary Units Along B34
CL – 24% Approach**



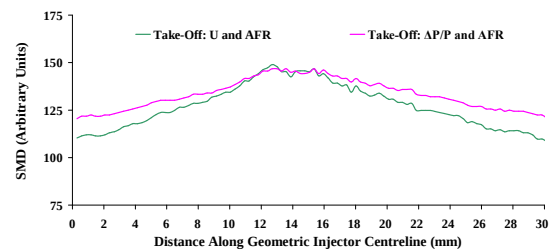
**Figure 6.33: SMD in Arbitrary Units Along B34
CL – 30% Approach**



**Figure 6.34: SMD in Arbitrary Units Along B34
CL – Cruise**



**Figure 6.35: SMD in Arbitrary Units Along B34
CL – Climb**



**Figure 6.36: SMD in Arbitrary Units Along B34
CL – Take-Off**

The SMD is small in the very near nozzle region along the fuel injector centreline. In pilot only and 30% Approach cases, SMD values peaked at a downstream distance of $\sim 13\text{mm}$ and then declined further downstream. However, they continued to rise due to droplet coalescence and secondary atomisation at the Cruise, Climb and Take-Off conditions after a minor inflexion at $\sim 13\text{mm}$ to a downstream distance of $\sim 16\text{mm}$ and then gradually reduced thereafter. In mixed cases, strategy (a) yielded smaller droplet SMD values. This was mainly due to the 30 – 40% higher fuel flow rate requirements and larger air mass flow rates to maintain $\Delta P/P$ at 3.3%. More significant was that introduction of the main spray from the airblast atomiser reduced PLIF intensities despite the presence of at least 50% extra fuel.

This result could lead to an over-estimation of AFR and under-prediction of NO due to its exponential dependence on flame temperature controlled by the AFR. The extent of signal loss due to both radiation trapping and aerodynamic influence of the main spray on the pilot should be measured in further work to calculate image correction factors. PLIF image data was processed to obtain two-dimensional maps of local AFR using an informed estimate of the LVF and application of calculated rig air and fuel densities.

Overleaf, Figure 6.37 shows AFR images in arbitrary units. Images also measured 120 x 329 pixels and corresponded to a spray size of 35.4 x 97.2mm.

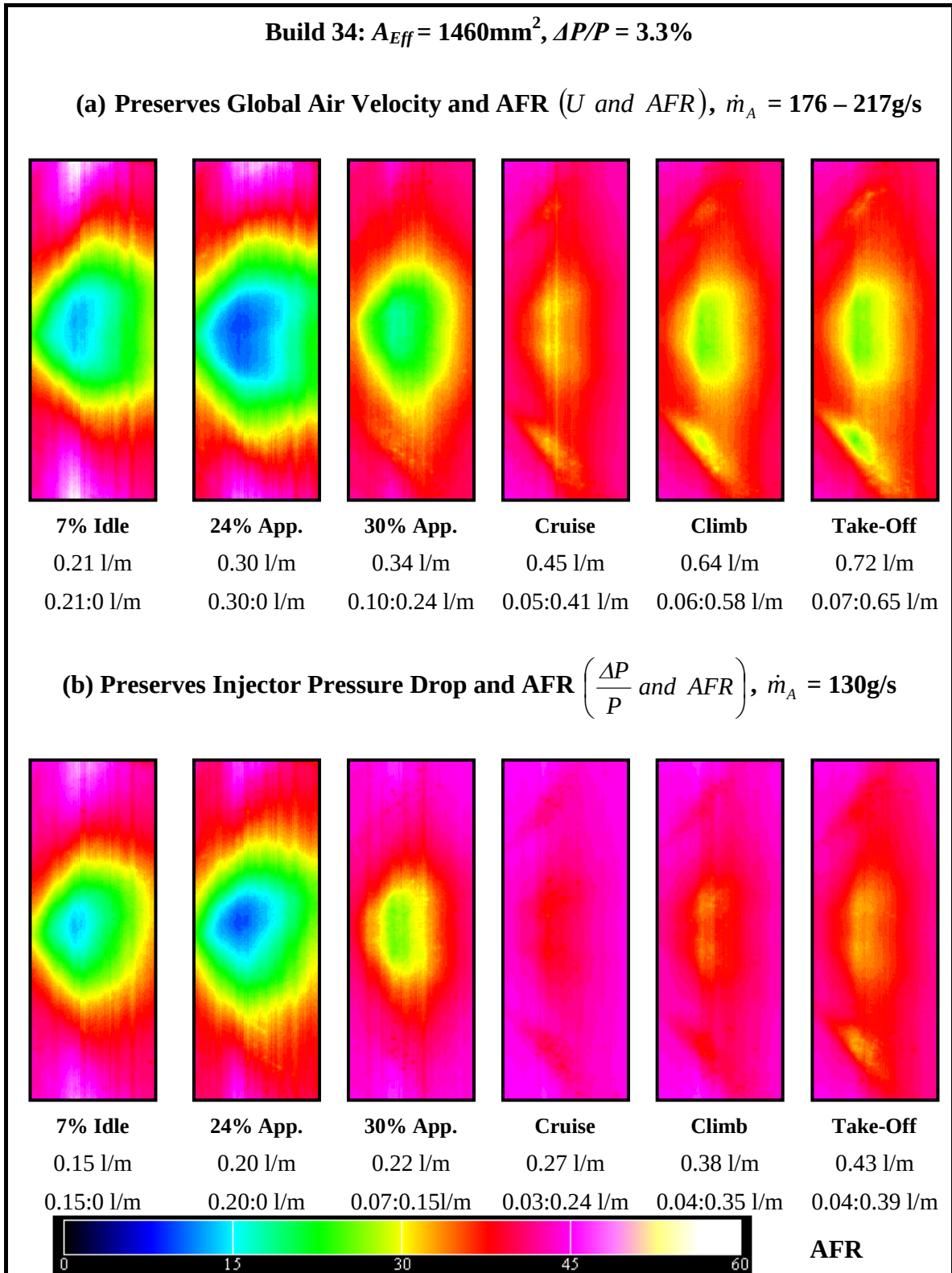


Figure 6.37: AFR Images in Arbitrary Units for B34 Using Two Scaling Strategies

Overleaf, Figure 6.38 to Figure 6.43 plot AFR in three radial planes perpendicular to the injector centreline; again in three radial planes of $X = 25\%$ (8.86mm), 50% (17.73mm) and 75% (26.59mm). Results showed that strategy (b) yielded leaner sprays due to the lower fuel flow rate requirements. Spray asymmetry was, however, more pronounced in strategy (a) over (b).

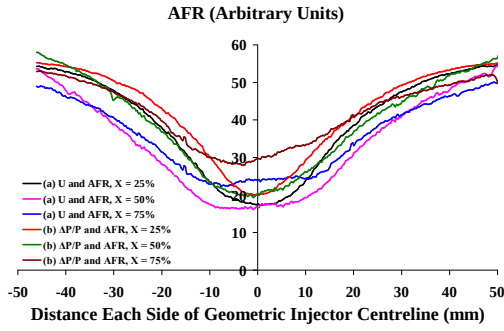


Figure 6.38: B34: 7% Idle: (a): $U = 103$ m/s, $\dot{m}_A = 176$ g/s, $Q = 0.21$ l/m (0.21:0 l/m), (b): $Q = 0.15$ l/m (0.15:0 l/m)

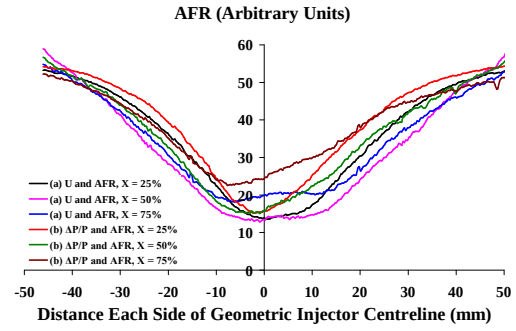


Figure 6.39: B34: 24% App.: (a) $U = 112$ m/s, $\dot{m}_A = 195$ g/s, $Q = 0.30$ l/m (0.30:0 l/m), (b) $Q = 0.20$ l/m (0.20:0 l/m)

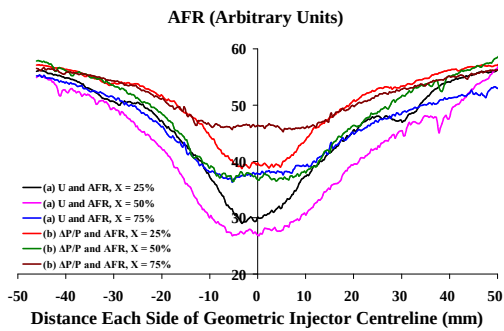


Figure 6.40: B34: 30% App.: (a) $U = 114$ m/s, $\dot{m}_A = 199$ g/s, $Q = 0.34$ l/m (0.10:0.24 l/m), (b) $Q = 0.22$ l/m (0.07:0 l/m)

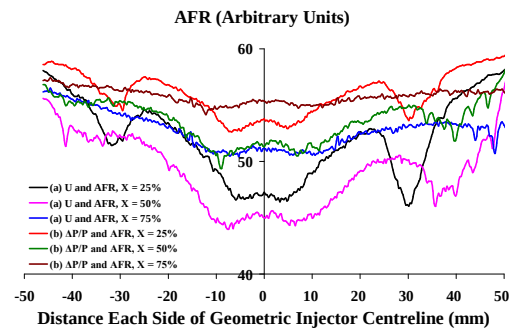


Figure 6.41: B34 : Cruise (a) $U = 123$ m/s, $\dot{m}_A = 217$ g/s, $Q = 0.45$ l/m (0.05:0.41 l/m), (b) $Q = 0.27$ l/m (0.03:0 l/m)

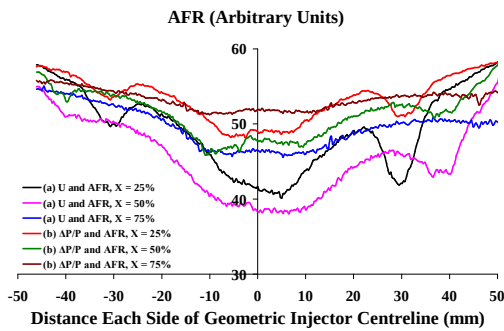


Figure 6.42: B34: Climb: (a) $U = 123$ m/s, $\dot{m}_A = 217$ g/s, $Q = 0.64$ l/m (0.06:0.58 l/m), (b) $Q = 0.38$ l/m (0.04:0.34/m)

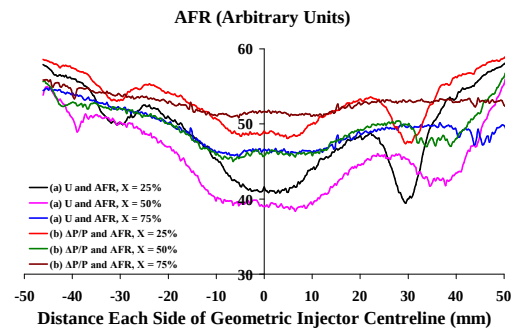


Figure 6.43: B34: Take-Off: (a) $U = 123$ m/s, $\dot{m}_A = 217$ g/s, $Q = 0.72$ l/m (0.07:0.65 l/m), (b) $Q = 0.43$ l/m (0.04:0.39/m)

6.5.3 AFR Results and Discussion for ANTLE Weak Modules

Overleaf, Figure 6.44 shows AFR images for Builds 34C, 43 and 45. The scaling strategy preserved U and AFR for comparative analysis of injector performance as a function of injector design features and rig operating conditions. Charts on pages 143, 144, 145 and 146 plot AFR values along the same radial planes as before in each image.

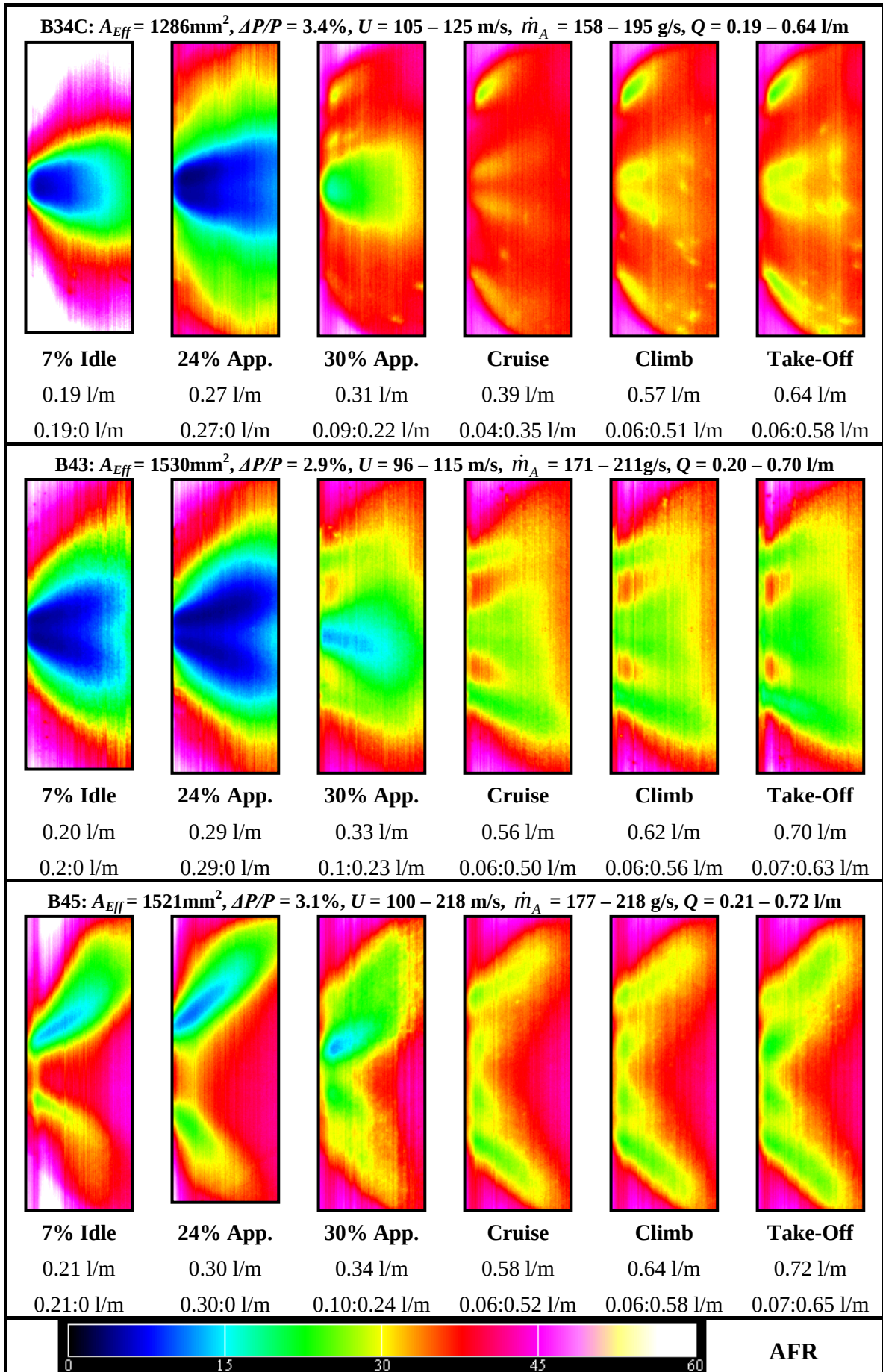


Figure 6.44: AFR Images in Arbitrary Units for B34C, 43 and 45

The general spray structure was similar per dataset. The relative fuel momenta in pilot only cases was greater than air momenta to give very rich central regions, deep axial spray penetration and good symmetry. All sprays attained a better symmetry further downstream. As fuel flow rates increased the spray patterns became richer and broader. Barring Build 45, pilot only cases were remarkably symmetrical. In mixed cases the main airblast spray had a wider cone angle than pressure-swirl sprays. Cone angles in the pressure-swirl spray were widest in Build 45 followed by Builds 43, 34 and 34C. However, in the main spray the cone angle was broadest in Build 34C followed by Builds 34, 45 and 43. The 30% Approach cases showed the main spray was leaner than the pilot spray. At Cruise, Climb and Take-Off the fuel split ratio of pilot:main changed from 30:70 to 10:90 and the AFR became comparable in both sprays. Although the need for optical access forbids total confinement of the spray the majority of air leaves the measurement volume to give leaner sprays. This practical limitation should be negligible in very near and near nozzle regions. In pilot only and 30% Approach cases AFR values were indeed lower than global AFR values given in Appendix D but higher at Cruise, Climb and Take-Off. This was largely due to higher air mass flow rates that were necessary for an equal $\Delta P/P$ across cases and more critically, to the very clear aerodynamic influence of the main spray on the pilot that obscured PLIF intensities.

Overleaf, Figure 6.45 to Figure 6.50 pertain to Build 34 and plot AFR values along the same three radial planes as before. Table 6.3 shows injector details and rig operating conditions. In pilot only cases either the air momenta attained dominance $\pm 20\text{mm}$ from the injector centreline or fuel droplets became small enough to become entrained in the secondary 45° airflow to yield a leaner spray in outer regions compared to rich central regions. At 30% Approach, the pressure-swirl spray was leaner due to a 66% reduction in fuel flow rate but the spray remained symmetrical. The main spray was asymmetrical in the very near and near nozzle regions at $X = 25\%$ and 50% but was symmetrical further downstream at $X = 75\%$. The spray pattern was essentially the same for Cruise, Climb and Take-Off, principally because air mass flow rates were constant and there was very little change in the fuel flow rates. Compared to 30% Approach, the Cruise condition required only half the pilot fuel flow rate but an increased main fuel flow rate of 70%. The lower fuel flow rate to the pressure-swirl atomiser leaned out the spray in the very near and near nozzle regions $\pm 5\text{mm}$ from the injector centreline. The larger fuel flow rate to the main had little impact on AFR values but considerably affected the degree of spray asymmetry in a region $\pm 25 - 35\text{mm}$ from the injector centreline. At Climb, the fuel flow rates increased by $\sim 40\%$ over the Cruise case. The spray became slightly richer and less symmetrical in the very near and near nozzle regions. At Take-Off, the fuel flow rate increased by $\sim 12.5\%$ over the Climb case. Spray asymmetry diminished in the pressure-swirl spray but increased in the main spray. The AFR was not single-valued and wake features were convected downstream. Inner and secondary

swirl flows were anomalous in the core but not the flow sense. The interface between fuel droplets and surrounding air appeared to be stable on the cone surface of the pilot spray as swirl angles were positive to limit occurrence of confined eddies that give variations in mixture strength, residence time and temperature. The interface appeared less stable however between the secondary and third swirlers.

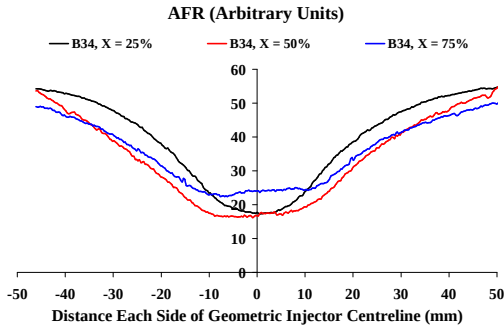


Figure 6.45: B34: 7% Idle: $U = 102$ m/s, $\dot{m}_A = 176$ g/s, $Q = 0.21$ l/m (0.21:0 l/m)

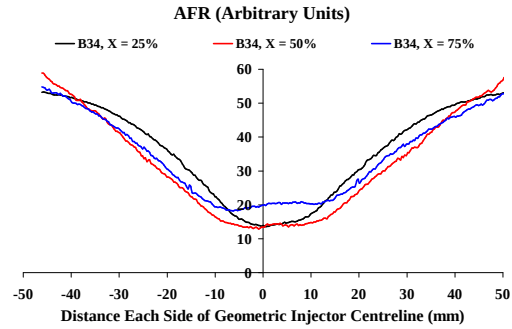


Figure 6.46: B34: 24% App.: $U = 112$ m/s, $\dot{m}_A = 195$ g/s, $Q = 0.3$ l/m (0.3:0 l/m)

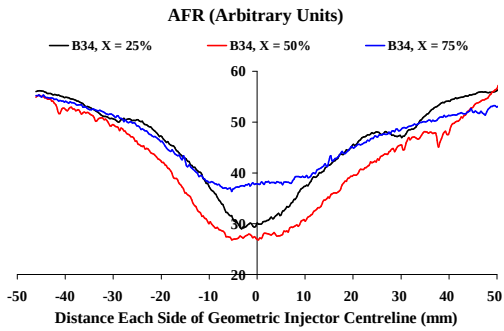


Figure 6.47: B34: 30% App.: $U = 114$ m/s, $\dot{m}_A = 199$ g/s, $Q = 0.34$ l/m (0.10:0.24 l/m)

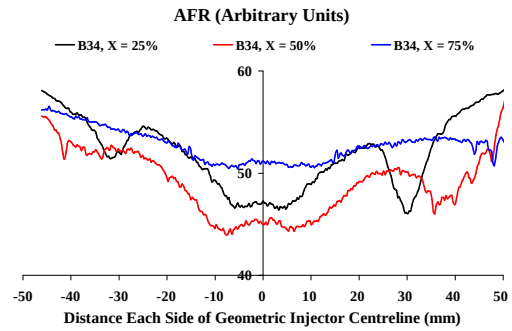


Figure 6.48: B34 : Cruise: $U = 123$ m/s, $\dot{m}_A = 217$ g/s, $Q = 0.45$ l/m (0.05:0.41 l/m)

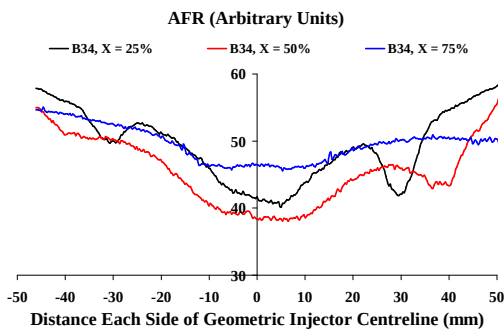


Figure 6.49: B34: Climb: $U = 123$ m/s, $\dot{m}_A = 217$ g/s, $Q = 0.64$ l/m (0.06:0.58 l/m)

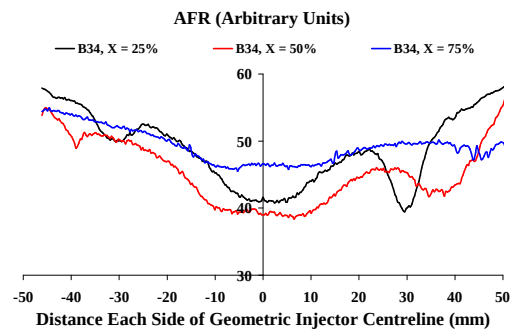


Figure 6.50: B34: Take-Off: $U = 123$ m/s, $\dot{m}_A = 217$ g/s, $Q = 0.72$ l/m (0.07:0.65 l/m)

B34: $A_{Eff} = 1460\text{mm}^2$, $\Delta P/P = 3.3\%$, $U = 102 - 123$ m/s, $\dot{m}_A = 176 - 217$ g/s, $Q = 0.21-0.72$ l/m		
Swirler 1	Swirler 2	Swirler 3
30°	45°	55°

Table 6.3: B34 Injector Details and Rig Operating Conditions

Figure 6.51 to Figure 6.56 pertain to Build 34C and Table 6.4 gives build details and rig conditions. A 10° rise in Swirler 3 vane angle and 12% less effective area vs Build 34 raised U but cut air mass flow rates to improve symmetry at the expense of marginally richer sprays. In the very near nozzle region at Cruise, Climb, and Take-Off the pilot spray was leaner $\pm 5\text{mm}$ of the centreline due to aerodynamic coupling with the main.

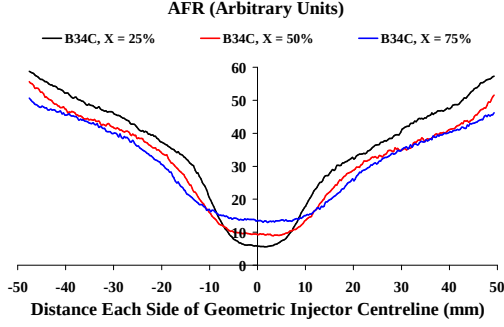


Figure 6.51: B34C: 7% Idle: $U = 105 \text{ m/s}$, $\dot{m}_A = 158 \text{ g/s}$, $Q = 0.19 \text{ l/m}$ (0.19:0 l/m)

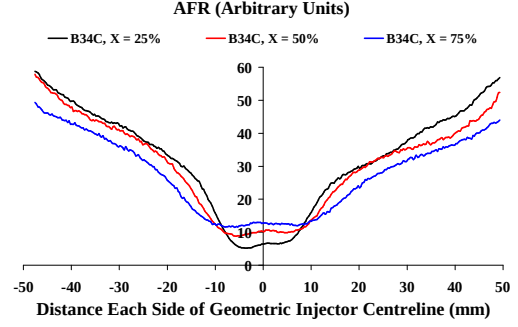


Figure 6.52: B34C: 24% App.: $U = 114 \text{ m/s}$, $\dot{m}_A = 174 \text{ g/s}$, $Q = 0.27 \text{ l/m}$ (0.27:0 l/m)

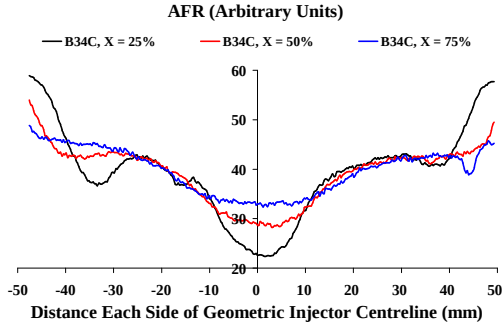


Figure 6.53: B34C: 30% App.: $U = 118 \text{ m/s}$, $\dot{m}_A = 181 \text{ g/s}$, $Q = 0.31 \text{ l/m}$ (0.09:0.22 l/m)

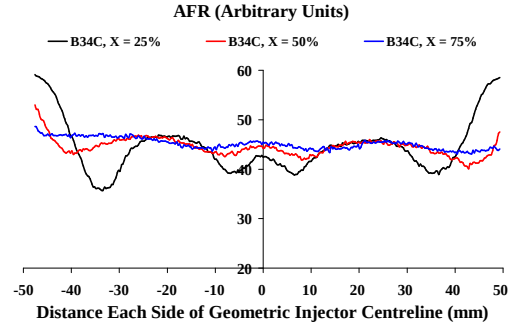


Figure 6.54: B34C: Cruise: $U = 121 \text{ m/s}$, $\dot{m}_A = 187 \text{ g/s}$, $Q = 0.39 \text{ l/m}$ (0.04:0.35 l/m)

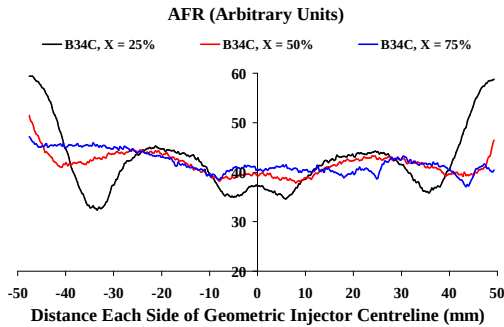


Figure 6.55: B34C: Climb: $U = 125 \text{ m/s}$, $\dot{m}_A = 194 \text{ g/s}$, $Q = 0.57 \text{ l/m}$ (0.06:0.51 l/m)

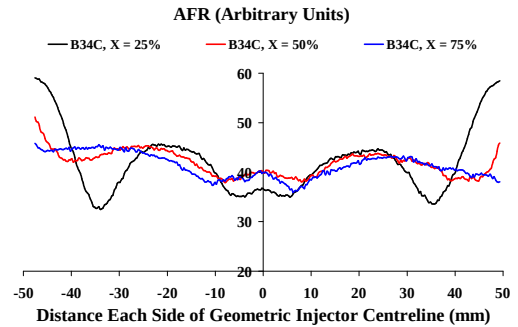


Figure 6.56: B34C: Take-Off: $U = 125 \text{ m/s}$, $\dot{m}_A = 195 \text{ g/s}$, $Q = 0.64 \text{ l/m}$ (0.06:0.58 l/m)

B34C: $A_{\text{Eff}} = 1286 \text{ mm}^2$, $\Delta P/P = 3.4\%$, $U = 105 - 125 \text{ m/s}$, $\dot{m}_A = 158 - 195 \text{ g/s}$, $Q = 0.19 - 0.64 \text{ l/m}$		
Swirler 1	Swirler 2	Swirler 3
30°	45°	65°

Table 6.4: B34C Injector Details and Rig Operating Conditions

Figure 6.57 to Figure 6.62 show results for Build 43 and Table 6.5 lists build details and rig conditions. Essentially, this was Build 34 with a reverse Swirler 3 and ~5% larger effective area. It increased axial spray penetration and asymmetry; gave a richer AFR; broader cone angle in the pilot but narrower cone angles in mixed cases so the fuel went mostly downstream. As a result, the flame occupied a different position from Build 34.

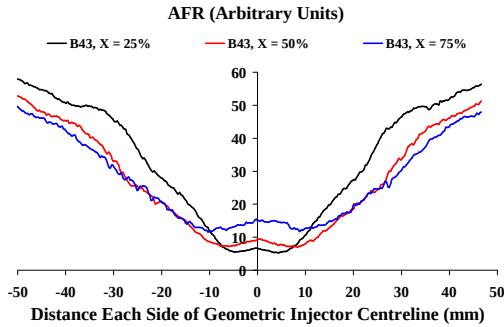


Figure 6.57: B43: 7% Idle: $U = 96$ m/s, $\dot{m}_A = 172$ g/s, $Q = 0.20$ l/m (0.2:0 l/m)

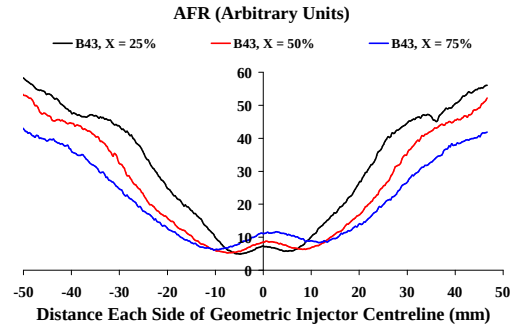


Figure 6.58: B43: 24% App.: $U = 105$ m/s, $\dot{m}_A = 189$ g/s, $Q = 0.29$ l/m (0.29:0 l/m)

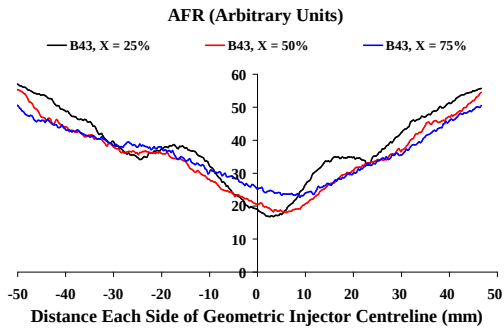


Figure 6.59: B43: 30% App.: $U = 107$ m/s, $\dot{m}_A = 194$ g/s, $Q = 0.33$ l/m (0.1:0.23 l/m)

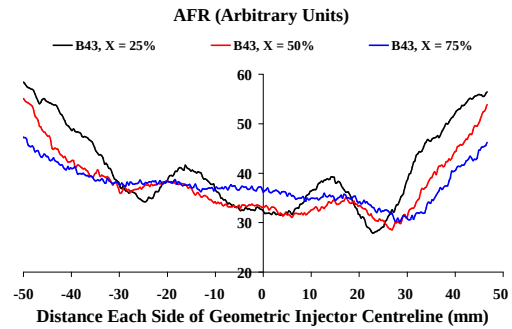


Figure 6.60: B43: Cruise: $U = 115$ m/s, $\dot{m}_A = 211$ g/s, $Q = 0.56$ l/m (0.06:0.50 l/m)

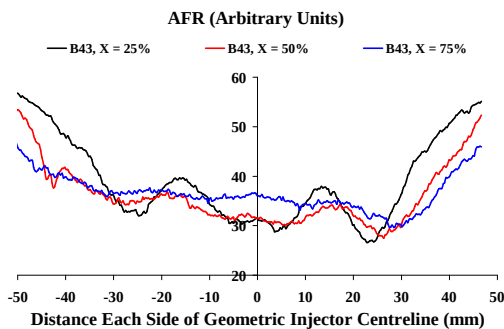


Figure 6.61: B43: Climb: $U = 115$ m/s, $\dot{m}_A = 211$ g/s, $Q = 0.62$ l/m (0.06:0.56 l/m)

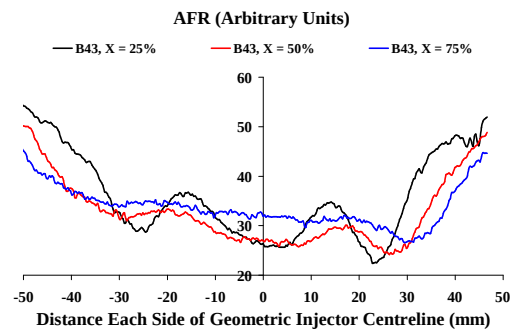


Figure 6.62: B43: Take-Off: $U = 115$ m/s, $\dot{m}_A = 211$ g/s, $Q = 0.7$ l/m (0.07:0.63 l/m)

B43: $A_{Eff} = 1530\text{mm}^2$, $\Delta P/P = 2.9\%$, $U = 96 - 115$ m/s, $\dot{m}_A = 171 - 211\text{g/s}$, $Q = 0.20 - 0.70$ l/m		
Swirler 1	Swirler 2	Swirler 3
30°	45°	-55°

Table 6.5: B43 Injector Details and Rig Operating Conditions

This may suggest less NO due to its completely different flame structure. The spray would eventually spread out further downstream but a growing proportion of its frontal area is likely to be consumed by air to make the flame leaner and burn more like a diffusion flame. In practice, Build 43 may create NO but the imaged area is too near the injector exit and may not capture it. Figure 6.63 to Figure 6.68 show Build 45 results.

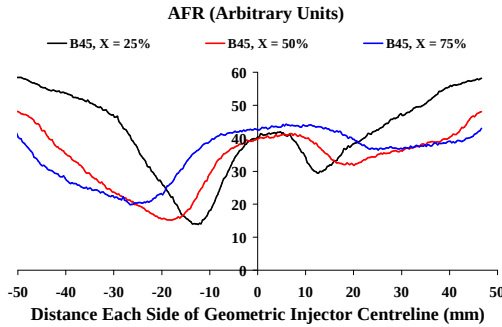


Figure 6.63: B45: 7% Idle: $U = 100$ m/s, $\dot{m}_A = 177$ g/s, $Q = 0.21$ l/m (0.21:0 l/m)

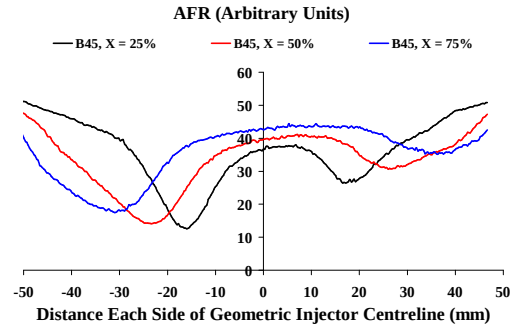


Figure 6.64: B45: 24% App.: $U = 109$ m/s, $\dot{m}_A = 196$ g/s, $Q = 0.30$ l/m (0.30:0 l/m)

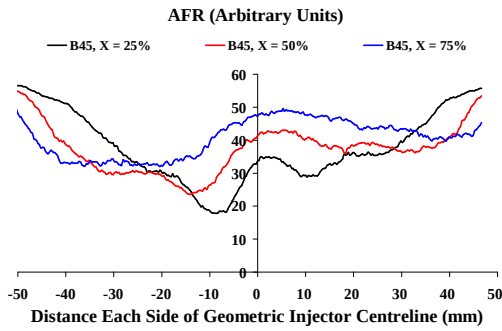


Figure 6.65: B45: 30% App.: $U = 111$ m/s, $\dot{m}_A = 200$ g/s, $Q = 0.34$ l/m (0.1:0.24 l/m)

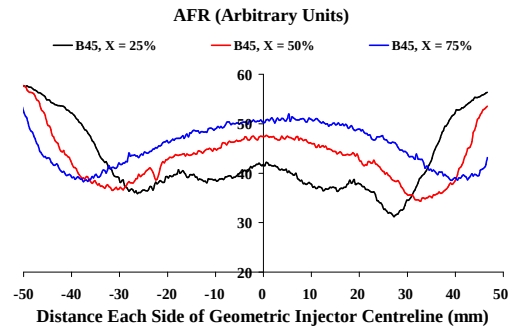


Figure 6.66: B45: Cruise: $U = 119$ m/s, $\dot{m}_A = 218$ g/s, $Q = 0.58$ l/m (0.06:0.52 l/m)

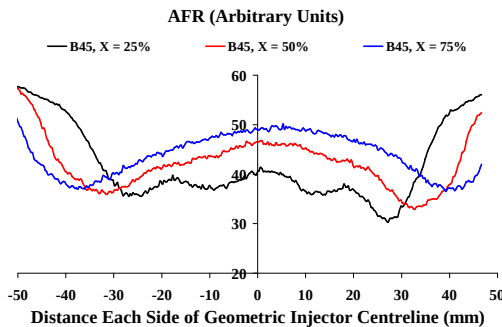


Figure 6.67: B45: Climb: $U = 119$ m/s, $\dot{m}_A = 218$ g/s, $Q = 0.64$ l/m (0.06:0.58 l/m)

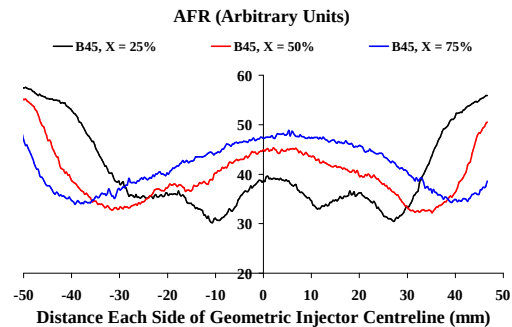


Figure 6.68: B45: Take-Off: $U = 119$ m/s, $\dot{m}_A = 218$ g/s, $Q = 0.72$ l/m (0.07:0.65 l/m)

B45: $A_{Eff} = 1521\text{mm}^2$, $\Delta P/P = 3.1\%$, $U = 100 - 119$ m/s, $\dot{m}_A = 177 - 218$ g/s, $Q = 0.21 - 0.72$ l/m		
Swirler 1	Swirler 2	Swirler 3
40°	45°	-55°

Table 6.6: B45 Injector Details and Rig Operating Conditions

Table 6.6 on the previous page showed Build 45 injector details and rig operating conditions. Although Build 45 was essentially Build 43 with a 40° swirler 1 vane angle instead of 30°, it again yielded a very different spray pattern. The interface between swirlers 1 and 2 destabilised, possibly due to the reverse swirler 3 to produce a rotating instability on the surface of the pressure-swirl spray that centrifuged fuel radially outwards to yield very lean sprays in central regions. There was also a significant level of spray asymmetry at pilot only and 30% Approach cases. Unlike Build 43, spray cone angles appeared insensitive to the reverse swirler 3 but aerodynamic interactions of the main on the pilot were more pronounced because fuel from the pilot was present in the very near nozzle region. This injector may also result in a low NO prediction due to its altered flame structure but this must be substantiated through calculating local flame temperatures and residence times.

Figure 6.69 and Figure 6.70 below show fractional discrepancies (Φ_{Hybrid}) for all datasets. Builds 34, 43, and 45 were scaled from lower pressure RR 5 Cell engine conditions where Φ_{Hybrid} diminished as fuel flow rate increased. Build 34C however was scaled from the higher pressure and temperature RR 18 Rig conditions and showed that Φ_{Hybrid} was substantially larger in comparison to scaling from the 5 Cell conditions and actually increased with fuel flow rate.

The previous chapter communicated that scaling engine operating conditions to atmospheric pressure conditions yielded considerable fractional discrepancies with the target engine condition. This provides an explanation for variations in the obtained and global AFR values shown in Appendix D. Although the undertaken atmospheric pressure rig tests cannot perfectly replicate the two-phase flow of the engine condition, they did permit an acceptable visualisation of spray structure to assist in filtering out injector designs that warranted further study. Such tests also highlighted improvements to the experiment and data analysis methods ahead of the expensive quantitative spray characterisation studies at elevated pressure conditions to minimise Φ_{Hybrid} in the UFR.

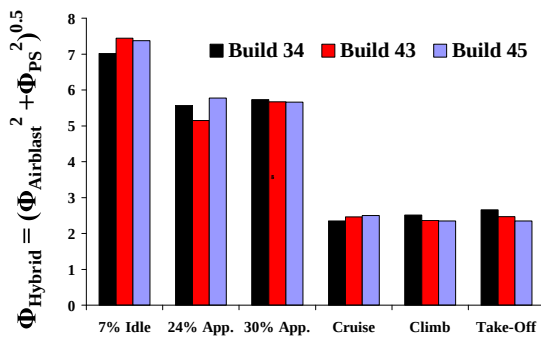


Figure 6.69: B34, 43, 45: $\Phi_{Hybrid}(\Phi_{AB}^2 + \Phi_{PS}^2)^{0.5}$

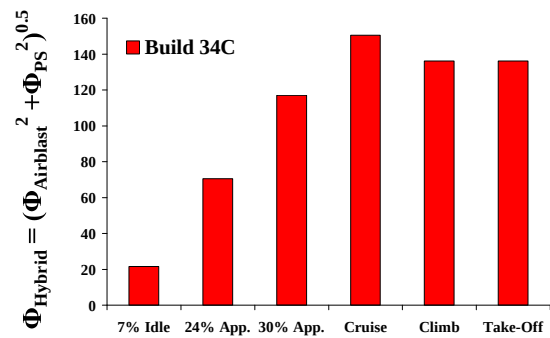


Figure 6.70: B34C: $\Phi_{Hybrid}(\Phi_{AB}^2 + \Phi_{PS}^2)^{0.5}$

6.5.4 Development of NO_x Prediction Tool

The NO formation model must capture the exponential dependence on flame temperature and near-linear relationship with residence time. An attempt to zone PLIF images into high, medium and low NO_x forming areas based on fuel concentration was unsuccessful. Three single pixel wide planes were examined in each image in the very near nozzle region, near nozzle region and further downstream regions. As expected, results did not agree with RR NO_x measurements for three reasons. First, the measurement regions were too small. Second, PLIF images were not flatfielded. Finally, Φ_{Hybrid} under atmospheric pressure conditions was significantly large. Instead, raw PLIF data was used to develop the image processing macros and spreadsheets that translated fuel placement data into two-dimensional maps of AFR. This procedure was applied to PLIF image data that was obtained at elevated pressures in the experiments described in Chapter Seven. The NO_x prediction method is outlined below.

The signal calibration work in Chapter Four used a PDA measurement and mean PLIF and LSD images to extract calibration constants for LSD (LSD_K) and LVF (LVF_K) for quantitative SMD and AFR measurements. LVF_K equates to the number of counts that correspond to a pixel filled 100% with fuel. LSD_K was subsequently used in Chapter Eight to calibrate images. LVF_K was used in Chapter Seven along with air and fuel densities to PLIF derived LVF images to yield quantitative two-dimensional maps of AFR and local equivalence ratio, ϕ . The commercial package GASEQ was used to calculate local adiabatic flame temperatures at constant pressure for a given ϕ range. Initial concentrations of N₂, O₂ and H₂O were recorded above 800K in 100K increments and the equation of the line from the plot of temperature versus ϕ was applied to each pixel in the ϕ image to calculate local adiabatic flame temperatures. The effective residence time for thermal NO formation was estimated with division of the spray length by global air velocity. Strictly, residence time is a linear ramp and sensitive to swirl. However, key combustor geometry information was not disclosed to forbid its accurate calculation. As fuel patternation is sensitive to swirl and the model was based on patternation, it implicitly considered swirl. Finally, HOMREA was used to calculate NO formation under constant pressure from the calculated temperatures and initial concentrations of N₂, O₂ and H₂O given by GASEQ. The equation of the line from the plot of temperature versus NO production was applied to the complete image of local adiabatic flame temperatures to give a map of NO formation. Summation of NO values in each pixel should therefore correspond with RR NO measurements but they will be out by a factor given the two-phase flow does not perfectly replicate the flow in an operating combustor; the full spray is not imaged; the combustor geometry is not exact and more fundamentally, the AFR under non-combusting conditions differs because a flame would form a substantial blockage to appreciably change the resultant flowfield.

6.6 SUMMARY

This chapter described the Main Sprays Rig (MSR) and experimental configuration for Laser Sheet Dropsizing (LSD) and Planar Laser Induced Fluorescence (PLIF) measurements to acquire Sauter Mean Diameter (SMD) and Air to Fuel Ratio (AFR) in full size aero engine fuel sprays. The RR “21 AFR injector” and ANTLE Weak Module Builds 34, 34C, 43 and 45 were characterised under non-combusting, isothermal, atmospheric pressure conditions using a semi-confined combustor geometry. The first measurement campaign measured the influence of several rig scaling strategies that effectively scaled the same engine condition on spray atomisation quality and structure. This helped select optimum rig scaling strategies to replicate spray properties of genuine practical interest to CFD modellers and to predict NO formation in Chapter Seven. Results confirmed that atomisation quality was sensitive to the choice of rig scaling strategy. This finding informed development of scaling laws for airblast sprays described in Jermy, Hussain and Greenhalgh (2004), hybrid sprays covered in Chapter Five and the selection of optimum strategies where rig pressure is a free parameter.

Because images were not calibrated or flatfielded the datasets were normalised and presented in arbitrary units. For each dataset the SMD and AFR were plotted in three radial planes perpendicular to the injector centreline in the very near (8.86mm), near (17.73mm), and further downstream (26.59mm) nozzle regions. Measurement of key spray properties in these regions can provide boundary conditions for CFD. Results allowed comparative analysis of spray structure as a function of injector design and rig operating conditions. Introduction of the main spray in hybrid injectors had significant aerodynamic impact on the pilot spray and obscured PLIF intensities in central regions. The extent of signal loss due to radiation trapping and aerodynamic influence of the main on the pilot should be measured to extract appropriate image correction factors. Attenuation-corrected AFR images showed each dataset yielded a similar fuel patternation that broadened as fuel flow rates increased. In pilot only cases, relative fuel momenta was larger than air momenta to yield a rich core, deep axial spray penetration and good spray symmetry. Swirl direction had substantial impact on spray structure and flame start position. It forced changes in flow velocities; occurrence of eddies; stability; mixture strength; cone angles; axial and radial penetration and asymmetry to possibly alter NO predictions in imaged regions. Further, the calculated fractional discrepancies could explain the differences between the measured and global AFR values. Qualitative measurements in this study showed promise in isolating injectors for quantitative study at higher pressures where the fractional discrepancies between engine and rig testing conditions theoretically reduces. Image data acquired in this chapter provided the necessary “grit for the mill” to test the NO_x prediction methodology and suggest several critical improvements to the entire data acquisition and image processing procedures.

CHAPTER SEVEN

ELEVATED PRESSURE EXPERIMENTS

7.1 INTRODUCTION

The backbone of this measurement campaign was application of Planar Induced Fluorescence (PLIF) to measure quantitative Air to Fuel Ratio (AFR) in fuel sprays from ANTLE Weak Module Builds 34, 43 and 61. Fuel concentration and placement as a function injector design and operating conditions was correlated with RR NO_x measurements. As NO increases exponentially with flame temperature, its generation is highly sensitive to local AFR. Therefore, the selected rig scaling strategy strived to replicate fuel patternation via conservation of the air to fuel momentum flux ratio and injector pressure drop ($\Delta P/P$). Seven sprays were characterised in Builds 34 and 61 and six in Build 43 within the Unsteady Flow Rig (UFR) under non-combusting, isothermal conditions at a constant $\Delta P/P$ of 4%, pressures of 200 – 490kPa, fuel flow rates of 0.42 – 0.90 l/m and injector AFRs of 28.4 – 72.3. To predict NO, each dataset was first averaged, background-subtracted, attenuation-corrected and flatfielded. Second, PLIF images were equated to local AFR and equivalence ratio. The commercial code GASEQ was used to calculate adiabatic flame temperatures under constant pressure. Third, spray length from spatial image resolution was divided by global air velocity to calculate species residence time. Fourth, HOMREA (Warnatz, 2002 and Bourgeois, 2003) used the temperature and residence time data to calculate NO formation. Finally, LabView fitted all the data and summed NO formation in each case for subsequent comparison against RR NO_x measurements.

LSD imaging of Build 61 fuel sprays indicated severe secondary atomisation in the extremely near nozzle region at the pilot only conditions. LSD was repeated alongside Phase Doppler Anemometry (PDA) measurements of droplet SMD along the spray centreline. LSD and PDA results agreed well in the extremely near nozzle region and an explanation for their deviation further downstream was put forth. LSD results validated the LSD calibration constant (LSD_K) derived in Chapter Four. More importantly, no step-change in SMD was found. However, the main spray was, however, clipped on each side of the pilot spray. Therefore, the camera field of view was increased by changing the optical set-up. Signal calibrations and flatfielding experiments described in Chapter Four were repeated for the PLIF only configuration to extract new image correction factors and revised LVF_K to calculate spray AFR. Extent of signal loss due to radiation trapping and aerodynamic influence of the main spray on the pilot was also measured but could not be corrected because this consisted of a combined structural and optical effect in the said region.

7.2 UNSTEADY FLOW RIG

Figure 7.1 shows a photograph of the UFR configured for point wise PDA and planar LSD and PLIF measurements. The UFR was finally commissioned in 2003 following extensive modifications by the author. It was used to operate full-size aero engine fuel injectors under non-combusting, isothermal conditions to a maximum pressure of 700kPa, temperature of 200°C and airflow of 2kg/s. Its design and manufacture was partly funded by the EU Framework 5 programme “Instability Control of Low Emission Aero-Engine Combustors” (ICLEAC) programme discussed in Chapter Eight. This investigated the spatial and temporal response of fuel sprays to acoustic forcing using a siren located upstream of the injector capable of modulating airflows up to a frequency of 500Hz. For the work reported in this Chapter, the siren assembly was removed to avoid wind-milling effects and inadvertent oscillations in the air inlet supply. The UFR pressure vessel is 0.7m in diameter and 2.5m long and has three steel sections. It had fittings for the instrumentation, air and fuel supplies set from a control room; airbox that acted as a plenum chamber to mount the fuel injector along its vertical axis; heated air-purged windows, moisture traps; traverse to raise/lower the airbox and exhaust to twin cyclones. Signal launch/collection optics were in fixed positions relative to the spray.

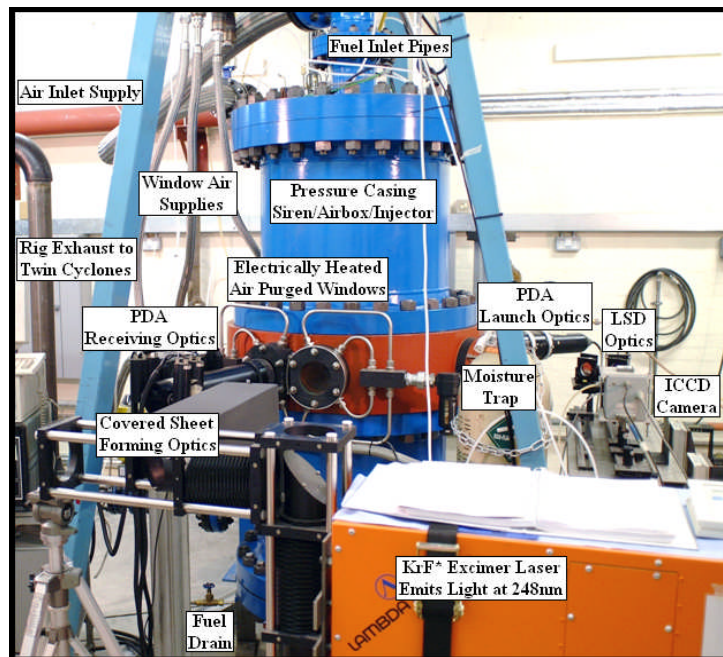


Figure 7.1: UFR Configured for PDA, LSD and PLIF Measurements

7.2.1 Air Supply

High-pressure air arrived from one of two industrial compressors via an external high-pressure line. The Ingersoll-Rand compressor supplied air up to a maximum pressure of 700kPa and cost £450/hour, whilst the Atlas-Copco compressor provided air up to 400kPa at £250/hour, in 2009 prices. Operation at 200 – 300kPa, however gives an

acceptable replication of key flow descriptors such as Re , We , Ma , Stk and p_D . The air supply entered the upper section via a control valve and vertical air inlet pipe into the airbox. Figure 7.2 shows a pressure gauge between the air isolation valve and UFR. Its reading ensured the air isolation valve was re-opened to the same position between 0° and 180° image datasets to unify standing waveforms in the air inlet supply. Ten minutes before air was admitted into the rig electric heater elements around launch and receiving windows were switched on to warm the glass to $\sim 30^\circ\text{C}$. This prevented condensation from residual moisture in the air supply line. Second, the main window air purge valve was closed to avoid fouling from contaminants in the air supply on internal window surfaces. Air was then admitted into the rig by opening pneumatic air control valves shown below in Figure 7.3 that adjusted two butterfly valves. These set P_{Gauge} ($P_{Absolute} - P_{Atmospheric}$) and the pressure difference between the rig and airbox (ΔP). Calibrated Druck PDCR 4000 series pressure transducers measured the pressure to an accuracy of $\pm 0.04\%$. After several minutes the main window air purge valve was opened and P_{Gauge} and ΔP were set to the required condition. All fuel flow was switched off before the air supply was turned off. Air valves were closed in the following sequence: window air purge; inlet air control; outlet air control and isolation. The spill valve was then opened and the industrial compressor switched off.



Figure 7.2: Pressure Gauge Upstream of UFR

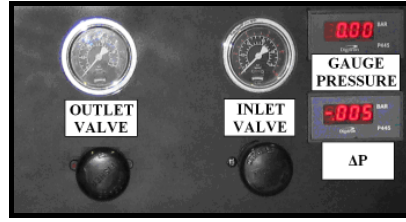


Figure 7.3: Inlet and Outlet Air Control Valves

7.2.2 Fuel Supply

Figure 7.4 shows main and pilot fuel tanks. Both were cleaned for PLIF measurements at 248nm as Exxsol D80 was now doped with 0.0118g/l of M-Terphenyl instead of 0.1125g/l of 2,5 Diphenyloxazole (PPO) used in the previous study at 308nm.

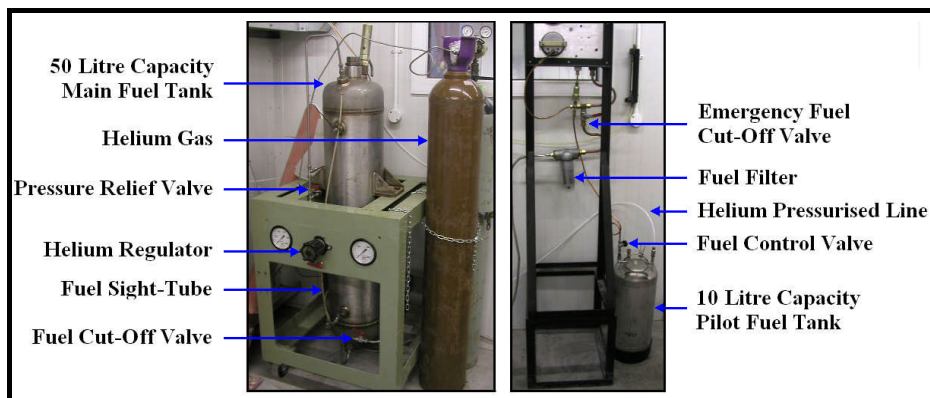


Figure 7.4: Main and Pilot Fuel Tanks

A fuel filter was also installed upstream and downstream of the UFR (RS-196-2707 filter and RS-196-2713 housing) and a helium butt pressure of 500 – 1500kPa was used to pressurise both tanks. The higher fuel pressure also stabilised the fuel flow rate that tended to fluctuate as fuel was consumed. Fuel supplies were calibrated by recording the time to collect one litre of fuel at various valve settings. Figure 7.5 and Figure 7.6 show calibration plots. Nylon pipes delivered fuel to the upper section of the UFR. This contained two braided flexible pipes to the airbox. Fuel was admitted once the fuel sight-tube nut was tightened, pressure relief valve closed and tanks pressurised. Pneumatic fuel control valves were switched on and rotameter valves were opened. To switch off the fuel all external valves were closed and pressure relief valve was opened.

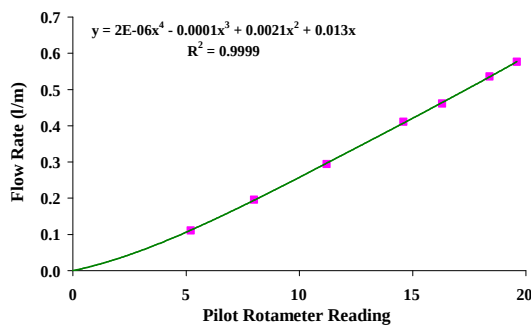


Figure 7.5: Pilot Fuel Flow Rate Calibration

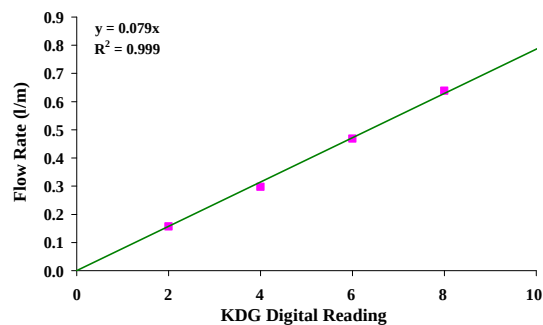


Figure 7.6: Main Fuel Flow Rate Calibration

7.2.3 Airbox

Figure 7.7 shows the cylindrical plenum type airbox in the separated UFR. This installed the fuel injector along its vertical axis and had fittings for a thermocouple, pressure transducer and fuel supplies. Internal fuel lines were leak-checked before the airbox was sealed and a second leak check was performed after installation in the UFR. Fake combustor walls featured slots for optical access through the injector centreline. However, there was insufficient clearance to raise the upper section over the mid section with the walls attached to the airbox. These were subsequently installed via one port window after the UFR was sealed. This port also gave access to the exterior handle on the airbox to rotate the injector through 180°. An adaptor piece between the air inlet and airbox was also manufactured to locate the spray in the correct field of view.

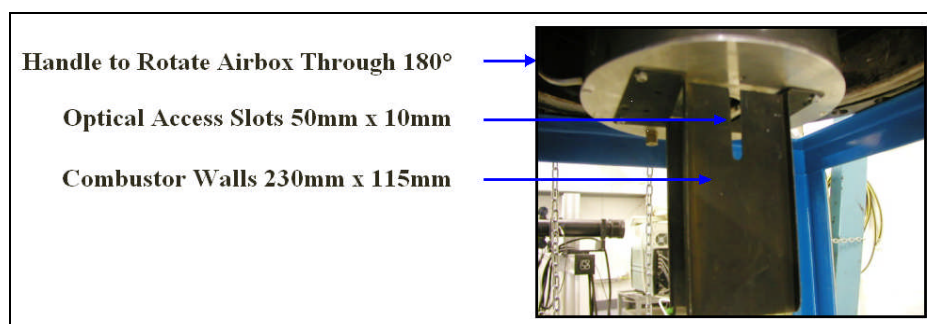


Figure 7.7: Airbox Installed in UFR

7.2.4 Windows

Ports were strategically located in the UFR mid-section to facilitate point-wise or planar measurements. Figure 7.8 shows the laser launch optics window. Window design was essentially as described in Section 6.2.3 but was modified to include a moisture trap and prevent fogging. The exit diameter of the internal cone was also increased from 55 to 120mm to improve the camera field of view. The left hand edge of the launch optics window and right hand side of the adjacent window used by PDA receiving optics were machined to give clearance for the air purge pipe work and a clear optical line of sight.

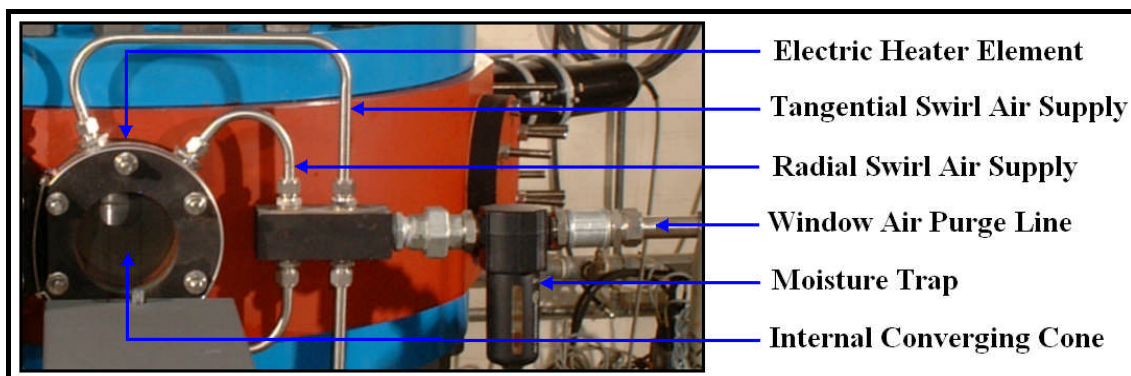


Figure 7.8: UFR Window Design

7.2.5 General Schematic of UFR Sprays Testing Facility

Figure 7.9 shows a general schematic of the UFR sprays testing facility. It depicts the traverse; siren; airbox/fuel injector; laser and camera access windows; rig air and fuel supplies; all control valves; pressure instrumentation and twin cyclone exhaust system.

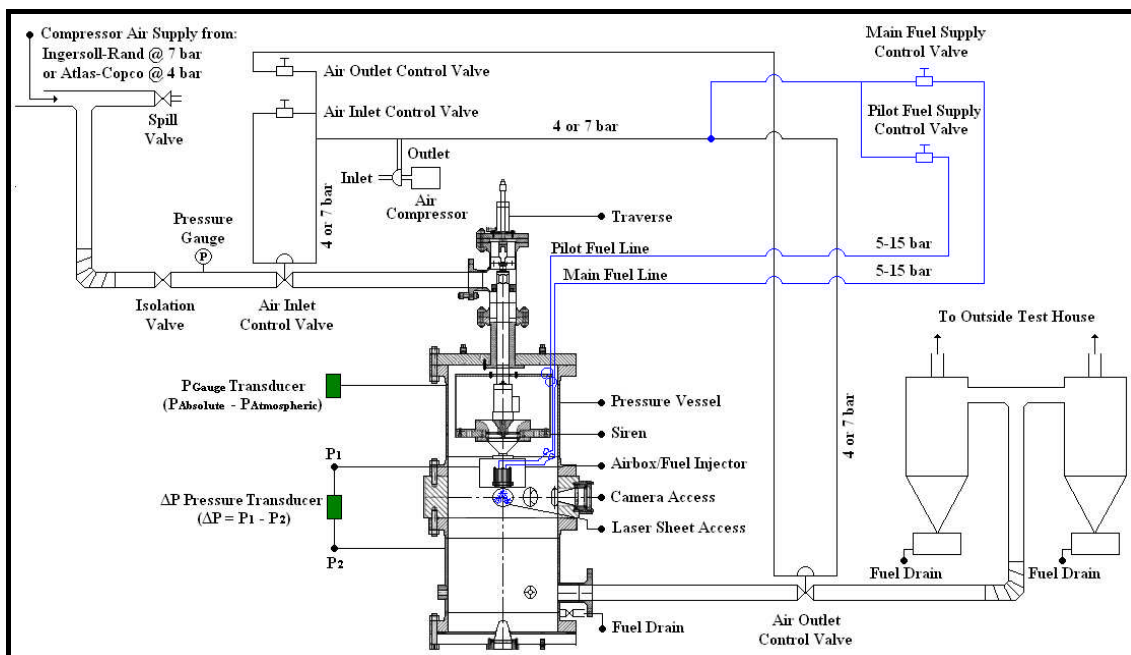


Figure 7.9: General Schematic of UFR Sprays Testing Facility

7.3 LSD AND PLIF EXPERIMENTAL CONFIGURATIONS

Figure 7.10 shows the experimental configuration for LSD and PLIF measurements. This shows the UFR; excimer laser; sheet forming optics; instrumentation to synchronise the laser pulse with the camera shutter; LSD and PLIF signal collection optics and ICCD camera. Appendix G gives the sprays imaging checklist for the UFR and Appendix H shows the scaled UFR operating conditions for the investigated builds. In brief, a Krypton Fluoride (KrF*) Lambda Physik CompEx 110 Excimer Laser provided light at 248nm and pulse energy of 100mJ. Two cylindrical lenses of -75mm and 150mm focal lengths and spherical lens of 1m focal length formed a thin collimated light sheet through the injector centreline that measured $\sim 0.8 \times \sim 42\text{mm}$. Fluorescence was detected by the ICCD camera from M-Terphenyl dissolved in Exxsol 80. LSD results for Build 61 showed severe secondary atomisation at pilot only conditions and clipping of the main spray on each side of the central pressure-swirl spray. LSD was repeated in addition to PDA measurements of droplet SMD along the spray centreline before removing LSD imaging optics and installing a high aperture Nikon 50mm lens at $f/1.2$ for a PLIF only study on Builds 34, 43 and 61. Figure 7.11 and Figure 7.12 show both set-ups. The LSD four-mirror arrangement was described in Section 6.3.3 on page 123, except the Mie path now had a $248\text{nm} \pm 5\text{nm}$ interference bandpass filter.

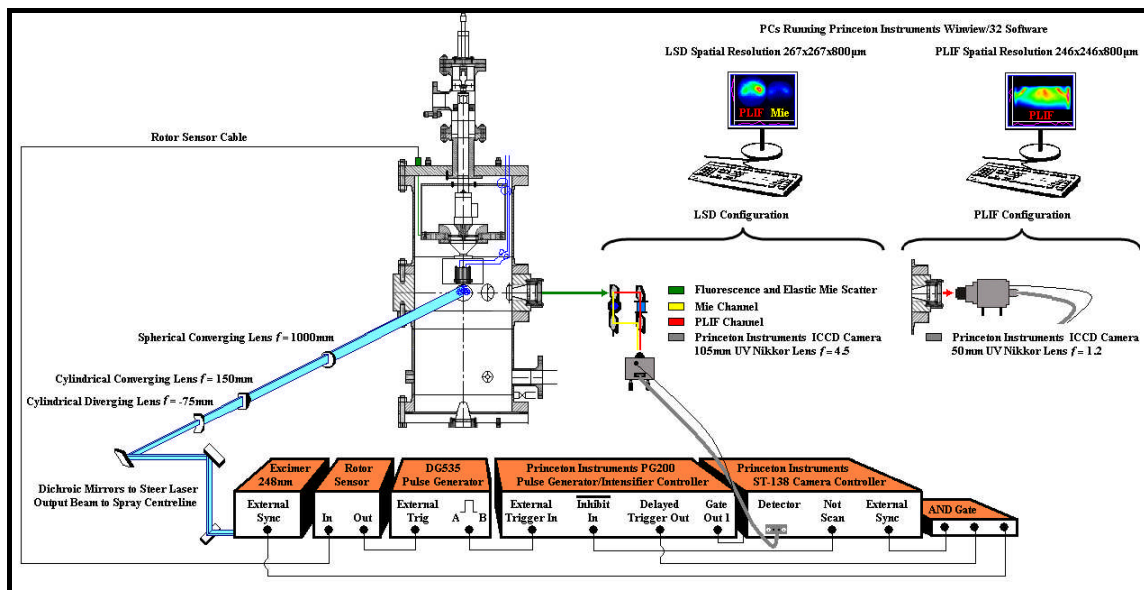


Figure 7.10: General Schematic of LSD and PLIF Spray Measurements in the UFR

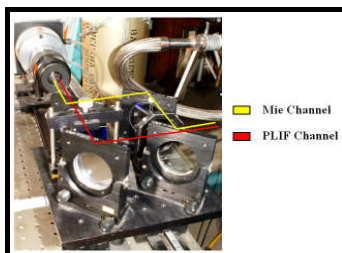


Figure 7.11: LSD Set-up

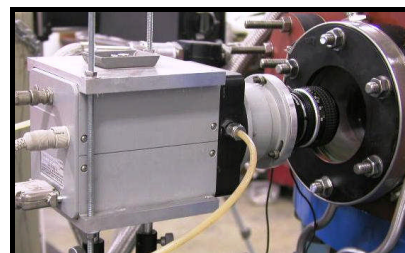


Figure 7.12: PLIF Set-up

7.3.1 Instrument Synchronisation

Figure 7.13 shows instrumentation timing sequences for LSD and PLIF measurements. The rotor sensor instigated all electronics and triggered the DG535 pulse generator when holes in the rotor and stator were in coincidence. The DG535 was manually programmed depending on the phase angle under measurement to delay the pulse that triggered the camera to acquire an image and for the laser to fire. No delay was set for the static work reported in this chapter and the PG200 triggered the intensifier and laser when the camera was ready to acquire an image. The DG535 triggered the PG200 pulse generator and intensifier controller that monitored the ST-138 camera controller via 'Inhibit In' from 'Not Scan'. The PG200 also sent a delayed pulse to the laser via 'Delayed Trigger Out' at a delay of 201ns set by 'Gate Delay' to ensure it operated when the logical AND operation was true and the camera shutter was open. The camera had an exposure time of 3 μ s to bracket the 25ns laser pulse. When the camera shutter closed, 'Not Scan' went high until the camera loaded the acquired image from the chip to the camera controller and transferred it via a serial cable to a PC that ran Princeton Instruments WinView/32 Software. The laser repetition rate was $\sim$ 2Hz. The camera then cleaned the chip and set 'Not Scan' to low indicating its readiness to acquire another image. The timing was iteratively optimised to bracket the laser sheet with incremental reductions in the 'Gate Delay' and increases in 'Gate Width'. The PG200 intensifier operated at 700V. For both LSD and PLIF set-ups the PG200 had a Gate Delay of 201ns; Gate Width of 3 μ s; Trig Level of 3.10 and Delayed Trig of 267ns.

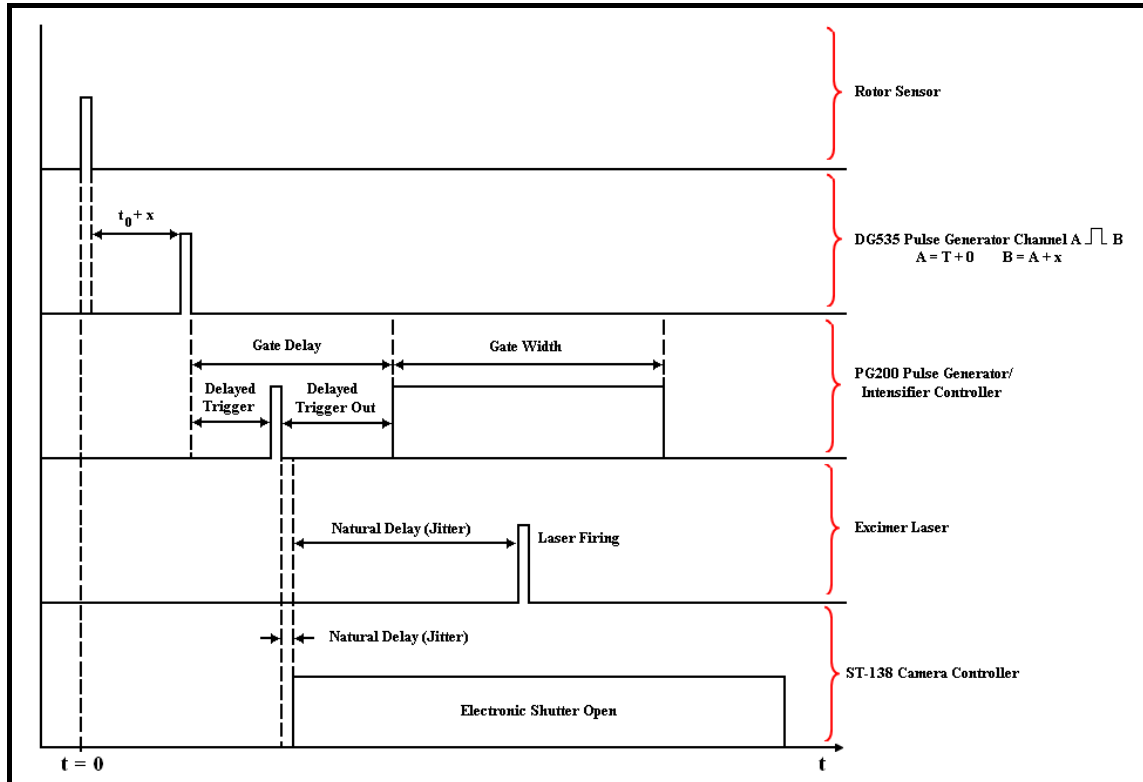


Figure 7.13: UFR Instrumentation Timing for PLIF and LSD Measurements

7.3.2 LSD and PLIF Signal Calibration

Chapter Four discussed the LSD and PLIF signal calibration method for quantitative SMD and AFR fuel spray measurements. This selected the fuel fluorophor for PLIF at 248nm; discussed laser sheet alignment and sheet thickness measurement; calculation of the ICCD array pixel resolution and PLIF and Mie image manipulation factors to divide corresponding PLIF and Mie pixels in LSD processing. The central portion applied acetone fluorescence imaging to define the laser sheet region and measure variations in laser sheet intensity and ICCD intensifier pixel response. The final stage extracted LSD and PLIF calibration constants using a piezoelectric droplet generator and PDA in combination with planar LSD imaging or PLIF imaging depending on the optical set-up.

7.4 CHARACTERISATION OF BUILD 61 FUEL SPRAYS

This section first describes LSD measurements of qualitative AFR and droplet SMD at six simulated engine operating conditions in Build 61 fuel sprays. Rig fuel and air flow conditions were scaled from the RR 5 Cell scaled conditions given in Appendix C to the cold flow conditions described in Appendix H by matching the air to fuel momentum flux ratio and injector pressure drop ($\Delta P/P$). This first dataset consisted of 100 images acquired at 0° and then 180° with the injector rotated about its centreline. Images were averaged, background-subtracted and corrected for the effects of laser attenuation through the spray. Results indicated severe secondary atomisation in the pilot only conditions and clipping of the main spray on each side of the pilot spray.

Several improvements to the experimental configuration took place before double-checking the major step change in SMD and changing the optical set-up to increase the camera field of view. First, the laser was serviced to fix an unstable energy output that fluctuated from 83 – 96mJ instead of a fixed 100mJ. Second, all optics were cleaned and realigned. Third, all image manipulation factors were recalculated. Fourth, an acetone fluorescence flatfielding experiment was conducted simply to define the laser sheet region as LSD does not strictly require PLIF images to be corrected. Fifth, an extensive LSD signal calibration study was undertaken. Sixth, a beam-dump was installed to minimise spurious light scatter from shiny surfaces as the prospect of reflections increased after paint was stripped from inner UFR surfaces to prevent contamination of fuel and filtration systems. Finally, LSD was repeated at the pilot only condition but this time 1,000 PLIF and Mie image pairs were acquired in each 0° and 180° dataset. In addition, PDA was applied to measure the droplet SMD along the injector centreline. Although secondary atomisation did not prove to be an authentic feature of the spray, its possibility led to key improvements and diversion from LSD measurements towards the PLIF only measurements for injector Builds 34, 43 and 61.

7.4.1 Preliminary LSD Results and Discussion

Figure 7.14 shows SMD and AFR results on a false colour scale. LSD images measured 192×212 pixels and correspond to a spray size of 51.26×56.6 mm. AFR images were 273×275 pixels and correlated to a spray size of 72.9×73.4 mm. Observations showed an abrupt change in droplet SMD values over distance in the extremely near nozzle region. In mixed cases, PLIF intensities were much lower than Mie intensities and only the 30% Approach case yielded an LSD image. AFR images showed a rich central region in the pressure-swirl spray that subsequently leaned out as the main fuel flow was introduced. Both LSD and AFR images showed a clear absence of the main spray. Before resolving this issue, the SMD jump was investigated by repeating the LSD study that was further reinforced by a swift PDA measurement campaign along the fuel spray centreline.

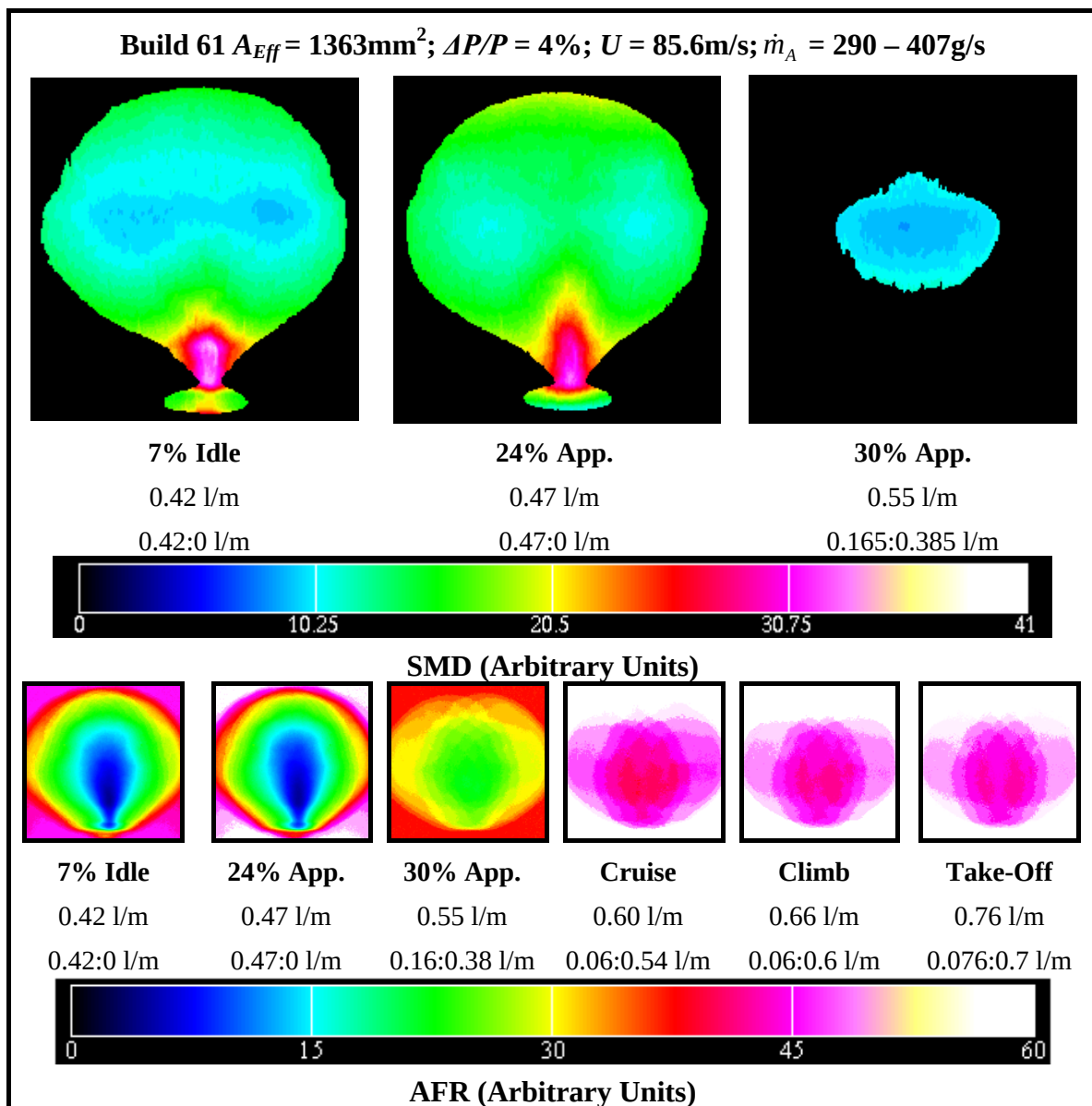


Figure 7.14: Preliminary SMD and AFR Results for B61

7.4.2 PDA Measurements and Repeat LSD Results and Discussion

Following the extensive LSD and PLIF signal calibration work reported in Chapter Four and improvements to the experimental method, LSD was repeated at pilot only conditions to determine if the first LSD dataset that suggested severe secondary atomisation was actually genuine. PDA measurements of droplet SMD were taken after each LSD measurement with the laser switched off. Droplet SMD was measured along the injector centreline in the extremely near nozzle region, 2mm from the injector exit and then in five 10mm increments thereafter. Chapter Three previously discussed PDA and its limitations and Section 4.4.2 on page 75 showed the PDA arrangement in the UFR. In this study, PDA was configured to measure droplet velocity and diameter in one-dimensional mode. Light at 514.5nm was provided by a Coherent Innova 70 5-watt Argon-Ion laser. This entered a Bragg cell to produce frequency-shifted beams that travelled into a Galilean telescope in the PDA launch optics that created an interference fringe pattern and measurement volume where droplets travel through. This was at the same location as the planar laser sheet. PDA receiving optics collected intensity modulated light from droplet refraction at 30° to the measurement volume. 1,000 PLIF and Mie images were acquired at 0° and 180°. Averaging removed cycle-to-cycle fluctuations towards the natural stability of the spray. Unless really wild features in the time spectrum existed any fluctuations above 0.2% were typically intrinsic to systematic variation with phase as opposed to the turbulence effect. The PDA data had a sample size of 200,000 validated droplets. Arguably, this combined level of LSD and PDA precision is uncommon but was deemed necessary to verify the observed step-change in SMD. Overleaf, Figure 7.16 shows LSD image processing for the 24% Approach case and includes the 7% Idle result. LSD images were averaged; background subtracted; attenuation corrected; calibrated to yield quantitative SMD and the acetone fluorescence image was used to mask weakly illuminated areas outside the laser sheet from particles inside the laser sheet. The final SMD image measured 41 x 120 pixels, equivalent to a spray size of 10.9 x 32mm. Figure 7.15 plots LSD and PDA results and shows the expected decline in droplet SMD over distance to rule out severe secondary atomisation.

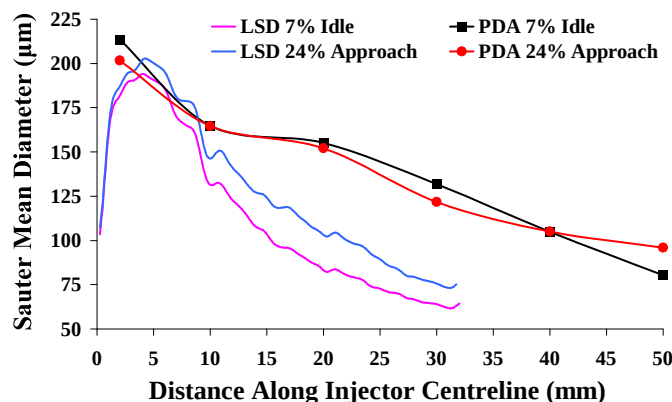


Figure 7.15: Plot Comparing LSD and PDA Results

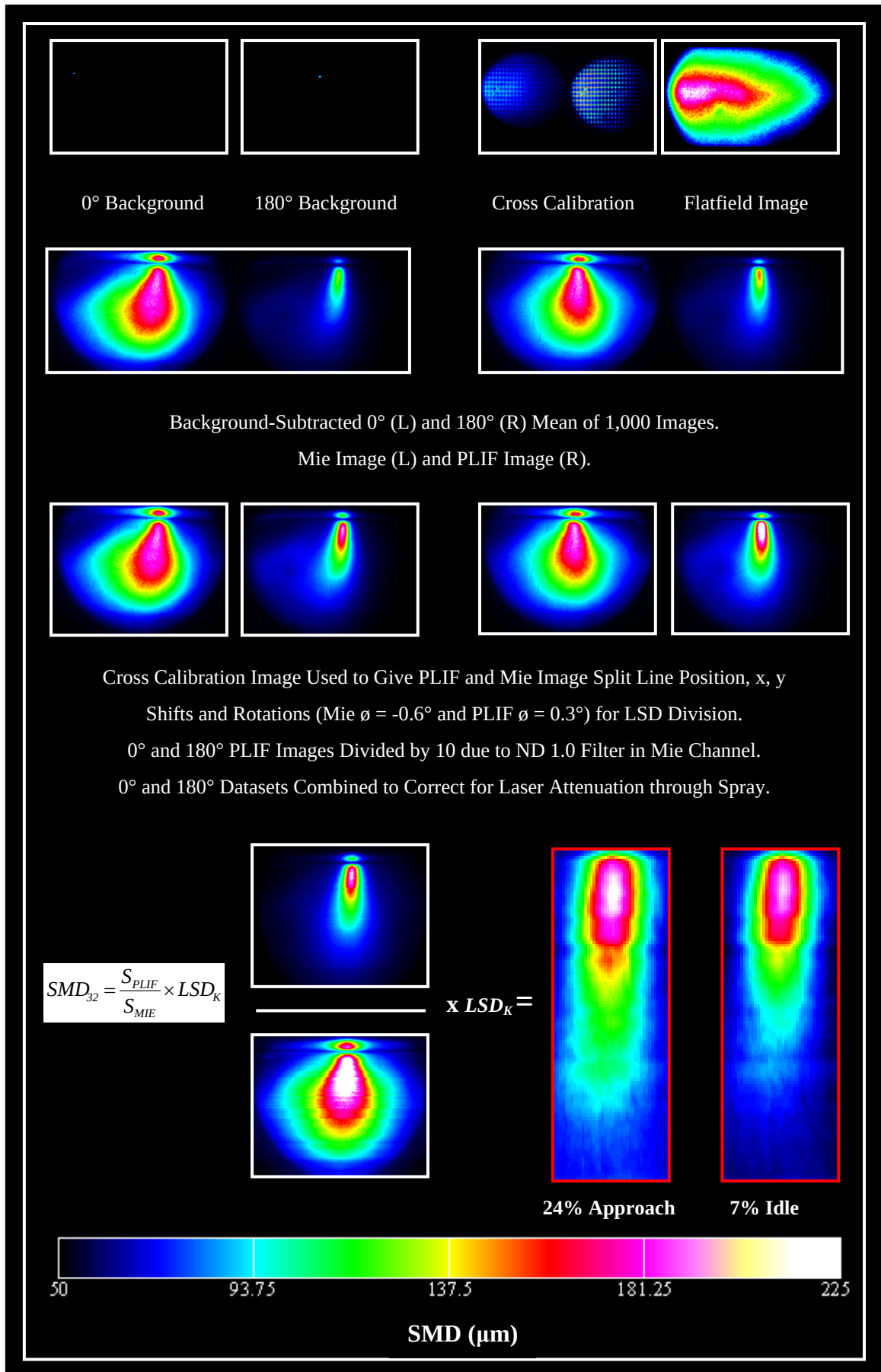


Figure 7.16: LSD Image Processing Routine for B61

Although PDA confirmed the absence of secondary atomisation its use is costly and complex (Greenhalgh, 1999) and it encounters problems in dense sprays due to multiple droplet occupancy in the measurement volume and beam attenuation (Zimmer *et al*, 2002). In the extremely near nozzle region there was very little spray to attenuate the beam outside the measurement volume. Therefore, PDA made a more representative measurement at this location. However, at this juncture the spray was not fully developed and the droplet size distribution was quite broad as depicted overleaf in each probability density functions (pdf) for the 24% Approach case shown in Figure 7.17 to Figure 7.22 . Appendix I shows pdfs for the 7% Idle case. LSD was less sensitive to multiple scattering caused by the spray cloud between the imaged area and ICCD camera. For this reason, both PDA and LSD measurements agreed in the extremely near nozzle region as shown earlier by the plot in Figure 7.15 to validate the LSD_K value derived in Chapter Four. It is worth noting that in a practical combustor the spray cloud would not exist in the same manner since it would combust. Beyond a downstream distance of $\sim 10\text{mm}$ the PDA measurement volume was surrounded by the spray mist to attenuate the beam. PDA uncertainties invariably increased above the prescribed 9% of Pierson *et al* (2000) and 11.2% of Kershaw (2007) to $\sim 40\%$. Overleaf, Figure 7.17 to Figure 7.22 show pdfs for $X = 2$ to 50mm downstream. Broad droplet size distributions typified the preferential rejection of weak signals from smaller droplets and the fact that few droplets actually exist in the hollow cone of a pressure-swirl spray.

LSD ratioed PLIF and Mie intensities to cancel most disparities in the laser sheet intensity distribution and intensifier pixel response. Therefore, LSD coped better in denser sprays over PDA measurements of phase difference modulation. LSD was also less hampered by probe attenuation and multiple scattering than PDA as it used a more powerful pulsed laser in comparison to the continuous wave type in PDA. In addition, as LSD did not resolve individual droplets but instead ratioed PLIF and Mie signals it beneficially registered the weaker intensities from smaller droplets. LSD also accounted for spray asymmetry whereas PDA did not. Finally, LSD gave better spatial resolution. In this study it was $267\mu\text{m}$ versus 1mm for PDA. LSD, however, relied on a Mie signal squared dependency with droplet diameter. Domann and Hardalupas (2002) modelled the LSD signal and reported that uncertainties increased from 4 to 31% as droplet diameters declined from $150 - 10\mu\text{m}$. This is important considering that SMDs under $70\mu\text{m}$ are considered to be necessary for good fuel and air mixing and low emissions performance. In experiments, Réveillé (2005) showed that LSD results deviated by $\sim 25\%$ over PDA and both effects were in evidence here $\sim 10\text{mm}$ downstream of the injector exit as the droplet diameters steadily declined. However, the measured differences were more probably due to PDA beam attenuation and not to the disrespected Mie squared dependence with droplet diameter as the calibration in Chapter Four was based on droplet SMD values of $\sim 90\mu\text{m}$ in the absence of PDA beam

attenuation. Therefore, in this particular set-up the LSD results were more credible than PDA measurements.

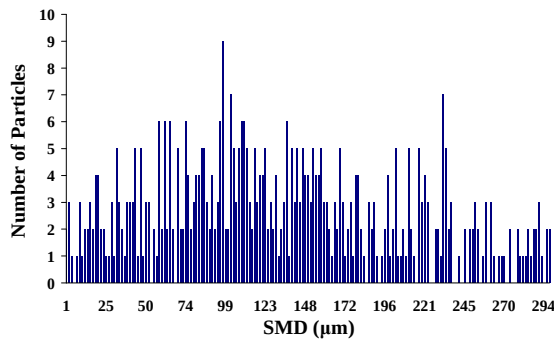


Figure 7.17: 24% Approach, $X = 2\text{mm}$

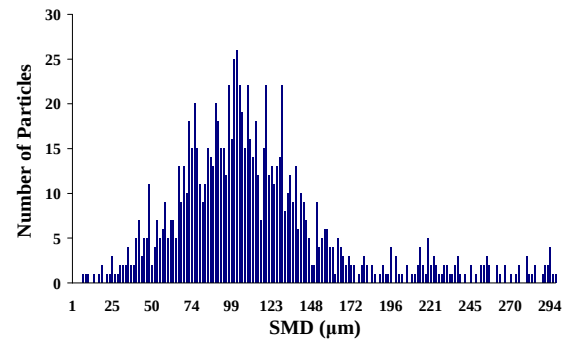


Figure 7.18: 24% Approach, $X = 10\text{mm}$

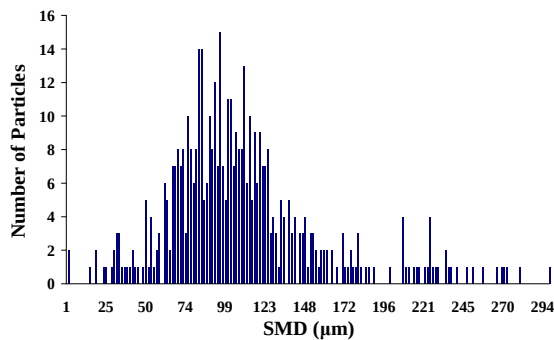


Figure 7.19: 24% Approach, $X = 20\text{mm}$

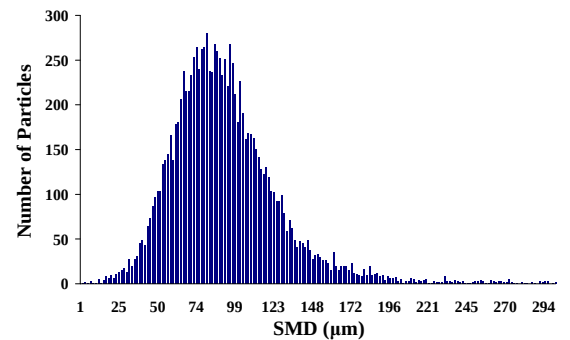


Figure 7.20: 24% Approach, $X = 30\text{mm}$

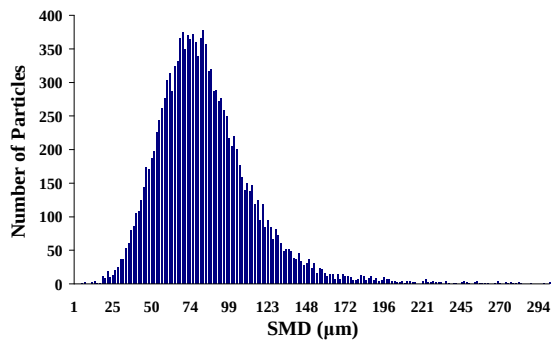


Figure 7.21: 24% Approach, $X = 40\text{mm}$

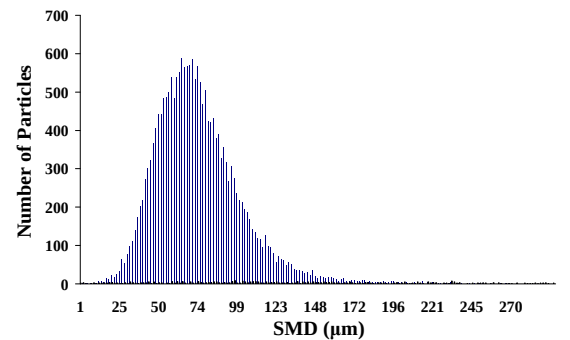


Figure 7.22: 24% Approach, $X = 50\text{mm}$

7.5 PLIF FUEL SPRAY MEASUREMENTS TO PREDICT NO_x

This section describes PLIF fuel spray measurements in the UFR and image processing macros to yield quantitative AFR. This drew on the previous work on signal calibration, rig scaling strategies and attempts to correlate spray quality with NO. A comparison was made between the predicted and actual RR NO_x measurements. As the AFR results were obtained under low-pressure, cold flow conditions over a small section of the combustor the model was unable to predict absolute NO_x values; rather it

predicted the overall trends and was therefore a partial success. Replication of fuel patternation was essential to predict NO. NO formation is highly sensitive to combustor temperature that depends on the degree of fuel and air mixing (Fletcher and Heywood, 1971). In atmospheric pressure experiments using methane Fric (1992) reported that spatial and temporal variations in fuel and air unmixedness increased NO_x. Therefore, this study conserved air to fuel momentum flux ratio and $\Delta P/P$ to yield similar spray cone angles and fuel patternation as in engine conditions. As combustor geometry, nor volume was disclosed, the residence times were calculated for each condition at no detriment to the NO prediction methodology that sought to blend experiments with theory to predict NO emissions at ~4% of the usual full-scale engine testing costs.

7.5.1 PLIF Measurements

Upon conclusion of the ICLEAC study reported in Chapter Eight, the LSD four-mirror arrangement was removed and a PLIF only measurement campaign ensued to extract AFR data in fuel sprays at simulated engine conditions of 7% Idle, 24% Approach, 30% Approach, Cruise, Climb and Take-Off. Appendix C gives RR scaled 5 Cell conditions and Appendix H shows UFR operating conditions. The Ingersoll-Rand compressor provided high-pressure air for the 7% Idle Engine condition in Builds 34 and 61. A Lambda Physik CompEx 110 excimer laser provided light at a wavelength of 248nm and pulse energy of 100mJ. Two cylindrical lenses and one spherical lens were used to make a thin laser sheet 0.8mm wide and 42mm tall. This travelled vertically through combustor wall slots and spray centreline into the beam-dump. Fluorescence from M-Terphenyl dissolved in Exxsol D80 was imaged onto a Princeton Instruments ICCD camera located in front of the rig access window as shown earlier in Figure 7.12 on page 155 to increase its field of view and image the complete spray. This used a Nikon 50mm lens at $f/1.2$. Closer proximity to the spray region increased spatial resolution by 7.5% to 246 μ m over the LSD set-up. Intensifier gain was thus reduced from 70 to 60 to limit “blooming” that can occur when charge from one pixel spills into adjacent pixels (Princeton Instruments, 1999). The signal calibration procedure considered blooming and included all pixels registering an intensity to extract LSD_K and LVF_K . The larger aperture lens however visualised rays that had converged and diverged to increase multiple scattering by ~5%. The camera was electronically synchronised to collect fluorescence for 25ns around the laser sheet pulse. 1500 instantaneous snapshots of fuel distribution were acquired at each operating condition: 750 with the light sheet propagating in one direction and another 750 from the opposite direction. The airbox was manually rotated through 180° via the UFR access port. PLIF images were background-subtracted, attenuation-corrected and flatfielded. Fluorescence was proportional to the LVF . Application of air and fuel densities and LVF_K converted LVF images into two-dimensional maps of AFR and was the beginning of the NO prediction.

7.5.2 Image Processing and Results

PLIF image processing routines and macros were successfully developed, tested and debugged with qualitative data from atmospheric pressure measurements. These extracted quantitative AFR in six stages. First, 0° and 180° datasets were averaged. Second, applicable backgrounds acquired by imaging the airbox with the fuel off were subtracted to remove false intensity contributions from dark current build-up on the camera chip and surface reflections from the pipe work, airbox, injector, combustor walls and fuel. The 0° and 180° background intensities were found to vary between 50 – 150% to make background acquisition and subtraction fundamental for the low fuel flow rates in this study. However, the actual background may also vary because the spray itself is a source of illumination to imply that background removal with the spray off introduces a potential source of error. It is advisable to subtract a background at low fuel flow rates as the light scattered by the spray itself to the background structures is considerably less than at the higher fuel flow rates. Third, 0° and 180° background-subtracted images were divided by the normalised acetone fluorescence image obtained from the experiment described in Section 4.3.3 on page 71. This action compensated for non-uniformities in the ICCD pixel response and laser sheet intensity distribution normal to the light sheet to give a *LVF* image. Fourth, regions outside the laser sheet and combustor walls were masked. Fifth, the LVF_K value from Chapter Four was applied with fuel and rig air densities of the given rig operating condition to transform 0° and 180° background subtracted; flatfielded *LVF* images into AFR. Spray structure contributed to measured variations in PLIF intensity for equivalent fuel concentrations to camouflage actual spray symmetry. Therefore, the sixth and final macro combined 0° and 180° images to correct for laser attenuation through the spray with the method of Talley *et al* (1996). The 180° mean image was horizontally mirrored and aligned with the 0° mean image. Both images were multiplied and the square root taken. As light travelled parallel to horizontal rows, each row was scaled to match the intensity on the unattenuated edge of each image. Scaling factors were chosen to limit streakiness by firstly taking the mean of four pixel rows and secondly by using a row-wise smoothing function. Both absorption and multiple scattering between the imaged plane and ICCD camera can reduce PLIF intensities. The latter can be corrected to some extent with the recently developed reverse Monte Carlo code of Berrocal (2006). The third source of error identified by Talley *et al* from particles outside the laser sheet was addressed by the flatfield image. Figure 7.23 overleaf summarises image processing in the Build 61, 0°, Take-Off dataset and Eq. 7.1 shown below defines the corrected PLIF image.

$$S_{PLIF_{Corrected}}(x,y) = \frac{S_{PLIF_{Mean}}(x,y) - B_{PLIF}(x,y)}{S_{Flatfield_{Mean}}(x,y) - B_{Flatfield}(x,y)} \quad \text{Eq. 7.1}$$

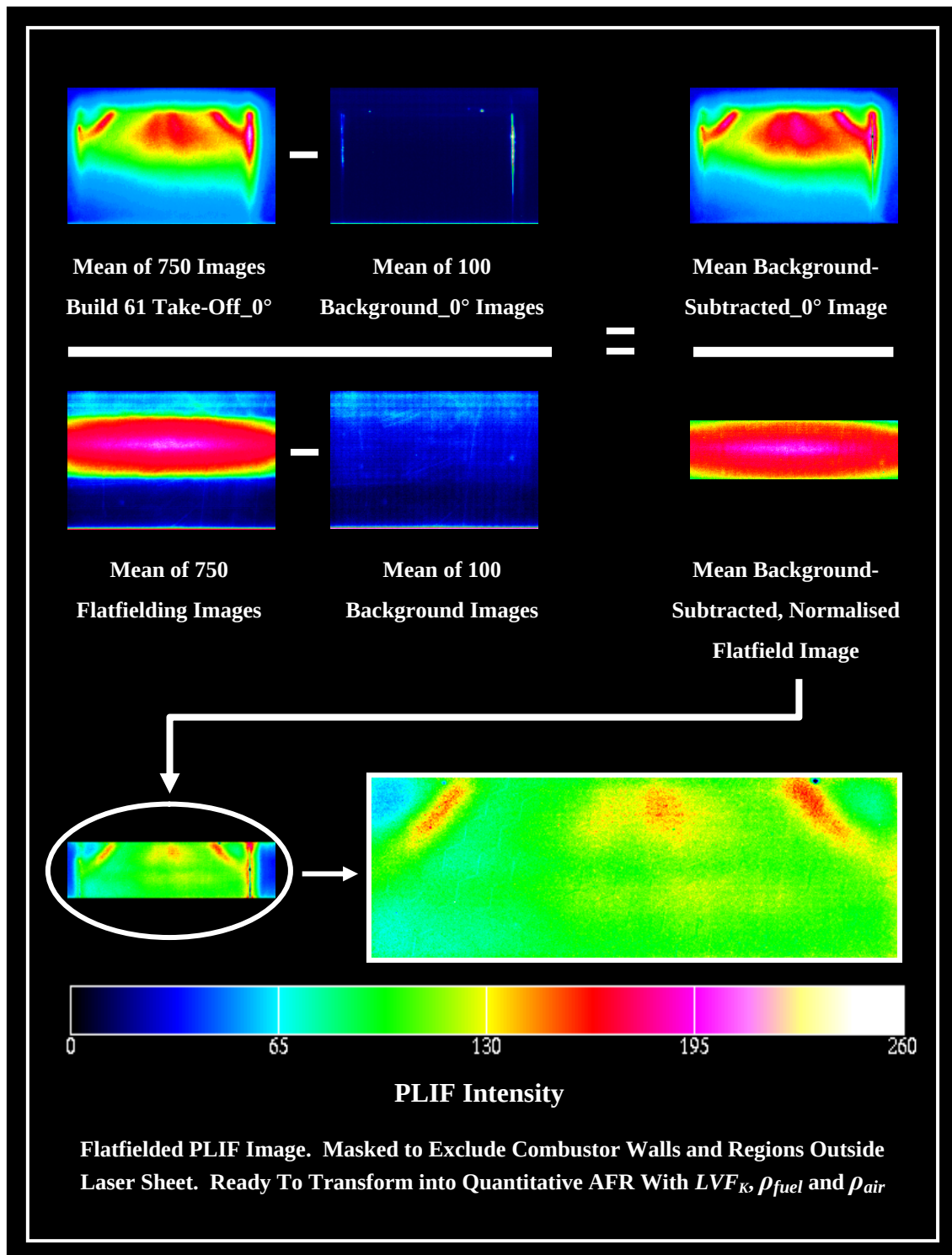


Figure 7.23: PLIF Image Processing in Build 61: 0° Take-Off Dataset

Figure 7.24 and Figure 7.25 on pages 160 and 167 show PLIF and quantitative AFR results for all sprays. Spray direction was downwards. Images measured 432 x 154 pixels to give a size of 106.7 x 38.3mm. UFR operating conditions are shown below each image. Air mass flow rate, $\dot{m}_A$ was varied in each build to retain $\Delta P/P$ at 4%. In Build 43, 34 and 61 it was 200 – 300g/s, 212 – 298g/s and 222 – 319g/s, respectively. In the 7% Idle Engine cases for Builds 34 and 61, $\dot{m}_A$ was 654g/s and 490 g/s. U was constant for all cases at 85.6m/s.

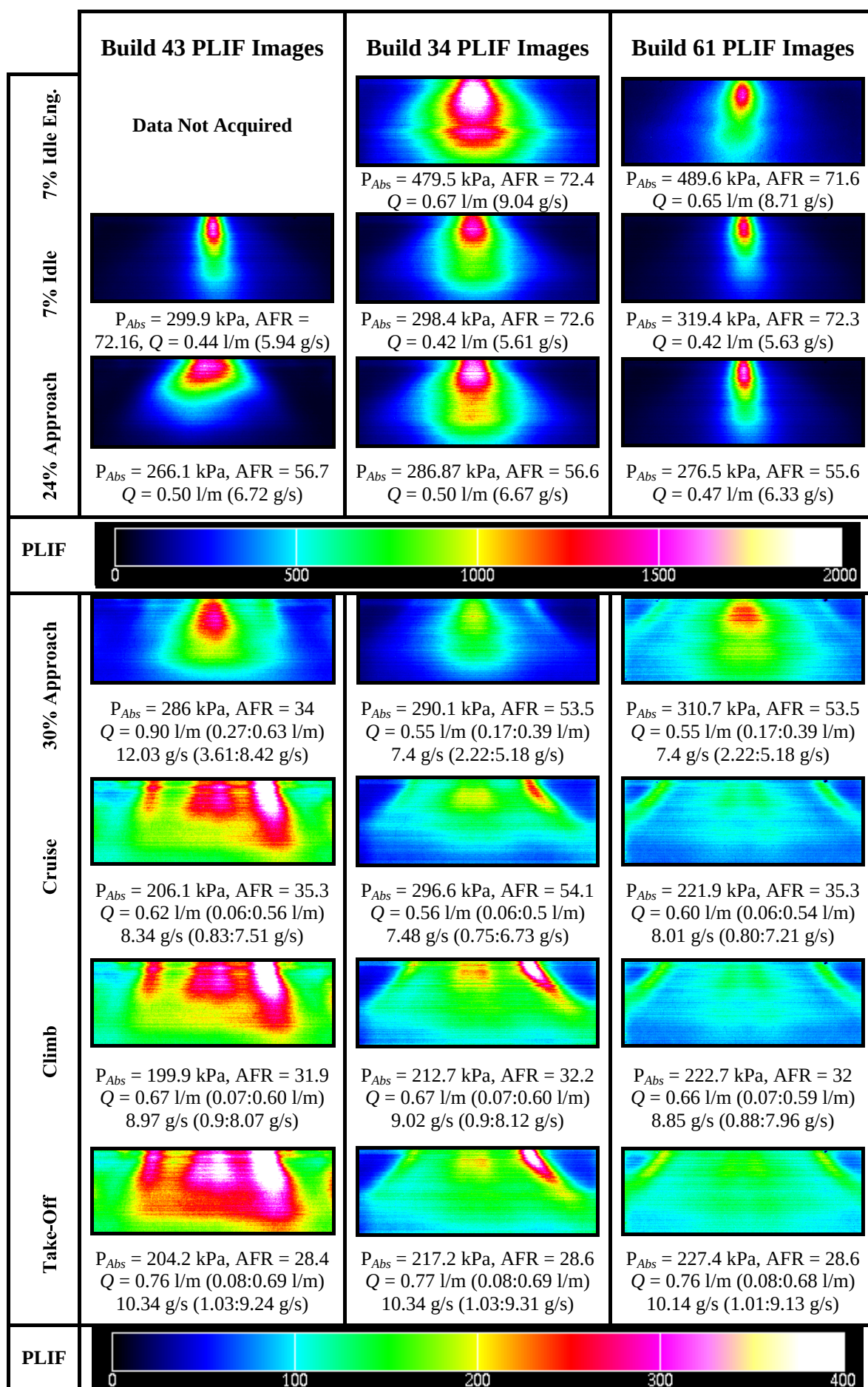


Figure 7.24: Processed PLIF Images for B43, 34 and 61

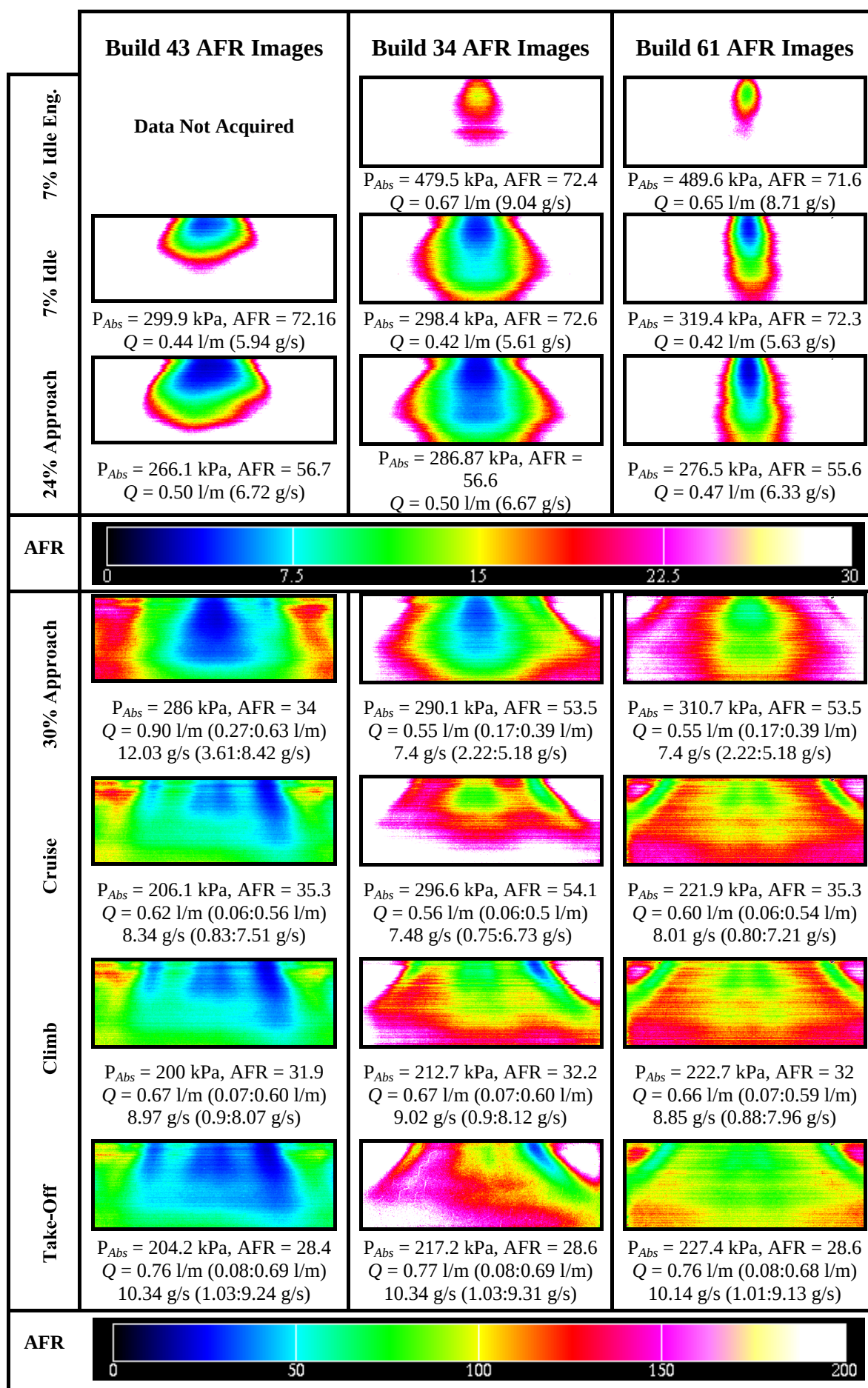


Figure 7.25: Quantitative AFR Results for B43, 34 and 61

Observations showed Builds 34 and 61 had similar cone angles and fuel patterning. Spray asymmetry in Build 34 and narrow cone angle in Build 43 resurfaced at the elevated pressure conditions to concur with the results from atmospheric pressure measurements described earlier in Chapter Six. The aerodynamic effect of the main on the pilot, however, persisted and the resultant signal loss was therefore measured before further progress was made to predict NO from acquired PLIF images of fuel placement.

7.5.3 Measurement of Signal Loss Due to Radiation Trapping

The pilot fuel spray was shrouded by the main spray at engine conditions of 30% Approach, Cruise, Climb and Take-Off. Consequently, PLIF intensities in the pilot region were reduced as the main fuel flow rate was increased. Signal loss in the pilot region was due to “radiation trapping”, more commonly known as “multiple scattering”. Black *et al* (1996) defined a scattering event as the interaction of a light ray with a particle. If a photon is scattered several times it carries information about more than one droplet and blurs the final image. Multiple scattering therefore increases in dense sprays. Farrugia (1995) investigated radiation trapping using the flame from a Bunsen burner. This was placed behind a wind tunnel and imaged. The wind tunnel was then filled with a stoichiometric flame and the Bunsen flame was re-imaged. The mean signal loss due to radiation trapping by the flame in the wind tunnel was calculated several times for different image pairs and a signal loss with a mean of 4.8%, rms 1% was measured. A correction for radiation trapping was not applied because the structure of the signal loss in the individual images was unknown. Jermy *et al* (2004) simulated multiple scattering in a gas turbine fuel spray and concluded that 3% of photons were singly scattered and that on average a photon was scattered seven times to bring errors in the final *LVF* map. The loss of spatial structure was ~6% but was corrected because the degree of signal loss across the complete structure of the fuel spray was known.

In this study the main spray was measured to have a structural and also a significant optical impact on the pilot spray. Fuel bounced off the combustor sidewalls into the pilot zone and dissipated energy into the pilot spray to increase the internal recirculation rates and reduce the measured PLIF intensities. The degree of signal loss was successfully measured by acquiring the mean of 100 shots in the pilot only region, pre and post introduction of the main. Figure 7.26, Figure 7.27 and Figure 7.28 on pages 169, 170 and 171 considered the four mixed cases in Builds 43, 34 and 61. All images were background-subtracted and flatfielded. Three PLIF images are shown for each case. In each row the first image shows pilot only operation. Second and third images show the effect on the pilot region as a consequence of introducing the main fuel supply to the airblast atomiser circuit. The main plus pilot images were acquired at 0° and 180°. Fuel flow rates are shown under each image. Spray direction was downwards.

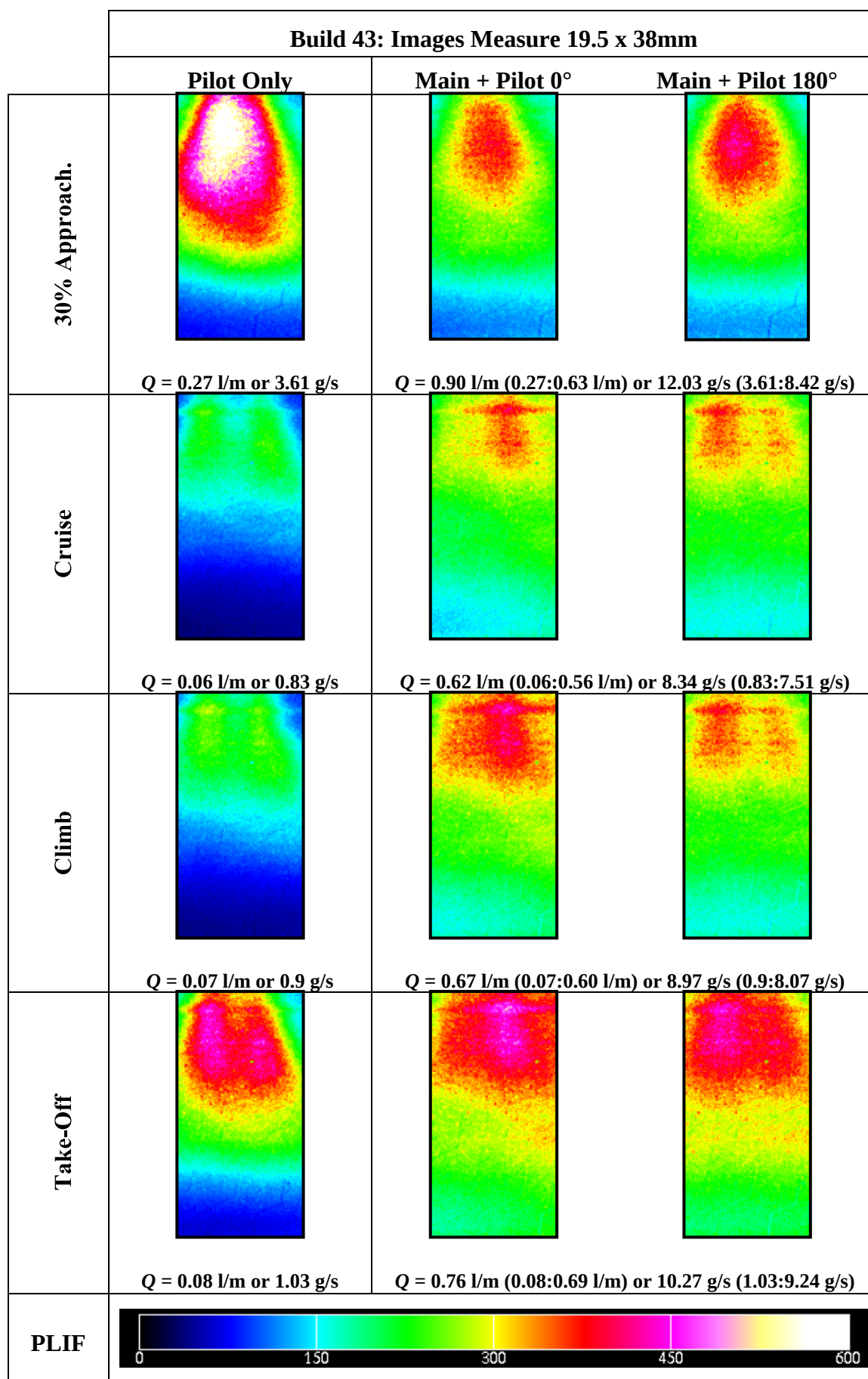


Figure 7.26: B43 Radiation Trapping Images

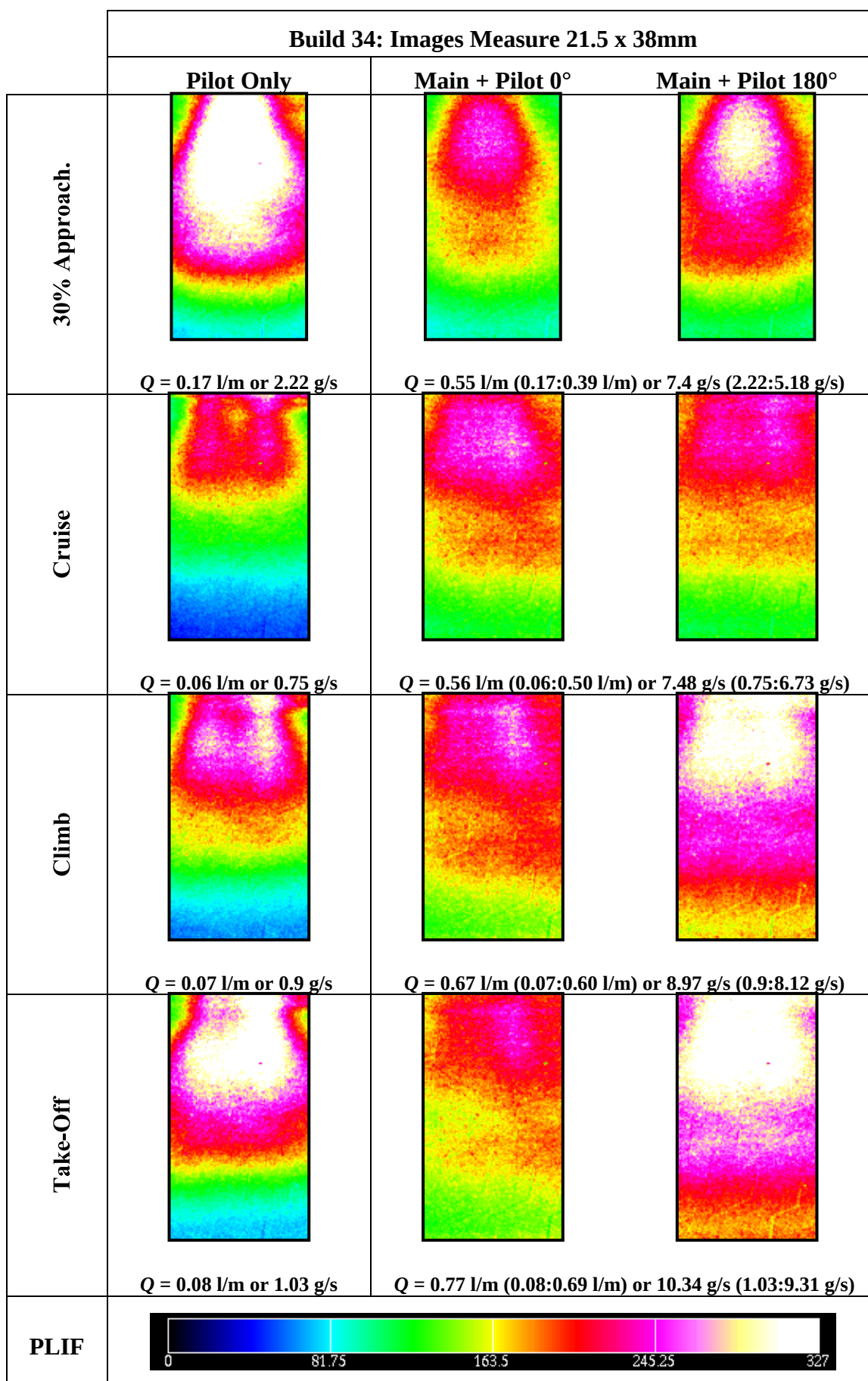


Figure 7.27: B34 Radiation Trapping Images

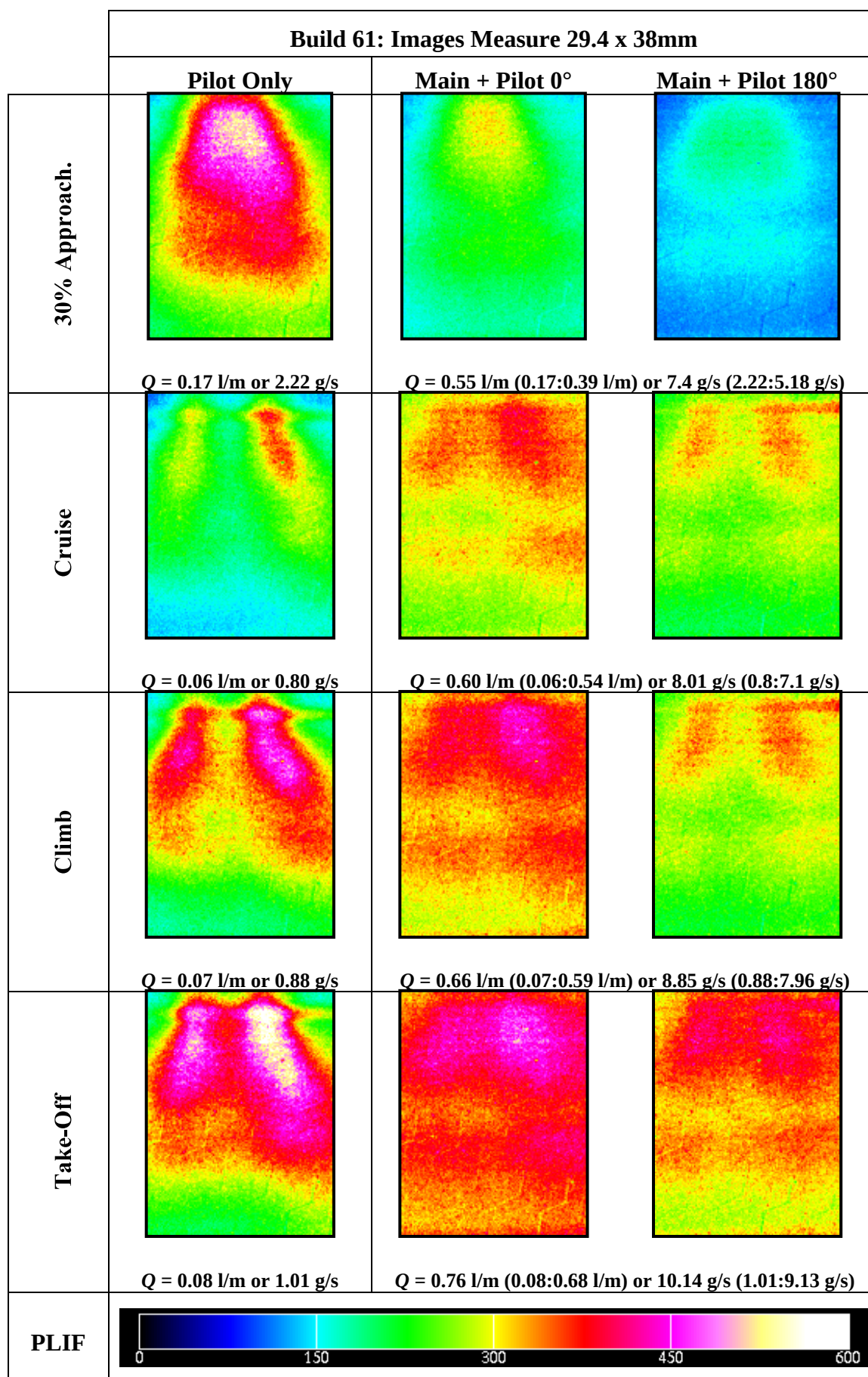


Figure 7.28: B61 Radiation Trapping Images

The mean PLIF intensities in pilot only regions were ratioed in accordance with Eq. 7.2 to calculate the degree of signal loss as a consequence of introducing the main supply.

$$S_{PLIF\ Signal\ Loss} = 0.5 \times \left(\frac{S_{PLIF\ Pilot - 0^\circ}}{S_{PLIF\ Main + Pilot - 0^\circ}} \right) + \left(\frac{S_{PLIF\ Pilot - 0^\circ}}{S_{PLIF\ Main + Pilot - 180^\circ}} \right) \quad \text{Eq. 7.2}$$

Figure 7.29 shows a plot of image correction factors for pilot only regions and showed the extent of radiation trapping and aerodynamic influence of the main on the pilot. This reduced PLIF intensities by a factor of 0.53 – 1.94. In all cases, the discrepancy was greatest in the 30% Approach case where the pilot used 30% of the combined fuel flow rate compared to the other cases where it used just 10% of the total fuel flow rate.

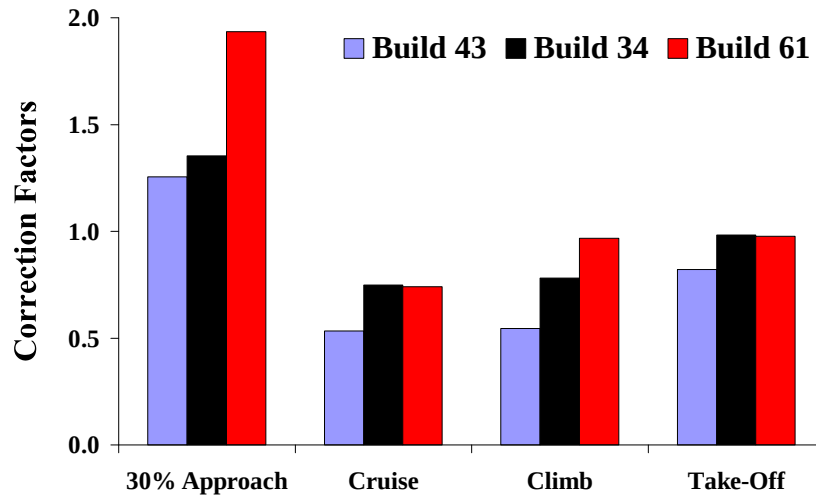


Figure 7.29: Radiation Trapping Correction Factors

Pilot intensities were higher than combined pilot plus main intensities. Hence there existed a clear optical and structural impact of the main spray on the pilot although there was no attenuation on the peripheral regions of the main spray. The laser sheet was attenuated by the main spray before reaching the pilot region and this reduced PLIF signals. Internal recirculation rates also increased as the main fuel flow rate was increased. It is likely that the main spray produced an entirely momentum dominated aerodynamic recirculation in the pilot spray that dissipated energy into the pilot to reduce the measured PLIF intensities. Given the maximum error that was likely to exist due to attenuation, it was only possible to apply a linear correction in the pilot region. However, if applied it would have equated to inventing something false as the required factor actually varied with spatial location and was dependant on the structure of the spray that was naturally unknown. Attenuation in the pilot only region was therefore reluctantly accepted because the effect was aerodynamic and not just a simple case of a change in signal magnitude. Therefore, it was not possible to apply a correction in the pilot only regions of mixed pilot and main cases.

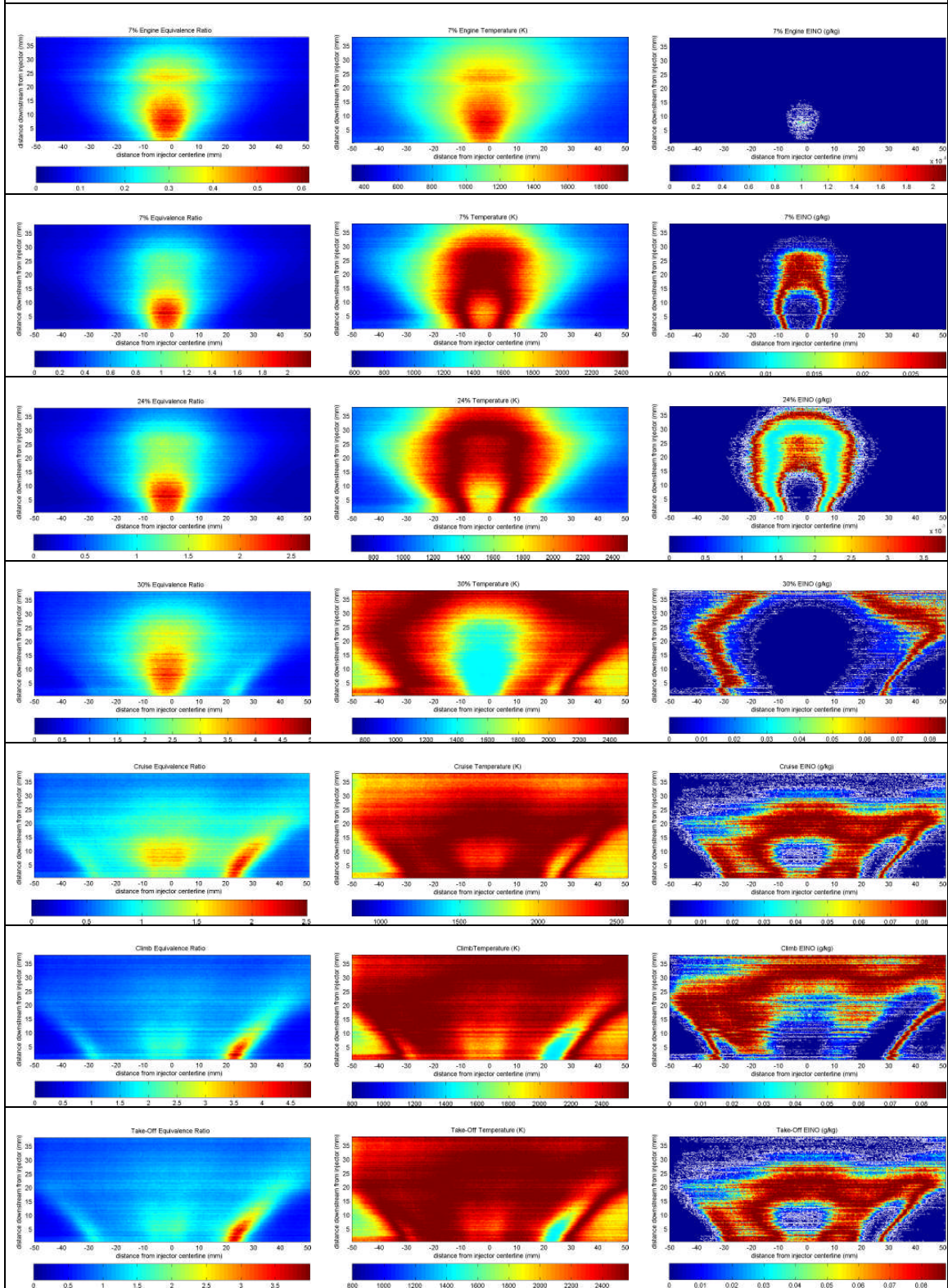
7.6 NO_x PREDICTION, RESULTS AND DISCUSSION

GASEQ (Morley, 1995) and HOMREA (Warnatz, 2002 and Bourgeois, 2003) were used to predict NO from AFR images. The LVF_K value derived in Chapter Four was applied with rig air and fuel densities to yield two-dimensional maps of AFR. The stoichiometric AFR value for kerosene was taken as 14.7 and divided by the local AFR to yield local equivalence ratios, ϕ . GASEQ calculated local adiabatic flame temperatures at constant pressure for the ϕ range within each image. Initial concentrations of N₂, O₂ and H₂O were recorded above 800K in 100K increments and the equation of the line from the plot of temperature versus ϕ was fitted using LabView, courtesy of Beyer (2005) and applied to each pixel in the ϕ image to calculate local adiabatic flame temperatures. Spray length was calculated from pixel resolution and divided by U to estimate residence time. Strictly, residence time is a linear ramp and the ratio of volume to volumetric flow rate. It is also sensitive to swirl. However, as combustor geometry was undisclosed it forbid accurate calculation. As fuel patternation is sensitive to swirl and the model is based on patternation, swirl was implicitly considered. HOMREA calculated NO formation using the Jet-A thermodynamic data coefficients of McBride *et al* (1993) under constant pressure from the calculated temperatures and initial concentrations of N₂, O₂ and H₂O from GASEQ. The equation of the line from the plot of temperature versus NO production was fitted using LabView and applied to the complete image of local adiabatic flame temperatures to give local maps of NO formation. For a combustor of constant volume, Eq. 7.3 calculated the burnt gas density, $\rho_{Burnt Gas}$ in each pixel. Strictly, $\rho_{Burnt Gas}$ should have been multiplied by the combustor volume but since this was constant the sought after trend was therefore insensitive to its absence. Eq. 7.4 gave EINO in mg/kg in each pixel, where RMM of NO is 30.01. Each row in Figure 7.30, Figure 7.31 and Figure 7.32 show local ϕ , temperature and NO formation at each condition for Builds 34, 61 and 43, respectively. Final plots compare measured results with RR NO_x measurements. Results were out by a factor given that RR NO_x measurements were made at the engine exhaust; the two-phase flow between engine and test conditions was not perfectly matched; the total fuel spray was not imaged; combustor geometry was estimated, and more fundamentally, the local AFR under non-combusting conditions appreciably differed in the absence of a flame where under a combusting environment it would consume fuel and also form a substantial blockage to change the imaged flowfield.

$$\rho_{Burnt gas} = \frac{\rho_{Unburnt Air} \times T_{Input}}{T_{Local Burnt Gas}} \quad \text{Eq. 7.3}$$

$$NO_{Local} \times \frac{RMM}{1000} \times \frac{1}{\rho_{Burnt Gas}} = \frac{mg}{kg} \quad \text{Eq. 7.4}$$

Nitric Oxide Prediction from Local ϕ and Temperature in Build 34 Sprays



$B34: A_{Eff} = 1460\text{mm}^2, \Delta P/P = 4\%, P_{Abs} = 212 - 479.5 \text{ kPa}$
 $AFR = 28.66 - 72.6, U = 85.6 \text{ m/s}, \dot{m}_A = 213 - 654 \text{ g/s}, Q = 0.50 - 0.77 \text{ l/m} (6.67 - 9.31 \text{ g/s})$

Swirler 1	Swirler 2	Swirler 3
30°	45°	55°

Figure 7.30: B34 Nitric Oxide Predictions

Nitric Oxide Prediction from Local ϕ and Temperature in Build 61 Sprays

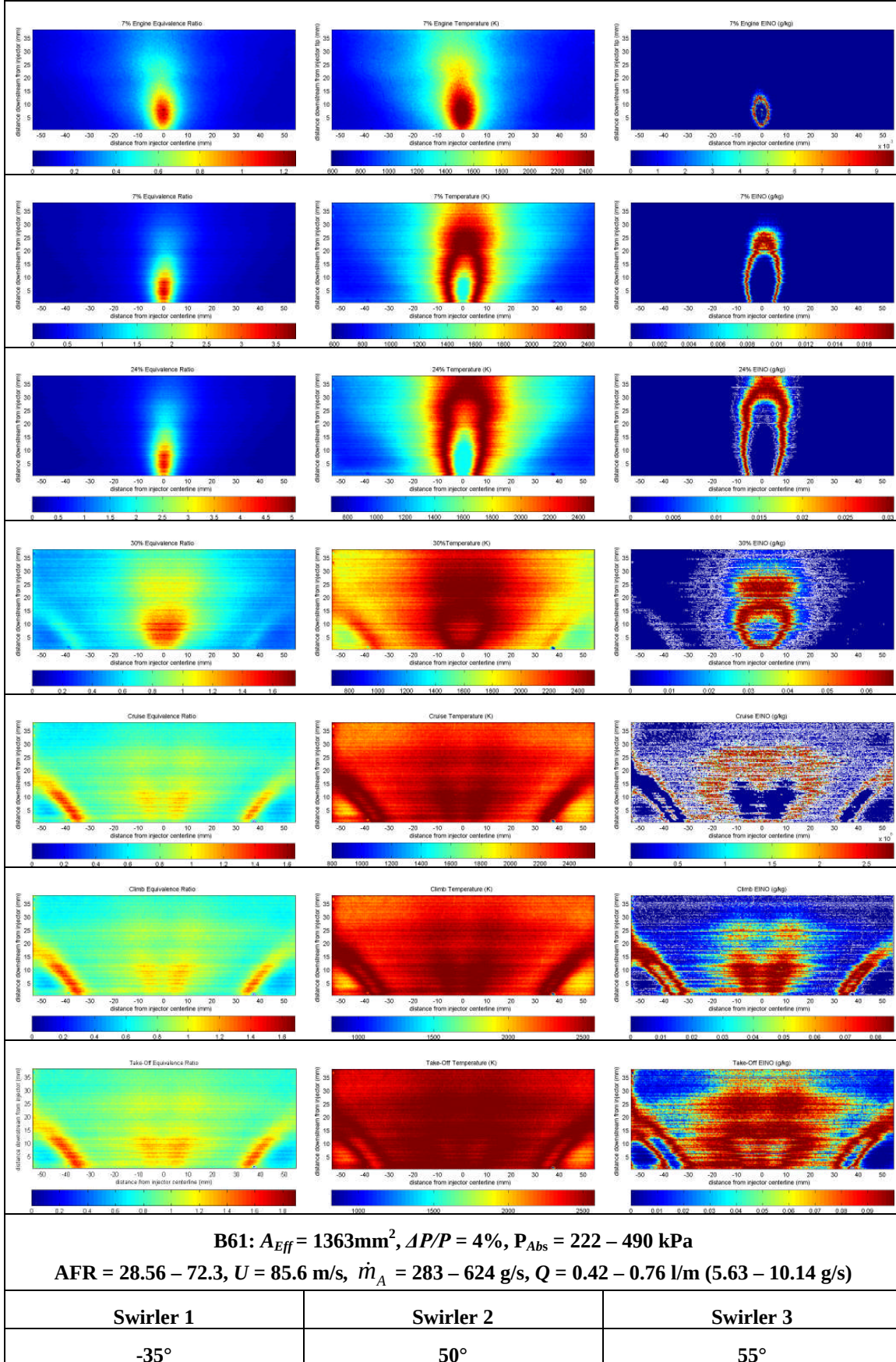


Figure 7.31: B61 Nitric Oxide Predictions

Nitric Oxide Prediction from Local ϕ and Temperature in Build 43 Sprays

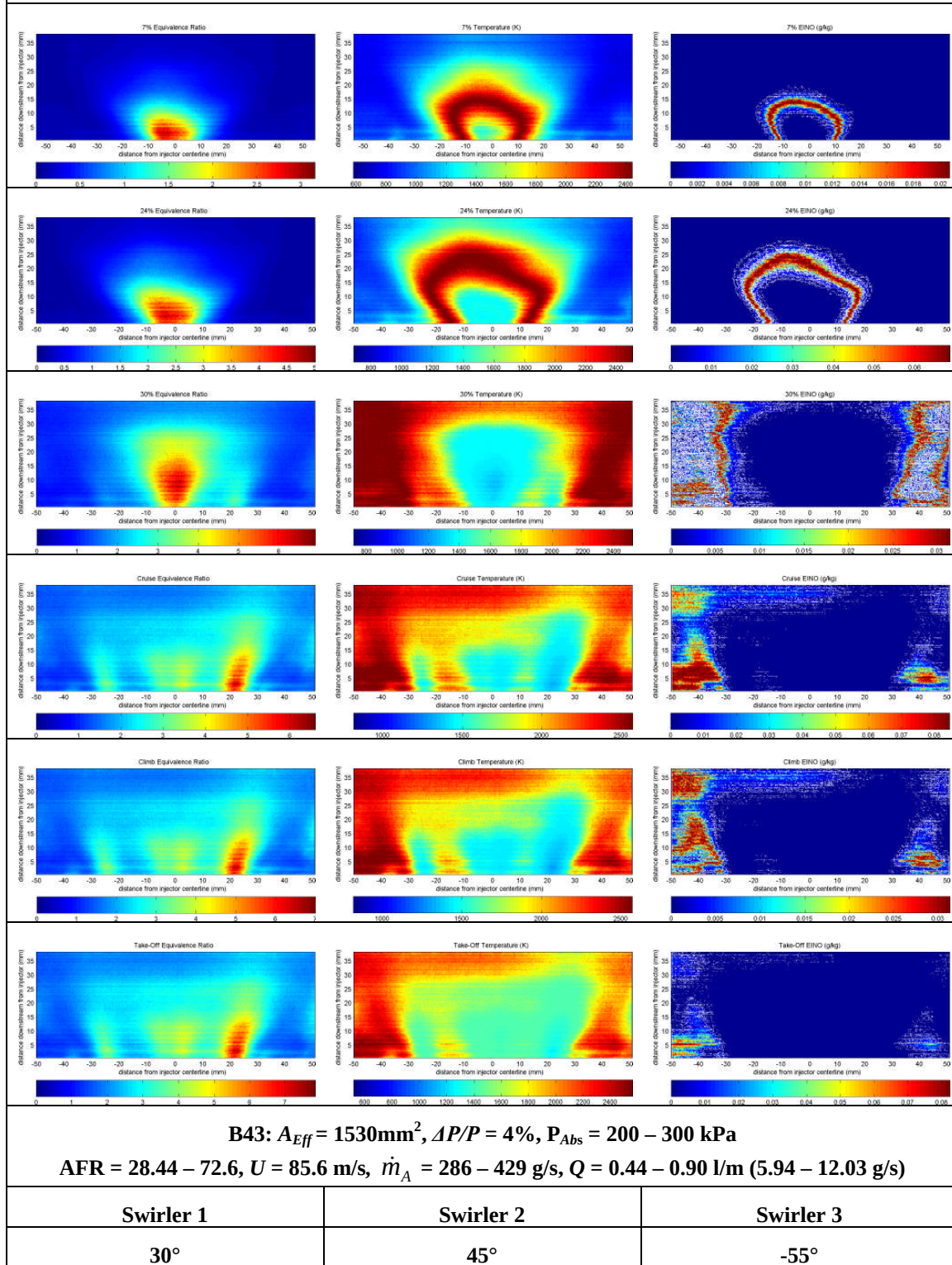


Figure 7.32: B43 Nitric Oxide Predictions

Actual combustor temperatures were in fact lower due to radiation but complex to estimate so the calculated NO formation at each condition was an upper limit value. Overleaf, Figure 7.33, Figure 7.34 and Figure 7.35 sum up the predicted NO formation in each image and plot the results against RR measurements of EINOx.

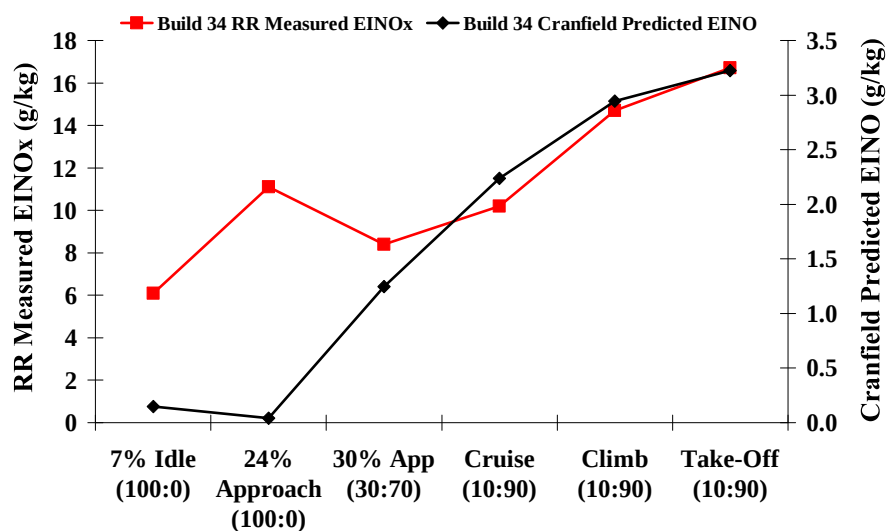


Figure 7.33: B34 Measured vs Predicted NOx

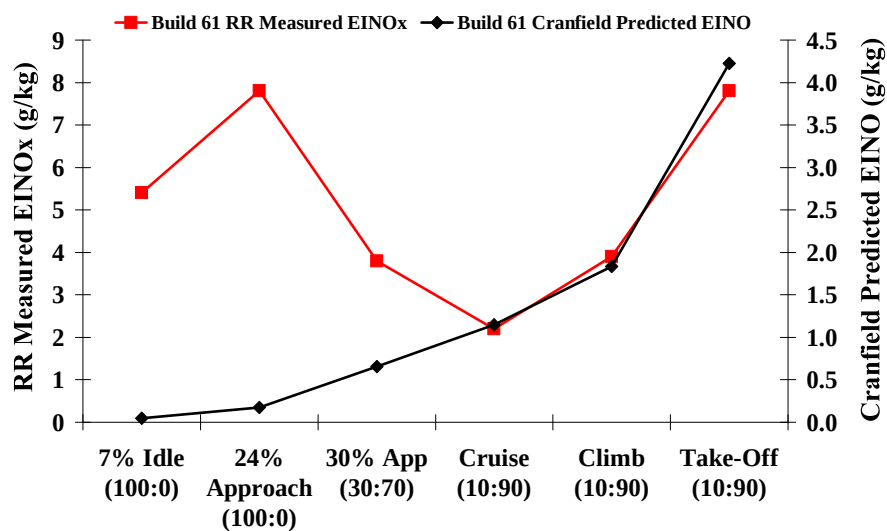


Figure 7.34: B61 Measured vs Predicted NOx

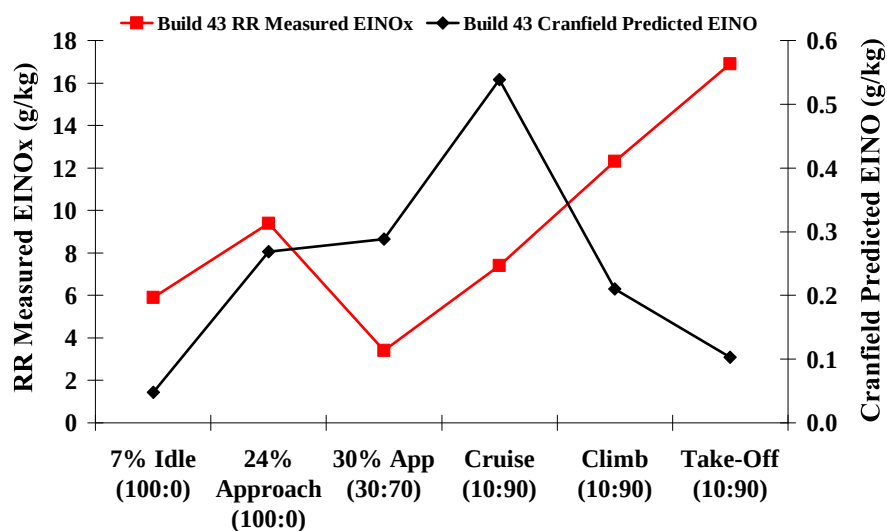


Figure 7.35: B43 Measured vs Predicted NOx

Figure 7.36 shows the fractional discrepancies for each of the investigated conditions.

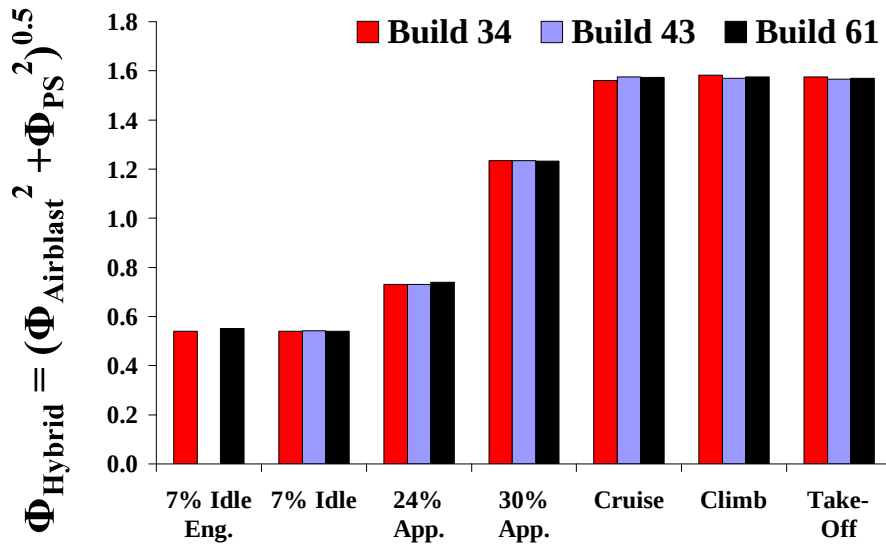


Figure 7.36: B34, 43, and 61: $\Phi_{Hybrid} (\Phi_{AB}^2 + \Phi_{PS}^2)^{0.5}$

The NOx model in this study was geared towards premixed situations and not diffusion flames. The fact it failed to predict NOx in the rich pilot region was a positive result because of the different physical mechanism used by the model. Although mixed cases in Builds 34 and 61 were not quite fully premixed, equating the local AFR to yield a local temperature was a sensible approach. The model did not predict any NO formation in pilot only cases as local AFR values were too rich and this limited flame temperatures and NO formation. The pilot flame was so rich that combustion could not occur until fuel and air mixtures passed through a stoichiometric contour as a diffusion flame. Relatively speaking, the NO would actually be higher than local AFRs suggest.

A positive correlation existed in premixed cases for Builds 34, 61, and the 24% Approach condition in Build 43. The principal feature in Build 43 responsible for the measured differences in spray structure and the poor NO correlation in comparison to the other injectors was its -55° contra-swirler. Comparison of Take-Off conditions between Build 34 in Figure 7.30 and Build 43 in Figure 7.32 showed very different spray structures. The reverse swirler in Build 43 contracted the spray cone angle to make the spray travel further downstream and diverge less in comparison to Builds 34 or 61. Build 43 had a very low NOx prediction, as suggested in Chapter Six due to its completely different flame structure. As the spray travels downstream it would eventually spread out and more of its frontal area would be consumed by air to make it progressively leaner. The main difference between Builds 34 and 61 in comparison to Build 43 is the sprays came out wider to increase the air and fuel mixing rates and therefore the physical correlations worked. Although in practice, RR measured NOx in Build 43, the imaged areas failed to capture its formation because the flame sat much

further downstream from the measured region. It occupied a very different position compared to the closer proximity flames from Builds 34 and 61. Due to the different flame location and fact that the developed NO_x model was based on mixture strength it did not apply in terms of where the flame in Build 43 was actually burning, as the flame structure was dramatically different. Fractional discrepancies across all injectors were similar and ~900% smaller in terms of key flow descriptors compared to atmospheric pressure rig tests to significantly influence the partial success of the NO model.

7.7 SUMMARY

This chapter introduced the Unsteady Flow Rig (UFR). This was commissioned to operate up to a maximum pressure of 700kPa, temperatures of 200°C and airflows of 2kg/s under non-combusting, isothermal conditions. Varying the rig pressure reduced fractional discrepancies in two-phase flow behaviour of the engine and rig testing conditions by ~900% over previous studies conducted at atmospheric pressure.

PDA, LSD and PLIF experimental configurations were described to obtain quantitative droplet SMD and AFR. A series of LSD and PDA measurements ruled out severe secondary atomisation in pilot only conditions of Build 61. This investigation also prompted fundamental improvements to the complete experimental method and data processing techniques. The camera field of view was increased to visualise the main spray. LSD dual imaging optics were removed to permit a PLIF only study in Builds 34, 43 and 61. The LVF_K calibration constant derived in Chapter Four was applied to LVF images with applicable rig air and fuel densities in each case to yield quantitative two-dimensional maps of AFR. However, images showed that introduction of the main spray had an optical and aerodynamic impact on the pilot region. Extent of signal loss due to radiation trapping and aerodynamic influence of the main was measured but a correction was not applied as it varied with spatial position in the image.

The NO_x model developed as a part of this study was based on mixture strength. AFR images were transformed into local equivalence ratios. GASEQ and HOMREA were used to calculate local adiabatic flame temperatures and NO formation for seven sprays in Builds 34 and 61 and six sprays in Build 43. The NO model was geared towards premixed situations and not diffusion flames. The fact that it failed to predict NO formation in the rich pilot region was a positive result because it yielded a good correlation with premixed conditions of Builds 34 and 61. Results confirmed the practicality and relevance of laser diagnostics at more representative flow conditions to help isolate fuel injector design features for low emissions at considerably less risk, cost and time than conventional full-scale combustion engine tests.

CHAPTER EIGHT

RESPONSE OF FUEL SPRAYS TO ACOUSTIC FORCING

8.1 INTRODUCTION

Lean Prevapourised Premixed (LPP) combustion systems reduce flame temperatures and NO_x emissions but strongly encompass the possibility of thermo-acoustic oscillations. Combustion instability along with flashback, weak extinction and altitude relight conspire to impede widespread entry into service of LPP systems. Unlike non-premixed, robust, well-anchored, stoichiometric flames lean flames are more susceptible to pressure perturbations that become non-linearly compromised if exposed to pressure or velocity perturbations in their constant efforts to locate in regions of higher stability.

Aero engine combustion chambers support travelling and static acoustic waves that interact with the fuel injector, the fuel and air mixing zone and the flame. Liquid-fuelled injectors are particularly susceptible to low-frequency oscillations between 60 – 120Hz (Zhu *et al*, 2002). These originate from interactions between pressure, unsteady combustion and operating conditions to modulate the local Air to Fuel Ratio (AFR) and fluctuate heat release rates. If for a particular acoustic frequency a mechanism exists that couples the oscillating component of pressure with the heat release rate and if the phase lag of that heat release rate to the acoustic pressure is $>-90^\circ$ and $<90^\circ$, known as the Rayleigh Criterion, the combustor will amplify the acoustic wave. This yields a self-exciting, amplifying and sustaining system that results in a “rumble” or “buzz”. Besides exceeding noise and passenger comfort levels, the phenomenon enhances heat transfer rates to adjacent components to increase material fatigue and shorten combustor life. Oyediran *et al* (1995) reported that combustors encompassed unique mechanisms that prompted instability. This would render application of a universal law, if indeed one existed that predicted instability virtually redundant. Instabilities must therefore be tackled late in engine development at high cost and inconvenience (Konrad *et al* 1998). Solutions entail injector redesign; acoustic damping devices or instability suppression methods with closed-loop fuel modulation of the type described by Lovett *et al* (2008).

This central thread of this chapter was therefore to correlate key spray properties with RR measured combustion instability data to identify injector design features that encouraged and discouraged combustion instability. The response of airblast fuel injector sprays to acoustic perturbations in the airflow was measured under cold flow, intermediate pressure, scaled conditions. Laser Sheet Dropsizing (LSD) and Planar Laser Induced Fluorescence (PLIF) were applied in the Unsteady Flow Rig (UFR) to measure droplet Sauter Mean Diameter (SMD) and AFR in fuel sprays from five RR

airblast atomisers, a Turbomeca Lean Module (TLM) and one pressure-swirl atomiser. The rig scaling strategy conserved air to fuel momentum flux ratio and U to replicate fuel patternation and acoustic impedance through each injector. UFR operating conditions for RR airblast atomisers and TLM were $\Delta P/P$ of 5.07%, rig pressures of 249kPa absolute; fuel flow rate of 0.46 l/m and injector AFRs of 7.66 – 11.05. Conditions for the pressure-swirl spray of ANTLE weak module Build 61 were $\Delta P/P$ of 7.05%; rig pressures of 215 and 247kPa absolute; fuel flow rates of 0.49 and 0.60l/m and injector AFRs of 49 and 64. A siren located upstream of the injector was used to perturb the air supply. Phase-locked SMD and AFR measurements were made at sixteen measurement points, every 22.5° in the siren cycle at 12, 100 and 200Hz. The involvement of the author ended with delivery of primary data to the Optical Diagnostics Group (ODG). This was subsequently processed to extract spray transfer function to describe the relationship between combustion unsteadiness and operating conditions. The temporal response of the fuel concentration and dropsizes to the forced airflow modulations was measured and the strength of the response to each modulation and quality of fit of the sinusoidal transfer functions was found to correlate with RR instability measurements. This proved the undertaken tests could inform oscillation-sensitive fuel injector design and give boundary conditions for spray computational codes. The ODG also conducted a separate analysis using standard statistical techniques to identify injector design rules for high stability. Airblast injectors were recommended to have a short prefilmer, low fuel flow number (F_N), and large angle between the dome vane and nozzle outlet plane. This study pertained to the RR “Instability Control of Low Emission Aero-Engine Combustors” (ICLEAC) engine demonstrator programme and results were published in ICLEAC (2004) and sanitised versions in Jermy *et al* (2004) and Greenhalgh *et al* (2004) due to the proprietary nature of the work.

8.2 LSD AND PLIF MEASUREMENTS FOR ICLEAC

Cranfield University was contracted to investigate the role of the fuel injector in encouraging or inhibiting combustion instabilities. The following extract from Annex 1 of ICLEAC contract number GRD-CT-2000-0215 describes the undertaken work. “An existing fuel injection rig with optical access will be modified to provide an oscillating inlet pressure. The spray behaviour will be investigated using existing instruments for a variety of fuel injectors of known combustion instability characteristics. Following initial tests at atmospheric conditions the rig will be modified for operation up to 3 bar and tests performed at elevated pressures. Correlations will be sought between pressure oscillation-spray behaviour and sensitivity to combustion instability” ICLEAC (2004). This chapter applied LSD and PLIF to provide quantitative SMD and AFR data at elevated pressures under forced acoustic oscillations at 12, 100 and 200Hz for the

second half of the ICLEAC contract. This processed the quantitative data to extract spray transfer functions to identify injectors for combustion instability.

8.2.1 Siren Design

Greenhalgh *et al* (2002) explored options to impose the desired acoustic oscillations in the airflow. These included an organ pipe or Helmholtz resonator, loudspeaker, rotating butterfly valve and siren assembly. Figure 8.1 shows the selected siren assembly design that featured four rectangular shaped holes in the stator and four rhombus shaped holes in the rotor to yield a near-sinusoidal modulation of the open area with time.

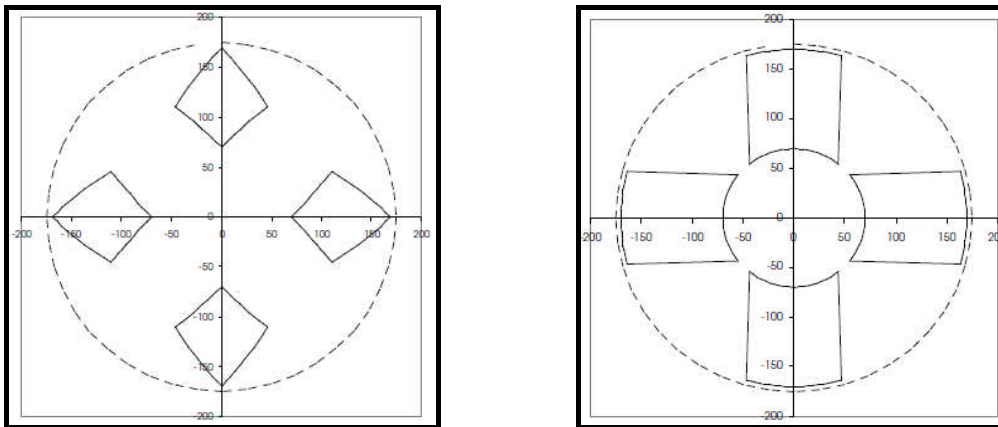


Figure 8.1: Siren Assembly Design (Greenhalgh *et al*, 2002)

A pressure difference occurs as the four rhombus-rectangular shaped holes in each plate go in and out of coincidence. In one siren revolution the air passages opened and closed four times to disrupt the air supply at the oscillation frequency determined by siren motor speed setting. The siren rotational position was detected by a sensor that was used to trigger the imaging system and collect data at the required phase in a given acoustic perturbation cycle. An oscilloscope was used to measure the period in one revolution at different motor speed settings. Measured periods were divided by four and its reciprocal, frequency, was plotted against siren motor speed for calibration. Figure 8.2 shows the siren in its half-open position and Figure 8.3 shows the obtained calibration plot of frequency versus motor speed setting.

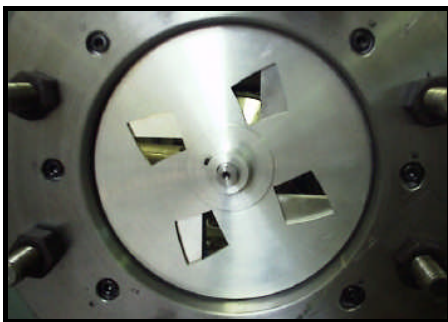


Figure 8.2: Siren in Half-Open Position

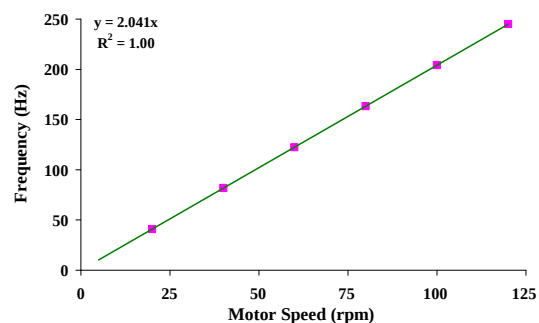


Figure 8.3: Siren Calibration Plot

Although the acoustic perturbation in the UFR was applied upstream rather than downstream of the injector as in the engine condition, it produced the intended cyclic change in pressure drop across the injector and hence air velocity through it. LSD and PLIF were applied to measure the temporal SMD and AFR response as a function of the air perturbation phase and spray position. Chapter Three briefly described these techniques and more detail is given in Le Gal *et al* (1999), Kelman *et al* (2000), Greenhalgh and Jermy (2002), Jermy and Greenhalgh (2000) and Réveillé (2005).

8.2.2 Signal Launch and Collection Optics

A KrF* Lambda Physik CompEx 110 excimer laser provided light at 248nm. Two cylindrical lenses and one spherical lens were arranged to form a vertical laser sheet that measured 0.8mm x ~42mm. This was passed through the spray centreline into a beam-dump. The laser pulse energy was 100mJ. Scattered light and fluorescence from the dissolved fluorophor was collected by a Princeton Instruments ICCD intensified camera fitted with a Nikon 105mm UV lens at f/4.5.

Section 7.3 showed the instrumentation synchronisation sequence where both the laser and camera were triggered by a rotational sensor in the siren via a delay generator. The LSD four-mirror arrangement was also described in Section 6.3.3 on page 123, but here the Mie path was obstructed with a $248\text{nm} \pm 5\text{nm}$ interference bandpass filter and a ND 1.0 filter to balance PLIF and Mie signal intensities on the ICCD chip. 100 PLIF and LSD images were acquired at 0° and 180° to subsequently correct for laser attenuation.

8.2.3 Fuel Supply

Chapter Four described the fluorophor and required concentration for PLIF studies at 248nm using the principles laid out in Jermy and Greenhalgh (2000). In this study, Exxsol D80 was seeded with 0.0118g/l of M-Terphenyl.

8.2.4 Signal Calibration

LSD and PLIF images were also calibrated in accordance with Chapter Four to yield fully quantitative values of SMD and AFR. The calibration involved taking images of a monodisperse droplet field from a piezoelectric droplet generator with a known AFR and SMD, the latter was measured by Phase Doppler Anemometry (PDA).

8.2.5 Injector Hardware

RR supplied five airblast injectors. These had three concentric air swirlers with the prefilmer and fuel gallery located between the inner and outer swirlers. All had

common geometries in terms of their outer dimensions, fuel galleries, inner and outer swirler radii and vane angles to permit installation in the same combustor. Table 8.1 shows the injector specifications.

RR Injector Part Number	Injector Effective Area (mm²)	Fuel Flow Number (UK gal/hr)/(√psi)
71257	230	4.25
73630	250	4.25
73686	202	3.61
73030	202	4.25
73685	180	3.61

Table 8.1: RR Airblast Injector Specifications

The TLM injector was a LPP device with a plain jet atomiser of effective area 140mm², one swirling and one non-swirling airstream.

8.2.6 UFR Operating Conditions

Engine operating conditions for the RR injectors and TLM were scaled to preserve key spray properties in the test rig according to the scaling laws described in Chapter Five. The scaling strategy conserved air to fuel momentum flux ratio and U to replicate the acoustic impedance and fuel patternation. Operating conditions were optimised to replicate the Re , Ma and Stk . Re and Ma determined the air streamlines and Stk determined the credibility of fuel droplets to follow the streamlines. UFR conditions were scaled from RR engine conditions of 317kPa absolute, 380K, 7.62 – 11.00 AFR injector. These were selected for the undertaken study because they displayed the highest contrast with the supplied RR combustion rumble intensity data. For the TLM device, Turbomeca advised Cranfield to set $\Delta P/P$ to yield an air velocity at the injector throat of 100m/s and the flow rates to produce a spray AFR of 25. Table 8.2 shows UFR operating conditions for the RR injector and TLM module.

Injector	$P_{Absolute}$ (kPa)	P_{Gauge} (kPa)	$\Delta P/P$ (5.07%)	Q (l/m)	Q (g/s)	T_a (K)	Φ_A
RR	249	149	0.126	0.46	6.18	316	0.01
TLM	300	200	0.175	0.16	2.15	316	0.01

Table 8.2: UFR Operating Conditions for ICLEAC

8.2.7 Data Acquisition

Phase-locked SMD and AFR measurements were made at the sixteen measurement points shown below in Table 8.3, every 22.5° in the siren cycle at 12, 100 and 200Hz.

	12Hz	100Hz	200Hz
Phase Angle (°)	Timing (ms)	Timing (ms)	Timing (ms)
22.5	20.83	2.5	1.25
45.0	41.67	5.0	2.50
67.5	62.50	7.5	3.75
90.0	83.33	10.0	5.00
112.5	104.17	12.5	6.25
135.0	125.00	15.0	7.50
157.5	145.83	17.5	8.75
180.0	166.67	20.0	10.00
202.5	187.50	22.5	11.25
225.0	208.33	25.0	12.50
247.5	229.16	27.5	13.75
270.0	250.00	30.0	15.00
292.5	270.83	32.5	16.25
315.0	291.66	35.0	17.50
337.5	312.50	37.5	18.75
360.0	333.33	40.0	20.00

Table 8.3: Spray Measurement Points at 12, 100 and 200Hz

8.2.8 Image Processing and Results

The 100 images taken at each phase and frequency at both 0° and 180° were averaged and background-subtracted. Mie and PLIF images were attenuation-corrected in accordance with the method of Talley *et al* (1996). In LSD, pixels in PLIF images were divided by corresponding pixels in Mie images and multiplied by LSD_K derived in Chapter Four to yield quantitative SMD. PLIF images were equated to AFR x 100 to prevent truncation of results upon conversion into integer format. Figure 8.4 to Figure 8.7 show AFR and SMD image sequences for the RR 71257 injector and TLM at 200Hz. Images measured 72.1 x 102.5mm and are shown on a false colour scale where hot colours indicate high AFR or SMD. Spray direction was upwards. In all cases the sprays were mostly symmetric and spray recirculation zones were visible. Phase angles were relative to the siren timing. Oscillations in AFR and SMD values were observed but not apparent as the amplitude of fluctuation was a small fraction of DC values.

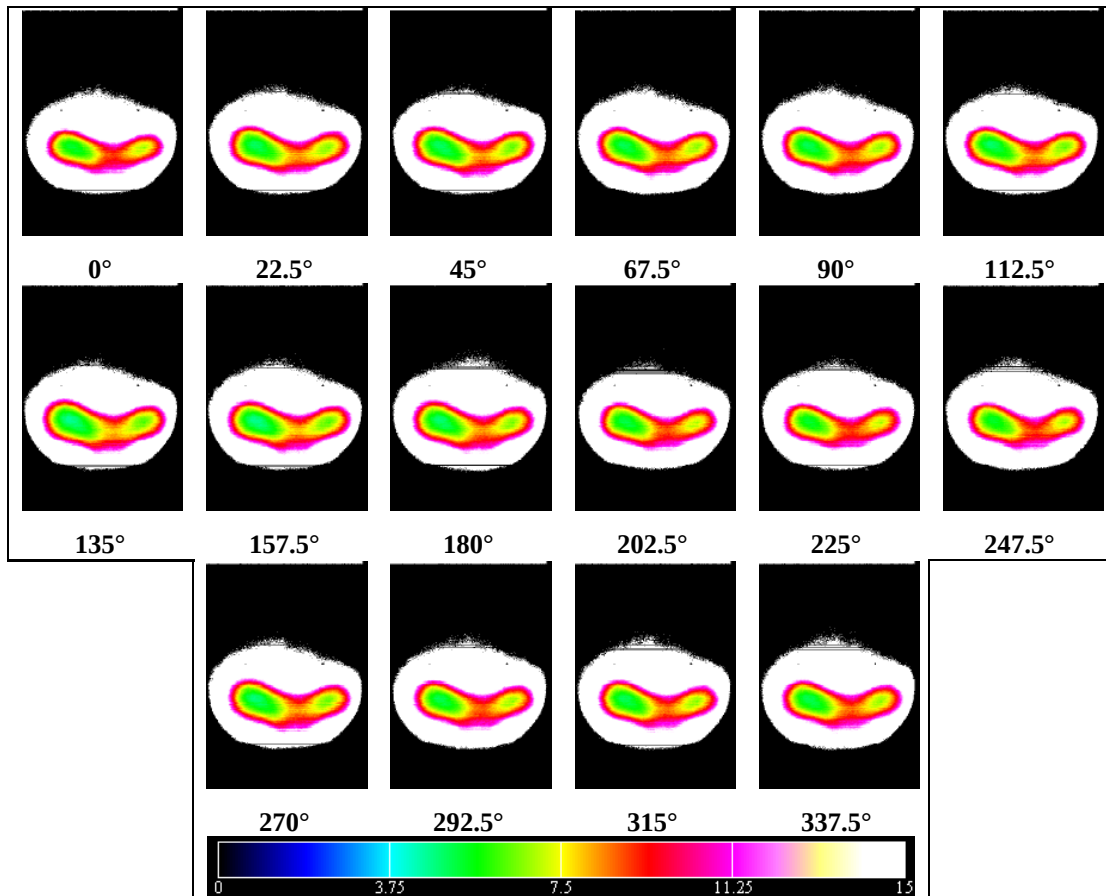


Figure 8.4: Seq. of AFR Images from RR Injector 71257 at 200Hz

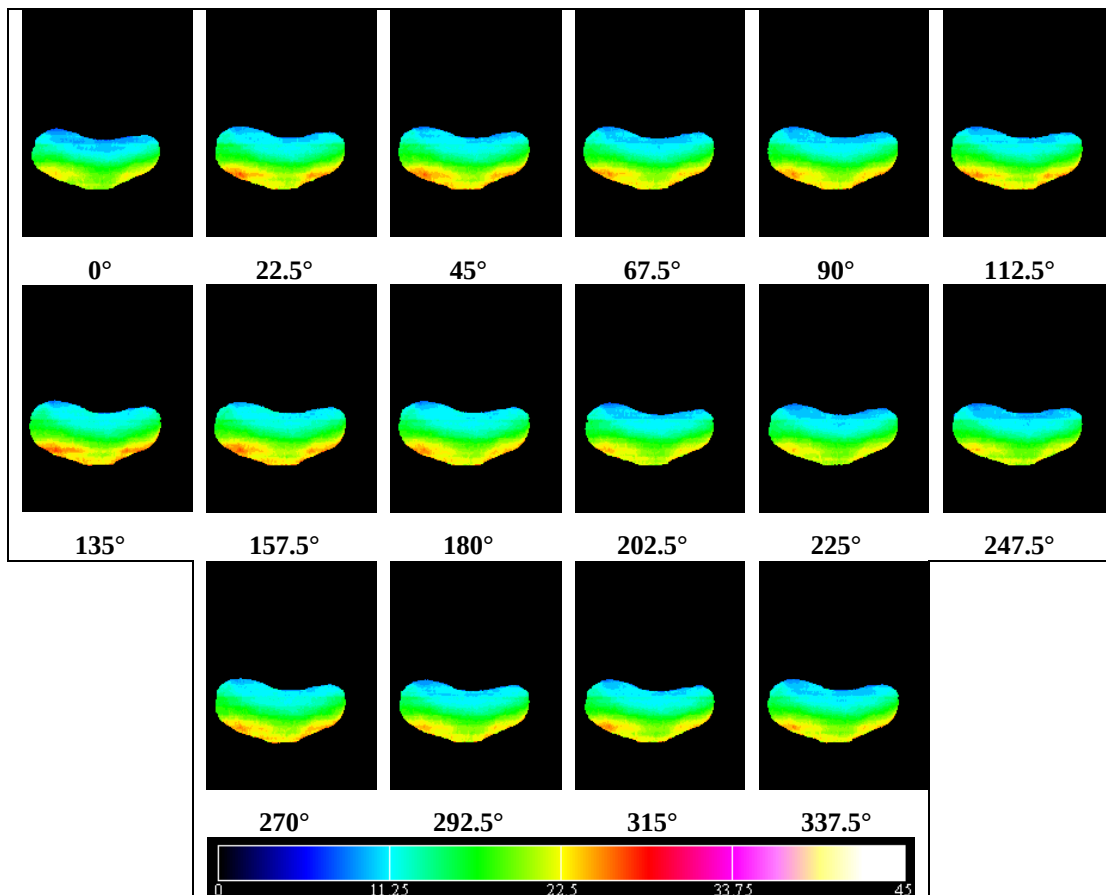


Figure 8.5: Seq. of SMD Images from RR Injector 71257 at 200Hz

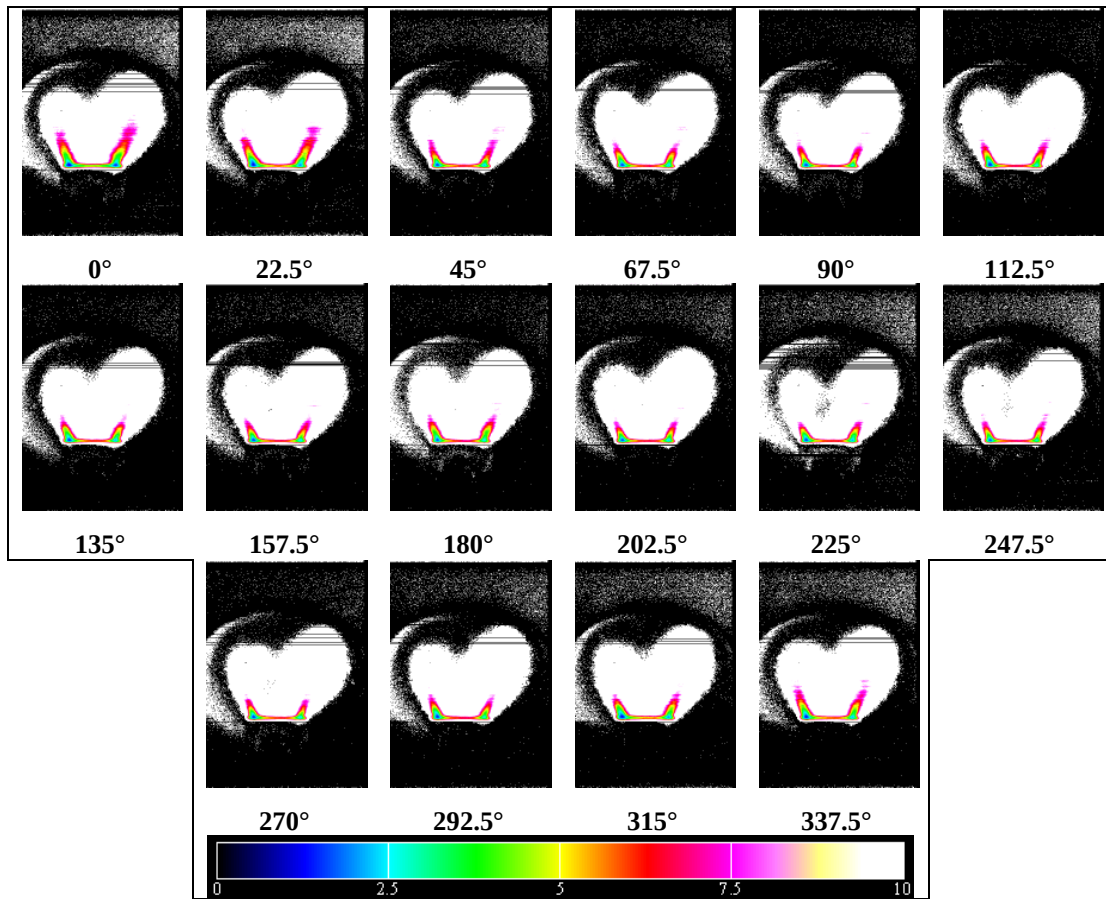


Figure 8.6: Seq. of AFR Images from TLM at 200Hz

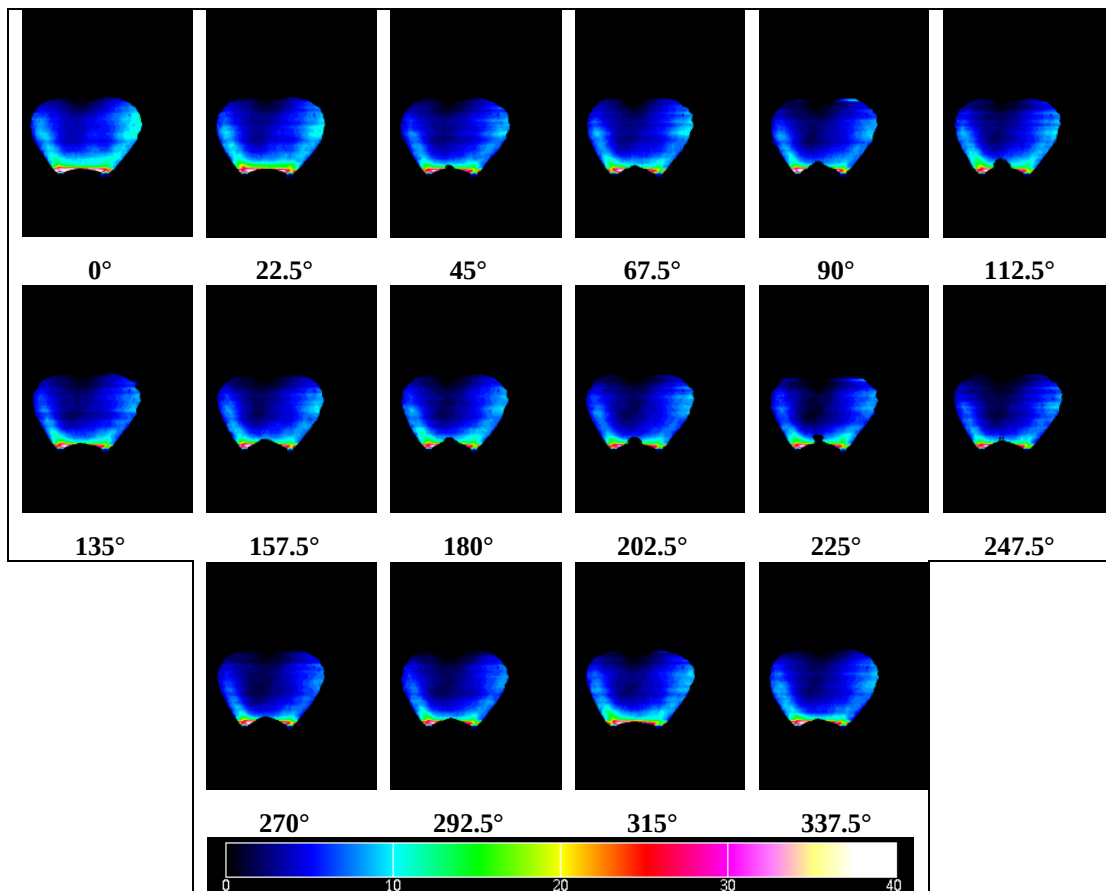


Figure 8.7: Seq. of SMD Images from TLM at 200Hz

The complete AFR and SMD dataset was supplied to the ICLEAC programme and is available upon request. Changes in spray cone angle as a function of airbox pressures and injector air pressure drops were measured and supplied to Cambridge University. The siren assembly was removed to avoid pressure oscillations in the air inlet supply. Table 8.4 and Table 8.5 show UFR operating conditions and cone angle results for the RR 71257 injector and TLM. The fuel flow rate to RR injectors was 0.46 l/m (5.2 g/s) and 0.16 l/m (2.1 g/s) for the TLM. As images were only acquired at 0° they were mirrored to perform the attenuation correction. In hindsight, this type of correction could also have been applied for the 0° “21 AFR” injector dataset discussed in Chapter Six although this is not a credible method to correct laser attenuation through sprays. Cone angles were defined as twice the angle between the vertical axis and a tangent that was drawn from the prefilmer exit to a contour on one side of each PLIF image at 50% of the maximum registered intensity value.

Condition	$P_{\text{Airbox Gauge}}$ (kPa)	ΔP (kPa)	Cone Angle (°)
0	145	12.1	130
1	174	6.5	120
2	176	7.5	125
3	-	-	-
4	168	0.4	130
5	141	22.3	110
6	66	66.9	
7	69	39.7	90
8	-	-	-
9	8	96	90
10	9	38	105

Table 8.4: UFR Conditions and Measured Cone Angles for RR Injector 71257

Condition	$P_{\text{Airbox Gauge}}$ (kPa)	ΔP (kPa)	Cone Angle (°)
0	200	181	65
1	210	260	65
2	219	2	-
3	227	17.5	75
4	242	17.3	60
5	55	16.1	60
6	150	17.3	60

Table 8.5: UFR Conditions and Measured Cone Angles for TLM

Figure 8.8 and Figure 8.9 show sample results for the RR 71257 injector and TLM.

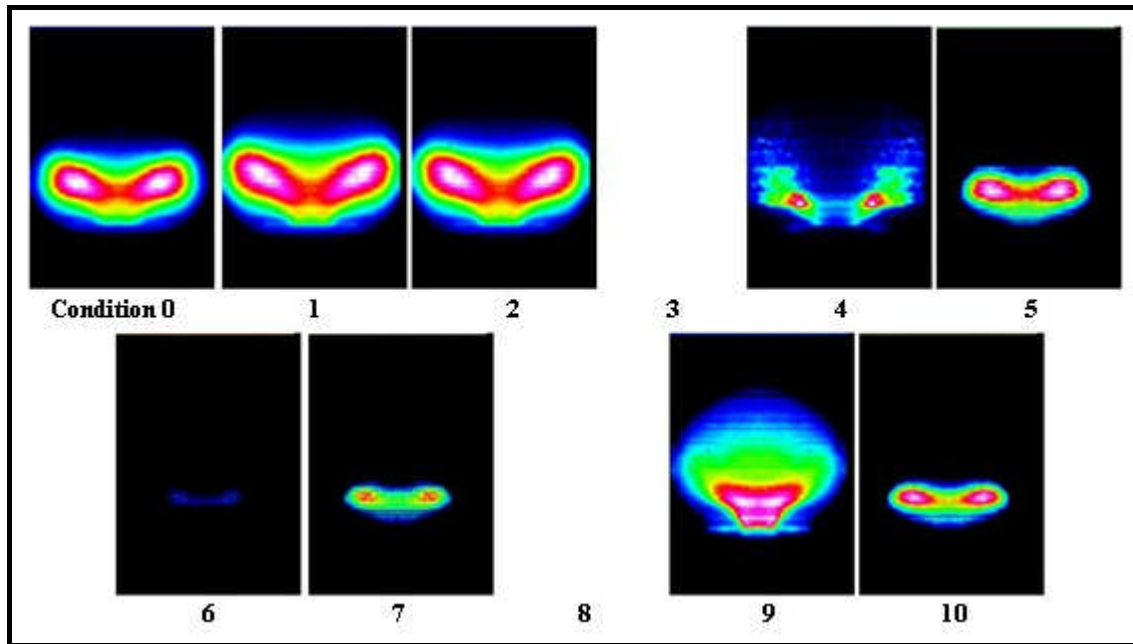


Figure 8.8: Images for Extraction of Cone Angle for RR Injector 71257

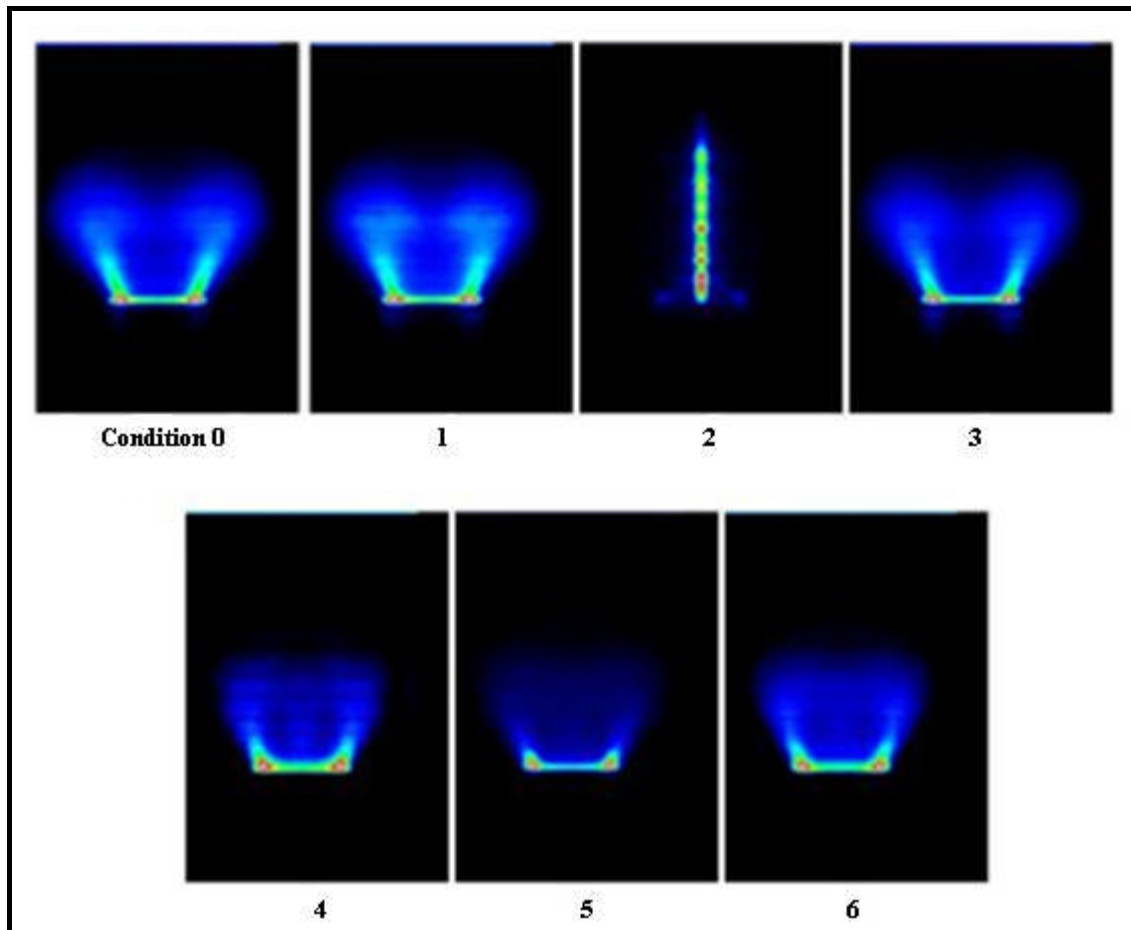


Figure 8.9: Images for Extraction of Cone Angle for TLM

The involvement of the author in the ICLEAC project ended with delivery of the primary data that consisted of fully quantitative SMD and AFR images to extract spray

transfer functions to describe the strength and phase of the dropsize and fuel concentration response to acoustic perturbations and also static image data to calculate spray cone angles. The supplied data was processed within the ODG to extract spray transfer functions that were subsequently correlated with measured rumble intensities.

8.2.9 Extraction of Spray Transfer Functions

The temporal AFR and SMD response in each case was measured in four 10 x 10 pixel regions depicted in Figure 8.10. The first region was in the centre of the recirculation zone. The second near the prefilmer exit. Third and fourth were on the injector centreline, firstly at the same downstream distance as the recirculation zone and then near the downstream spray limit. In some SMD cases this final region gave null results.

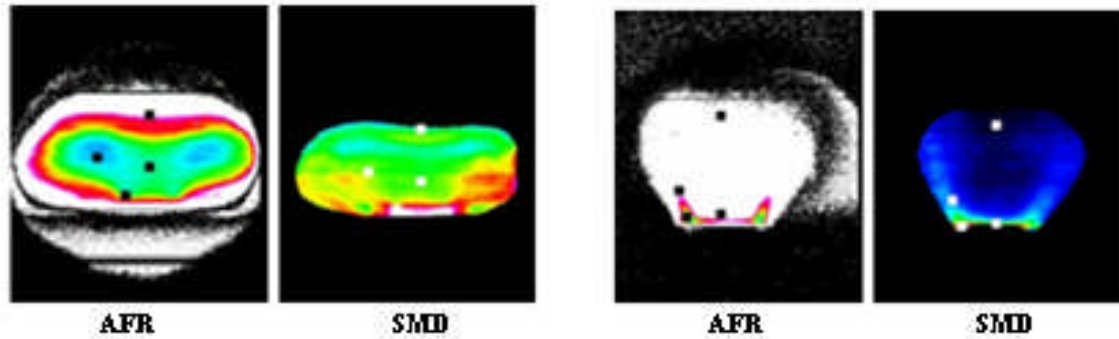


Figure 8.10: Selected Regions - RR Injector 73630 (L). TLM (R)

A time series of AFR and SMD values within each region over the 100 pixel area was found by averaging the intensity at each phase. The average over all phases, i.e. the DC component was subtracted to give the fluctuating or AC component. Eq. 8.1 was used to describe the relationship between the given spray property and pressure fluctuation.

$$Y = \bar{Y} + \tilde{P}A\sin(\omega t + \phi) \quad \text{Eq. 8.1}$$

Where Y is either AFR or SMD, at time t in the investigated spray region; $\tilde{Y}$ the fluctuating value; $\bar{Y}$ the mean value of Y ; $\tilde{P}$ the fluctuating component of airbox pressure measured in Pa; A the amplitude or coupling constant measured in AFR/Pa or $\mu\text{m}/\text{Pa}$; θ the phase of the siren in the AFR or SMD/phase relationship; ω the air perturbation frequency and ϕ the phase lag of the peak in Y with respect to the peak in air pressure. The airbox pressure-history was measured to have non-sinusoidal features. AFR and SMD time histories were therefore filtered to remove the components at harmonic frequencies. Eq. 8.2 was used to calculate the fit quality of the data:

$$\text{Fit Quality} = \frac{R^2}{A^2} \quad \text{Eq. 8.2}$$

Eq. 8.2 summed the deviations squared over the AC amplitude squared. If the latter was noisy or poorly sinusoidal, it showed that incoherent fluctuations were not siren driven. Eq. 8.3 is the ratio of the amplitude of the fluctuating component per unit pressure amplitude of AFR or SMD to its DC component.

$$\frac{A}{\bar{Y}} \quad \text{Eq. 8.3}$$

8.2.10 Discussion and Conclusions of Spray Transfer Functions

Table 8.6 shows the relationship between the transfer function variables and RR measurements of combustion rumble amplitude at 3 bar, 84AFR and 380K.

Injector	Rumble Amplitude (Pa)	$A / \bar{Y}$ Summed Over All Frequencies: SMD and AFR			R^2/AC^2 Summed Over All Three Frequencies: SMD and AFR		
		Recirc. Zone Centre	Near Prefilmer Exit	Centreline at Recirc. Zone Height	Centre of Recirc. Zone	Near Prefilmer Exit	Centreline at Recirc. Zone Height
71257	9235.28	7.65E-05	9.55E-05	7.00E-05	41.7	22.4	52.4
73630	8270.4	9.80E-05	1.00E-04	1.13E-04	18.7	30.0	15.2
73030	8270.4	5.24E-05	6.54E-05	4.06E-05	16.1	22.5	28.7
73685	344.6	6.66E-05	6.23E-05	5.42E-05	159.8	95.4	57.1
73686	1378.4	6.89E-05	1.14E-04	4.54E-05	9.9	20.6	29.1

Table 8.6: Transfer Function and Fit Quality vs Rumble

Both the AFR and SMD showed siren-driven fluctuations. Cyclic changes in the SMD and fuel transport rate are strong candidates for the feedback mechanism that contributes to combustion driven oscillations. Coherent fluctuations due to the oscillating airflow were perhaps in some regions weaker than natural fluctuations, yet still provided a mechanism that could be amplified to instigate combustion rumble. Providing there was some coherent behaviour above that frequency it could be amplified above the background noise. There was however no detectable oscillation in the spray cone angles at the investigated pressure amplitudes. The phase lag between the spray and air pressure fluctuations was constant throughout the spray as acoustic wavelengths were several times larger than the extent of the spray. However, the phase

lag varied between injectors. In a given region, the phase lag of the AFR and SMD fluctuations typically differed by $140 - 220^\circ$. AFR peaks were due to peaks in the air pressure that yielded corresponding troughs in the SMD as the air velocity, air momentum and shear forces were maximised. The DC component and phase varied between injectors due to design variations, flowfield changes and the 220° difference in phase lag of the AFR and SMD. The DC component varied with frequency to suggest that oscillations were influenced by the DC and AC spray structure. The amplitude of the fluctuations was greatest nearer the prefilmer exit and diminished further downstream along the spray centreline and recirculation zone. Larger fluctuations in the AFR and SMD occurred per unit amplitude of air oscillation at higher frequencies. Although injector natural frequencies respond strongly to air pressure fluctuations to impact the frequency of combustion oscillations, subsequent installation of a given injector in an engine would also influence the natural frequency of the combustion chamber, flow and mixing fields and perhaps alter the expected stability characteristics.

Eq. 8.2 increased if the fit between the sinusoidal transfer function to the measured data was poor. The data indicated some poor fits and hence incoherent fluctuations with the siren but was consistently high for RR injector 73685 that exhibited the weakest rumble in RR combustion tests due to its non-sinusoidal and non-coherent response to the siren. One possible explanation is that downstream edges of the spray lay partially inside the masked region to give zero AC amplitudes and poor fit qualities as the spray oscillated in and out of that particular region. Eq. 8.3 was summed over all three frequencies and over the AFR and SMD transfer functions. It was always high for RR injector 71257 to suggest a strong coherent response to the siren and this result also matched RR instability measurements. Since rig tests excluded several important combustion related processes that contribute to rumble the correlation between transfer function amplitudes and combustion rumble was therefore imperfect since combustion; combustor geometry; cooling airflows and stretch factor effects on vortex shedding would affect natural frequencies. Despite these omissions, results showed that laser diagnostics in fairly inexpensive, non-combusting, low pressure rig tests could predict injectors that encouraged and discouraged combustion stability to then warrant further investigation.

8.2.11 Correlation of Injector Geometry with Rumble and Discussion

Greenhalgh *et al* (2002) suggested that prefilmer design played a chief role in combustion instability. The ODG therefore correlated injector design features with combustion rumble with standard statistical techniques and subsequently reported results in Greenhalgh *et al* (2004). Prefilmer geometry was found to strongly influence AFR and SMD fluctuations that provide feedback mechanisms and encourage self-amplification of self-excited instabilities. The strength of the acoustic/injector coupling

was concluded to depend on injector geometry and its interaction within a combustion system. This is also influenced by subtle changes to the injector design. Table 8.7 shows the fuel injectors had a different prefilmer length defined as the axial length exposed to air from the inner swirler; effective area of the air passages; fuel flow number in (UK gallons/hour)/ $\sqrt{\text{psi}}$; overall flow number and swirler vane angle.

RR Injector	Prefilmer Length (mm)	Effective Area (mm²)	Fuel Flow Number (UK gal/hr/$\sqrt{\text{psi}}$)	Overall Flow Number	Outer Swirler Vane Angle (°)	Dome Swirler Vane Angle (°)
71257	2.08	230	4.25	6.07	60	42
73630	1.72	250	4.25	4.71	52	52
73686	1.38	202	3.61	3.88	72	54
73030	2.02	202	4.25	4.71	52	52
73685	1.26	180	3.61	3.88	57	55

Table 8.7: RR Injector Geometry

Table 8.8 shows combustion rumble amplitudes measured by RR at two conditions.

RR Injector	275.8kPa; 84AFR 350K	275.8kPa; 84AFR 380K
71257	9.24	6.62
73630	8.27	6.55
73686	1.38	0.34
73030	8.27	2.07
73685	0.34	0

Table 8.8: Rumble Amplitudes in kPa (Gallimore, RR, 2001)

Eq. 8.4 shows Spearman's coefficient that was used to correlate two sets of variables, $(x_1, x_2, \dots, x_n)$ and $(y_1, y_2, \dots, y_n)$, i.e. injector geometry with rumble.

$$\frac{\frac{1}{n} \sum_{i=1}^n x_i y_i - \bar{x} \bar{y}}{\sqrt{\left(\frac{1}{n} \sum_{i=1}^n x_i^2 - \bar{x}^2 \right) \left(\frac{1}{n} \sum_{i=1}^n y_i^2 - \bar{y}^2 \right)}} \quad \text{Eq. 8.4}$$

Where $\bar{x}$ is the mean of $(x_1, x_2, \dots, x_n)$. The coefficient took a value of 1 for a perfectly linear correlation and a value of -1 for a linear anti-correlation where one variable

increased as the other decreased and zero for no correlation. Results identified injector design parameters that promoted combustion stability. These were a short prefilmer, low fuel flow number and high angle between dome vane and nozzle outlet plane. Vane angle was less important than prefilmer geometry or flow number. Caution must however be applied in following these recommendations as suggestions were based on only five injectors. Further, one design parameter may benefit a certain aspect of combustion but hinder another, e.g. a shorter prefilmer may reduce rumble propensity at the expense of less heat transfer to the fuel but this would also keep the liquid viscosity and surface tension high to result in worse atomisation and greater pollutant emissions.

8.3 RESPONSE OF PRESSURE-SWIRL SPRAYS TO FORCING

Given the lessons learned from ICLEAC it became entirely logical to investigate the robustness of a pressure-swirl fuel spray of an ANTLE weak module that may possibly be more prone to combustion oscillations, especially since the pressure-swirl atomiser operated in the centre of three pulsating swirler airflows. The opportunity was taken to use the ICLEAC experimental configuration and measure the response of the pressure-swirl fuel spray from Build 61. Zhu *et al* (2002) reported that low-frequency combustion oscillations occurred at idle and sub-idle conditions and hence the 7% Idle and 24% Approach cases became natural candidates to investigate despite the absence of RR combustion instability data. LSD and PLIF were applied to measure the SMD and AFR response at the same measurement points shown earlier in Table 8.3 on page 185, every 22.5° in the siren cycle at 12, 100 and 200Hz. Although this study was outside the original scope of the thesis, results found pressure-swirl sprays were insensitive to acoustic oscillations in the airflow compared to airblast sprays since they were fuel momentum driven; whereas airblast atomisation is air momentum driven and more affected by pulsations in the airflow. To recap, Table 8.9 shows injector geometry and UFR operating conditions scaled from RR 5 Cell conditions with the rig scaling strategy that conserved U and air to fuel momentum flux ratio. Fractional discrepancies were however greater than in the ICLEAC work due to the larger injector effective area.

Case	$P_{Absolute}$ (kPa)	P_{Gauge} (kPa)	$\Delta P/P$ (7.05%)	Q (l/m)	Q (g/s)	T_a (K)	Φ_{PS}
7% Idle	247	147	0.175	0.49	6.59	316	0.77
24% App.	215	115	0.182	0.60	8.12	316	1.05
Geometry	Swirler 1 = -35°		Swirler 2 = 50°		Swirler 3 = 55°		

Table 8.9: UFR Conditions for B61 PS Atomiser and Geometry

Overleaf, Figure 8.11 and Figure 8.12 show quantitative AFR and SMD images on a false colour scale at 7% Idle and 200Hz. Spray direction was downwards.

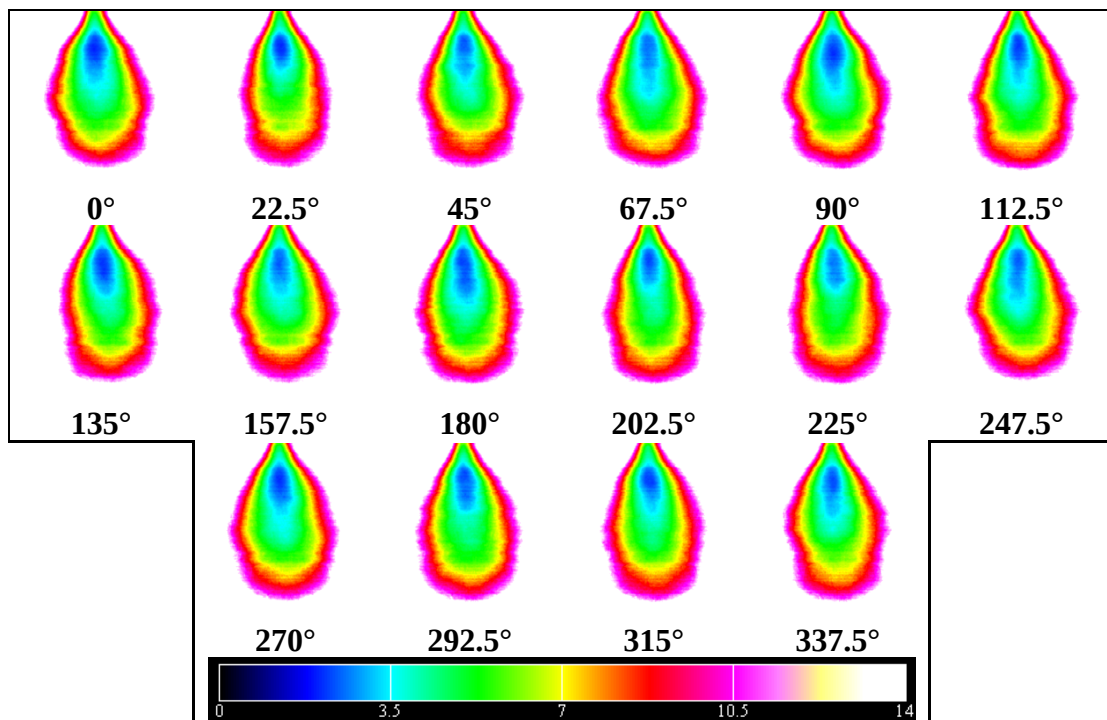


Figure 8.11: Seq. of AFR Images from Build 61 – 7% Idle at 200Hz

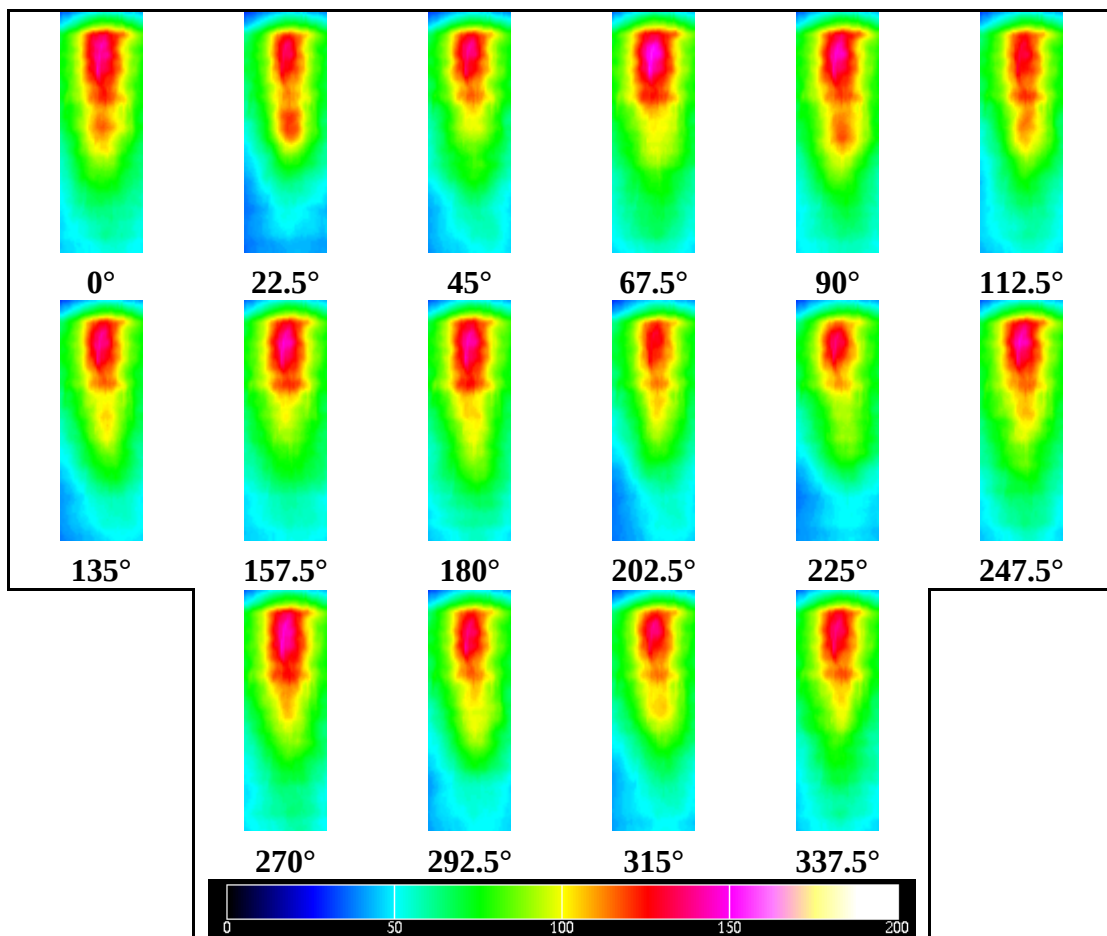


Figure 8.12: Seq. of SMD Images from B61 – 7% Idle at 200Hz

AFR images measured 163 x 190 pixels and were equivalent to a spray size of 43.5 x 50.7mm, whilst SMD images measured 41 x 120 pixels and represented a spray size of

10.9 x 32 mm. Appendix J contains the full image dataset for both conditions. It also includes plots of AFR and SMD values at 12, 100 and 200Hz along three radial planes perpendicular to the injector centreline in the very near, near and further downstream distances. AFR plots are at downstream distances of $X = 25\%$ (12.8mm), 50% (25.6mm) and 75% (38.5mm). SMD plots pertain to downstream distances of $X = 25\%$ (8.01mm), $X = 50\%$ (16.02mm) and $X = 75\%$ (24.03mm).

8.3.1 Discussion and Conclusions

This discussion pertains to the plots shown in Appendix J. For both operating conditions the AFR was 0.5 and 12.5. More variation existed in SMD values. In the 7% Idle condition at 12Hz, SMD was 50 – 150 μm but upper limit values increased to 225 μm in five cases. At both 100 and 200Hz, SMD values were also 50 – 175 μm . At 24% Approach the fuel flow rate was increased by 22% and the rig pressure was reduced by 13% to significantly impact the measured SMD range. At 12Hz, the peak SMD values declined relative to the 7% Idle condition to 50 – 100 μm . They dropped more steeply compared to the 7% Idle case at 100Hz and were 50 – 100 μm between 22.5° and 202.5° in the siren cycle and then climbed to 75 – 160 μm between 247.5° and 360°, where 0° and 360° represented the same point. At 200Hz, minimum SMD values increased relative to the 7% Ground Idle condition and were 75 – 175 μm .

Comparing each row of the SMD plots in Appendix J shows the effect of increasing frequency and perturbation levels in the airflow. At 7% Idle, the SMD values marginally increased in eight cases but significantly reduced in six cases to imply that previous SMD measurements at 12Hz were in fact dubious and more significantly, that the increase in frequency raised SMD values. SMD values changed little when the frequency was increased further from 100Hz to 200Hz. At 24% Approach the increase in frequency from 12 to 100Hz significantly increased SMD values in eight cases but was similar in five cases. The further frequency increase to 200Hz only raised SMD values in cases of the previous jump from 12 to 100Hz but had little impact in cases where the SMD was previously increased from 100 to 200Hz. In all cases, the troughs in the AFR corresponded with peaks in SMD because the airflow velocity, air momentum and shear forces increased with frequency to attain their maximum values at the siren open position. The AFR in the very near nozzle region at $X = 25\%$ (12.8mm) was consistently the richest in central spray regions. The temporal response of the AFR and SMD per unit amplitude of the air oscillation was negligible as pressure-swirl atomisation is fuel dominated.

The 22% increase in fuel flow rate and 13% decrease in rig pressure at the 24% Approach condition relative to 7% Idle reduced the AFR in outer spray regions at

100Hz between phase angles of $225^\circ - 360^\circ$. Similarly, it reduced the AFR at 200Hz at all phase angles. There was little change between each case at 12Hz. Spray cone angles oscillated as a function of phase angle and frequency. This was readily apparent at 24% Approach and 100Hz.

For both cases there was little change in the very near nozzle region where fuel momentum dominance was observed because the interaction of fuel with oscillating airflows was weak enough to prohibit better atomisation. Hence, further downstream the oscillations only affected the cone angle and not the SMD distributions. Although pressure-swirl atomisation is driven by fuel momentum and the fuel in these cases was not pulsed, the fuel spray was situated at the centre of three oscillating swirling airflows with vane angles of -35° , 50° and 55° . The innermost -35° contra swirler was designed to preserve the shape and distribution pattern of the liquid spray to give consistent mixture strengths for altitude relight purposes. Its role was to force liquid migration from peripheral spray regions into the secondary swirler airflow and subject this to larger velocities. The interface between the first contra and second co-swirler naturally had the largest instability. This should counter the contraction in spray cone angle as pressure increases but was not readily apparent if the 7% Idle and 24% Approach cases were compared, where the latter used a lower rig pressure. The second 50° co-swirler had higher angular momentum due to its interaction with the outermost 55° co-swirler. The prime function of the second swirler was to atomise fuel that left the prefilmer lip in airblast atomisation. However, in both pilot only conditions there was no fuel supplied to the airblast circuit. The third outermost swirler had the largest angle. Similar to swirler two its purpose was primarily to sandwich the liquid fuel sheet in airblast atomisation but its principal use was to spread out the liquid and manage the fuel patternation and flowfield geometry. Rate of spread is determined by the rate of recirculation in the enclosure. It was assumed that this would not alter by any significant amount in the undertaken measurements in very near nozzle regions.

The experiment could have been improved by measuring the response of a pressure-swirl fuel spray in more than one injector geometry. It would also have been useful to measure the stepwise contributions of the three airflows on the pressure-swirl spray to increase understanding on the robustness of the spray in an acoustic field and also the stepwise contribution of the various airflows on the spray although this would also have required imaging the air flowfield. The intention was to measure the influence of acoustic oscillations on hybrid sprays where both the pressure-swirl and airblast sprays were operational such as at the 30% Approach condition where combustion rumble may also occur. Apart from being beyond the scope of this work, this could not be accomplished due to the change in experimental set-up discussed in Chapter Seven that was necessary to increase the camera field of view and image the main airblast spray.

8.4 SUMMARY

Liquid-fuelled aero engine combustors tend to “rumble” between 60 – 120 Hz at the sub-idle and idle conditions due to interactions between pressure, unsteady combustion and operating conditions. This interaction modulates the local Air to Fuel Ratio (AFR) and heat release rates. If the Rayleigh criterion is obeyed it can increase noise, vibration and mechanical wear. The central thread of this chapter was application of Laser Sheet Dropsizing (LSD) and Planar Laser Induced Fluorescence (PLIF) to measure droplet Sauter Mean Diameter (SMD) and AFR in fuel sprays from five RR airblast injectors, one Turbomeca Lean Module and ANTLE weak module Build 61 using the pressure-swirl atomiser in isolation. Phase-locked SMD and AFR measurements were made at sixteen measurement points, every 22.5° in the siren cycle at 12, 100 and 200Hz. A siren located upstream of the injector in the Unsteady Flow Rig (UFR) perturbed the air supply. The scaling strategy conserved air to fuel momentum flux ratio and U to preserve fuel patternation and the acoustic impedance. No cone angle oscillations were observed in airblast atomisation. The cone angle did however vary as a function of airbox pressure and injector air pressure drop. The involvement of the author ended with delivery of primary data for the ICLEAC contract. This consisted of static images to calculate spray cone angles and fully quantitative SMD and AFR data to extract spray transfer functions that described the SMD and AFR temporal response at several regions in the spray to forced airflow modulations.

Results showed a cyclic change in both spray properties that was coherent with the applied acoustic perturbation. AFR and SMD fluctuations were identified as candidates for a feedback mechanism that sustained self-excited combustion instabilities. The amplitude and phase of the cyclic change varied between injectors and was frequency sensitive. The strength of the response to each modulation and quality of fit of the sinusoidal transfer functions correlated well with RR combustion instability tests, although it excluded some crucial aspects such as the actual combustion; geometry; cooling airflows; stretch factors and vortex shedding effects. Also ignored were other feedback mechanisms that related to the natural frequency of the combustion system and flow and mixing fields that affected the injector spray. Nevertheless, the undertaken spray characterisation study allowed the issue of combustion instabilities to be broken down into prosecutable chunks for more detailed analysis. Correlations between the measured transfer function amplitudes and quality of fit suggested that non-combusting and inexpensive rig tests had the potential to identify injector designs that were susceptible to combustion rumble at much earlier design stages before expensive combustion tests. Flame stability was found to depend on spray dynamics that can be investigated easily without combustion. A separate statistical analysis revealed aspects of airblast atomisers that correlated well with rumble amplitude. These were fuel flow

number; prefilmer length; dome swirler vane angle and effective area. The finding was that a long prefilmer length substantially increased the susceptibility of injectors to rumble. The undertaken work was for the Instability Control of Low Emission Aero-Engine Combustors (ICLEAC) engine demonstrator programme. Full results were reported in ICLEAC (2004), Jermy *et al* (2004a) with sanitised versions in Jermy *et al* (2004b) and Greenhalgh *et al* (2004) due to the proprietary nature of the study.

The opportunity was taken to use the ICLEAC experimental set-up to measure the temporal response in AFR and SMD of pressure-swirl fuel sprays from Build 61 at both pilot only conditions of 7% Idle and 24% Approach. The temporal response per unit amplitude of air oscillation was found to be near-negligible because pressure-swirl atomisation is fuel dominated, however the spray cone angles oscillated as a function of phase angle and frequency. There was little change in the AFR and SMD response in the very near and near nozzle regions due to fuel momentum dominance. Interaction of fuel with oscillating airflows was sufficiently weak enough to prohibit improvements in atomisation quality. This however strengthened downstream to only broaden the spray cone angles and not the AFR or SMD distributions. The experiment could have been improved by investigating pressure-swirl sprays in several injectors and by measuring the stepwise contributions of the three airflows on the pressure-swirl spray to confirm its robustness in an acoustic field. This would also have entailed imaging the airflow field by Particle Imaging Velocimetry (PIV). A second unfulfilled intention was to measure the influence of acoustic oscillations on hybrid sprays where both the pressure-swirl and airblast sprays operated together; especially at low power conditions such as 30% Approach where combustion rumble may occur.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

The three research goals have been met.

- Strategic recommendations have been made to RR
- A NO_x prediction tool has been developed and tested
- Combustion instability has been successfully measured

This section discusses key findings. All aero engine suppliers must develop low emissions technology to align with incoming changes in strategic operating context. RR responded better than rivals, GE or UTC to the harsh economic climate in 2009. All suppliers, however, face a large threat from new entrants in the aftermarket business. If threatened RR must collaborate or vertically integrate; enter the market and substitute from within. In the short-term RR must stay alert and responsive to market conditions; invest in alternative fuels; strengthen alliances; reduce in-service problems; clock stops; late deliveries; patent parts that sell at higher prices than patent costs; use dual sourcing strategies; improve supply chains; use data mining to identify profitable customers and secure more WIN-WIN engine lease agreements. In the mid-term, RR should consider collaborations with competitors in the lengthy ten to fifteen year pre-competitive; pre-technology; capability acquisition aero engine design phase to acquire joint patents and change the basis of competitive advantage from one of capability acquisition to the pace of technology transfer and in being the first to market to secure engine certification; exclusivity and maximum orders. In the long term, RR should invest in open rotor contra-rotating fan blade technology; discourage airlines from buying aero engines but if this happens lock them into maintenance contracts; expand to cope with more inventory; cut supplier switching costs; seek cheaper raw materials; use lobbyists and consultants to win sales and critically, learn from competitor actions.

Extraction of calibration constants for quantitative AFR and SMD was time consuming and fraught with difficulty. A faster much simpler technique is needed such as imaging a spray of known AFR to calibrate the PLIF signal. Although Domann and Hardalupas (2002) reported that LSD uncertainties increased from 4 to 31% as droplet diameters declined from 150 to 10 μ m and Réveillé (2005) showed that LSD results deviated by ~25% over PDA measurements, the calibration reported in the undertaken study was based on SMD values of ~90 μ m without PDA beam attenuation. Therefore, the Mie squared dependence with SMD was in the main respected, as measured values were 50 – 225 μ m. LSD performed better than PDA in dense sprays. The chapter on rig scaling delivered a robust method to help obtain two-phase flow similarity between engine and

rig operating conditions. A fractional deviation was used to judge the performance of each rig scaling strategy. Conservation of the air to fuel momentum flux ratio and injector pressure drop replicated the fuel patternation and gave economical fuel flow rates. Preservation of the air to fuel momentum flux ratio and global air velocity helped simulate the fuel patternation and acoustic impedance. Free pressure-strategies performed ~60% better than pressure-determining strategies. Gains, however, were small beyond a certain pressure and counter-productive if scaling to low pressure and temperature conditions. Sample calculations showed strategies demanded higher pressures at increased rig temperatures. When scaling to high engine temperatures and pressures the strategy that conserved momentum flux ratio and injector pressure drop improved $\Phi_{Airblast}$ by ~20% at 373K over 323K but when scaling to a lower temperature and pressure, both this strategy and those that conserved global air velocity improved $\Phi_{Airblast}$ by ~90% at 373K over 323K. At modest rig temperatures it is more likely to match the two-phase flow of idle and sub-idle engine conditions than higher power conditions. Hence, all strategies must be judged depending on the engine condition to be scaled. Atmospheric pressure measurements in the MSR tested the ability of rig scaling strategies to replicate spray properties of genuine practical interest. Normalised results allowed comparative analysis of spray structure as a function of injector design and rig operating conditions. Spray atomisation quality was sensitive to the choice of rig scaling strategy. This informed development of scaling laws for airblast sprays described in Jermy, Hussain and Greenhalgh (2004); hybrid sprays and the selection of optimum strategies where rig pressure was a free parameter. Introduction of the main spray in ANTLE weak modules had significant aerodynamic and optical impacts on the pilot spray. Swirl direction had substantial impact on spray structure and the flame start position to alter flow velocities; presence of confined eddies in the interface between fuel droplets and surrounding air; combustion stability; mixture strength; cone angles; axial and radial penetration and asymmetry to affect NO predictions in imaged regions.

Spray characterisation studies in the UFR reduced fractional discrepancies in two-phase flow between engine and rig testing conditions by ~900% over atmospheric pressure studies. Degree of signal loss due to radiation trapping in the pilot region as a consequence of introducing the main spray was measured but left uncorrected since it had an optical and structural impact in the pilot region. The NO model developed as a part of this study was based on mixture strength and geared towards premixed situations and not diffusion flames. Its failure to predict NO in rich pilot regions was a positive result as a plausible correlation with premixed conditions was found in two out of the three ANTLE Builds since flame start positions in these cases were in imaged regions.

The ICLEAC study took phase-locked SMD and AFR measurements at sixteen measurement points, every 22.5° in the siren cycle at 12, 100 and 200Hz in airblast fuel

sprays. The temporal response to each modulation and quality of fit of the sinusoidal transfer functions correlated well with RR combustion instability measurements. The spray cone angles did not oscillate. Results were reported in ICLEAC (2004), Jermy *et al* (2004a) with condensed versions in Jermy *et al* (2004b) and Greenhalgh *et al* (2004). Oppositely, the temporal response per unit amplitude of air oscillation in fuel momentum dominated pressure-swirl sprays was negligible in the very near and near nozzle regions but the spray cone angles oscillated as a function of phase angle and frequency. The interaction of fuel with oscillating airflows was sufficiently weak to prohibit any improvement in atomisation quality. This strengthened further downstream to broaden the spray cone angles but not AFR or SMD distributions. The experiment could have been improved by investigating the sprays from several injectors and also by measuring the stepwise contribution of each of the three swirler airflows on the pressure-swirl spray to confirm its robustness in an acoustic field. Results confirmed the practicality of the adopted methodology to help isolate injector design features for low emissions and combustion instability at ~4% of full-scale engine combustion tests.

The broad objective of this thesis, to first obtain and then correlate fuel placement data with RR NO_x and combustion instability measurements was met. The connection between injector design and fuel patternation with emissions performance was explored. Although the NO_x methodology somewhat predicted the RR measured trends it was naturally unable to predict NO_x emissions when the flame start position lay outside the imaged region. An attempt to image more of the spray region would defy the premise used in cold studies that spray behaviour is similar to combusting conditions in near nozzle regions. Therefore, it remains doubtful that cold flow studies can predict NO_x from injector sprays that anchor the flame further downstream. It would also have been interesting to predict NO_x formation under forced acoustic oscillations but this was beyond the scope of this work. Results could have been improved by using real combustor geometry in experiments; better residence time calculations; measuring spray sensitivity first to moving combustor walls in and out and secondly to rising fuel levels in the UFR during measurements that change rig frequencies and also propagate pressure waves upstream to influence atomisation quality; applying PIV to measure changes in flowfield structure and finally, by developing a CFD model to link all the data together to predict injector behaviour for intermediaries between the tested builds.

Although more work is needed to perfect the calibration; compensate for radiation trapping; understand the disrespected Mie squared dependency with droplet diameter in LSD and finally the methodology to predict NO_x emissions; overall findings suggest that application of optical diagnostics in non-combusting, low pressure, scaled rig tests can economically segregate those injector designs with a propensity to yield low NO_x emissions and high stability providing the flame start position is in the imaged region.

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APPENDIX A

PDA DATASETS FOR DROPLET GENERATOR

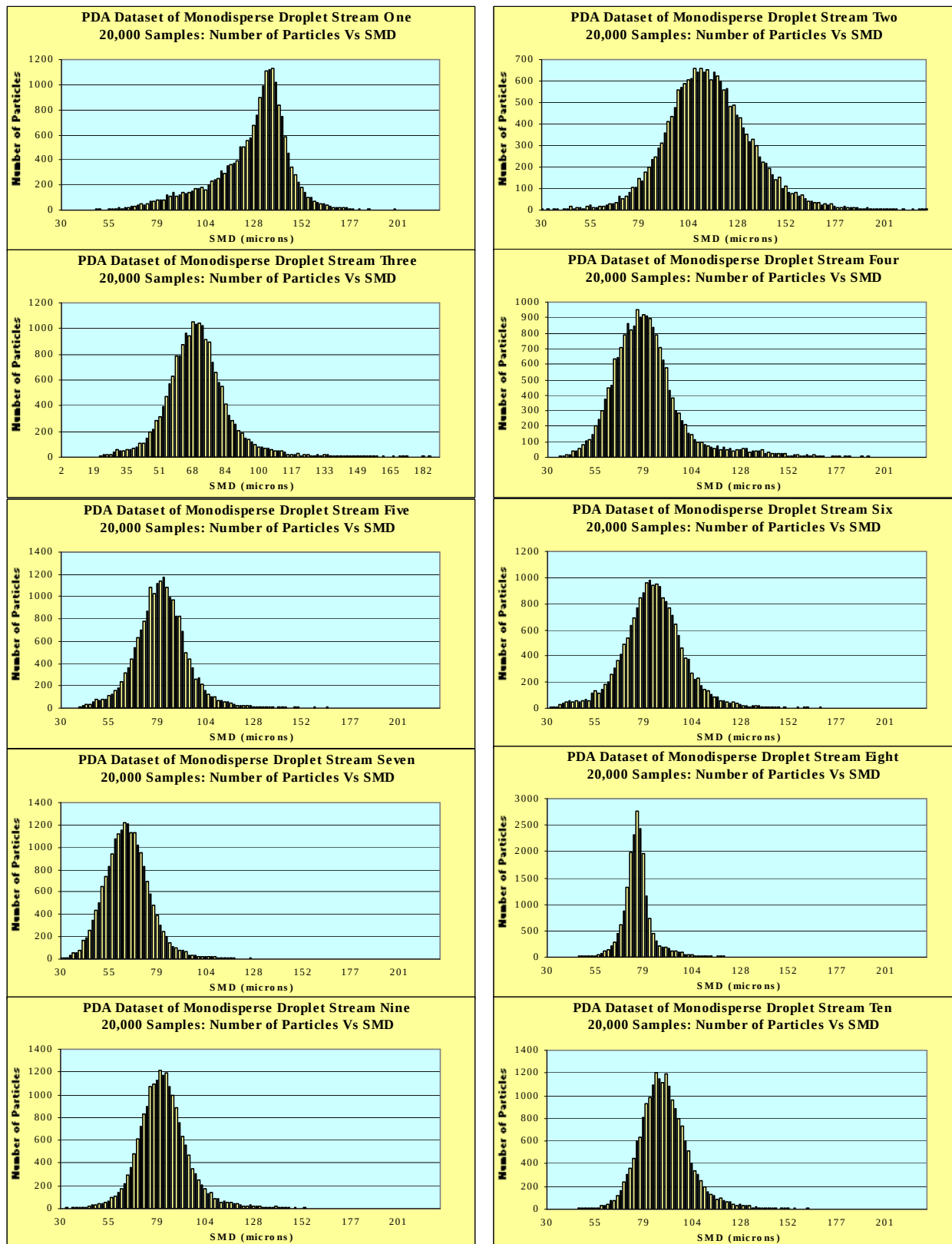


Figure 9.1: PDA Dataset for 20,000 Validated Samples

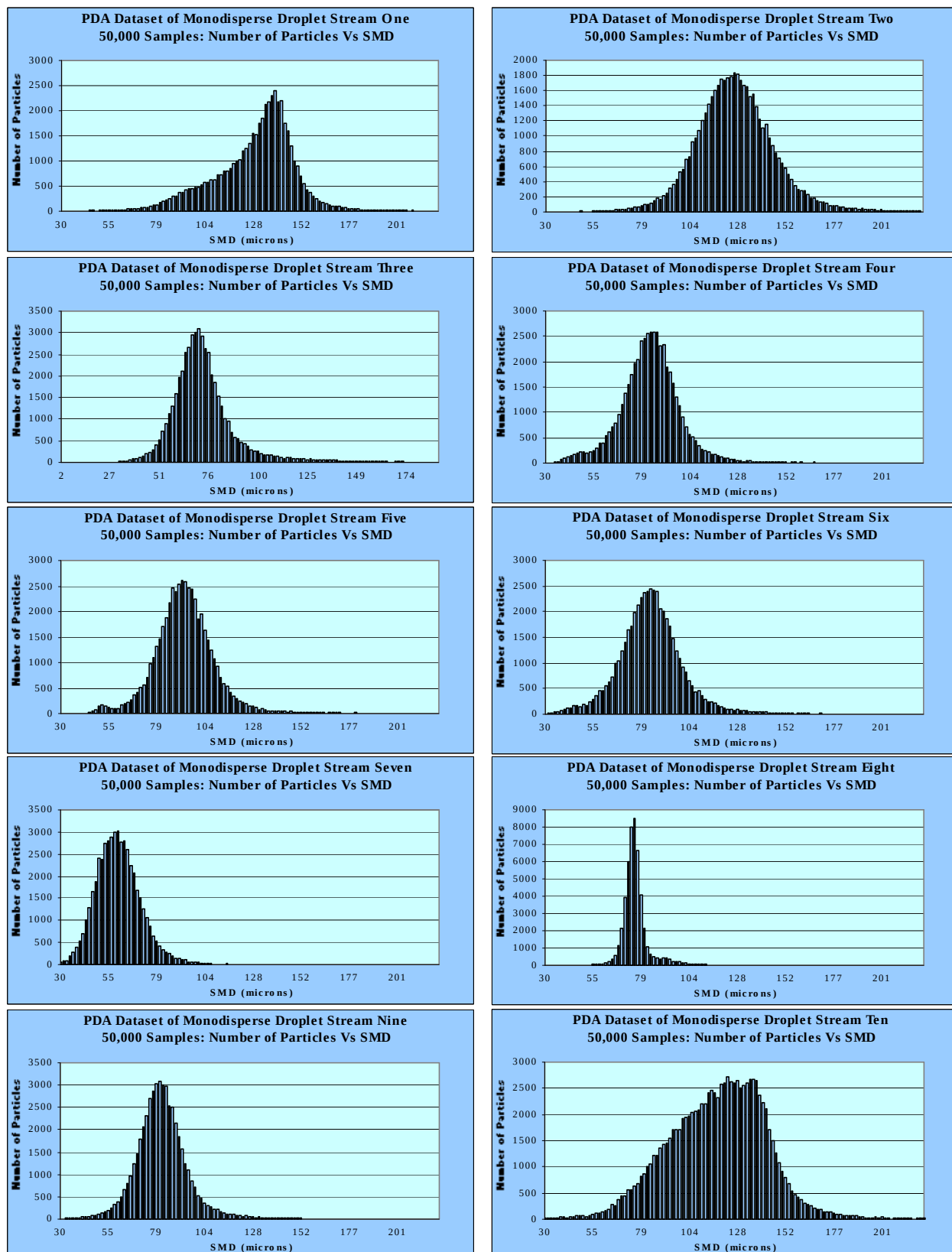


Figure 9.2: PDA Dataset for 50,000 Validated Samples

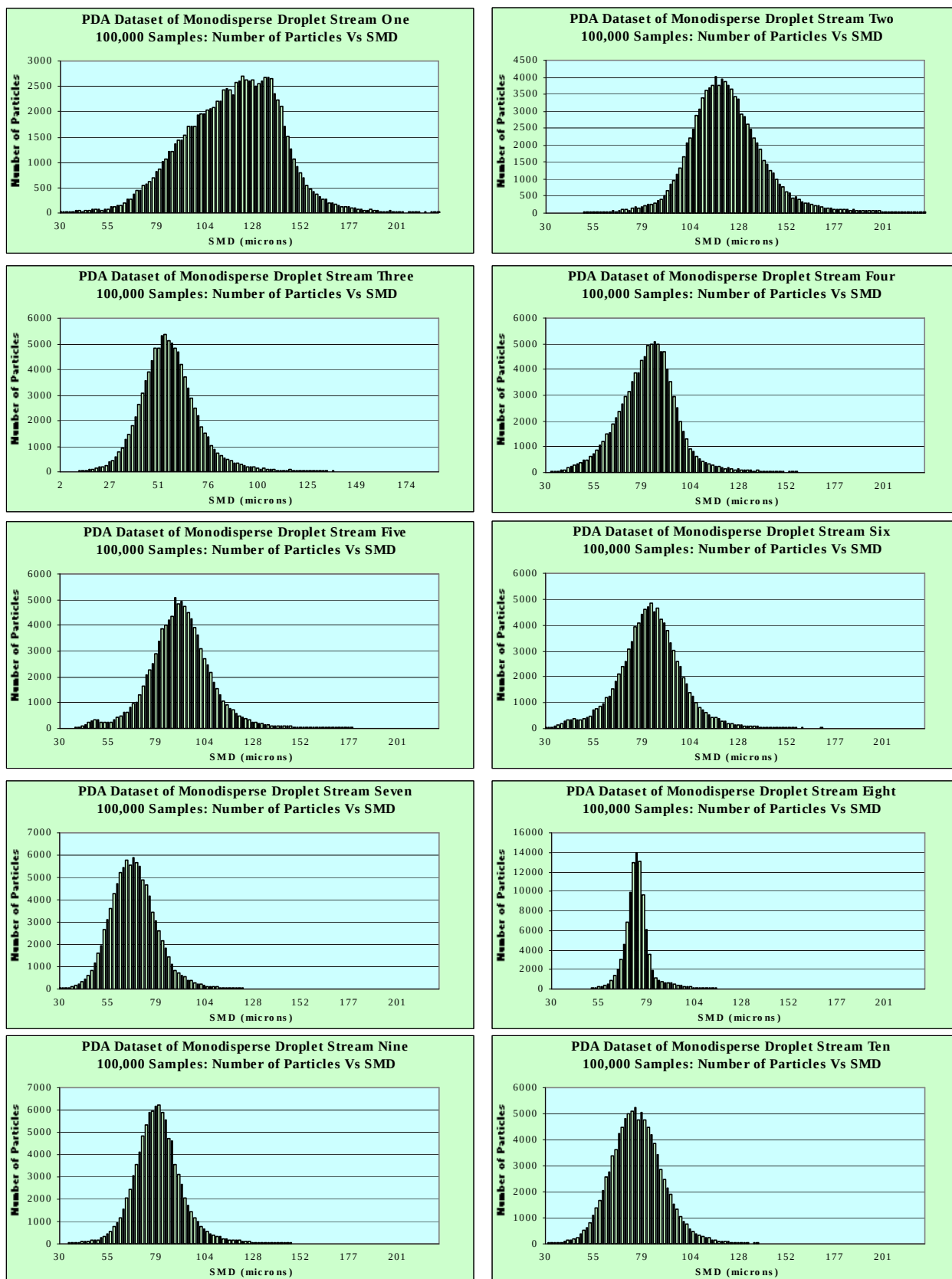


Figure 9.3: PDA Dataset for 100,000 Validated Samples

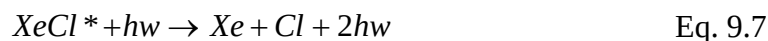
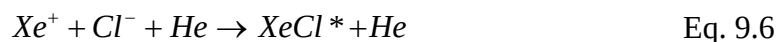
APPENDIX B

EXCIMERS AND SHEET THICKNESS EQUATIONS

The term excimer is short for “excited dimmer”. Eq. 9.1 and Eq. 9.2 show that an excimer forms if an atom in its excited state bonds with an identical atom in its ground state. Rare gas dimers include He_2^* , Ne_2^* and Ar_2^* . The word excimer also describes diatomic or triatomic molecule that forms under the same circumstances.



Although reaction sequences to describe the association and dissociation of Xe and Cl atoms or ions are widely available in the literature, three important types are outlined: ion-ion recombination, harpooning and secondary recombination. Eq. 9.3 and Eq. 9.4 show ion-ion recombination where electron impact excites a Xe atom to form a Xe ion. Further electron impact gives Xe^* . Eq. 9.5 shows the harpooning reaction where electrons dissociatively attach to the HCl halogen donor gas to form Cl ions. In the presence of a third body buffer gas, either Helium or Neon, Eq. 9.6 shows secondary recombination where Xe and Cl ions form an unstable rare gas halide, XeCl^* . Eq. 9.7 shows this rapidly loses internal vibrational energy by inelastic collisions during electronic transition to the ground state to emit light in the process.



The life of the bound upper state is $\sim 5\text{ns} - 5\mu\text{s}$ compared to $\sim 10^{-4}\text{ns}$ of the ground state to give a population inversion and high quantum efficiency. Figure 9.4 shows the energy level diagram where the electronic ground state is assigned $\text{X}^2\Pi$ and excited state $\text{A}^2\Sigma^+$. Four electron-vibrational transition bands (0,0), (0,1), (0,2) and (0,3) exist near 308nm. The 308nm XeCl line excites the (0,0) band and PLIF

experiments in this study detect the weaker, wavelength shifted fluorescence on the (0,1) band at ~343nm.

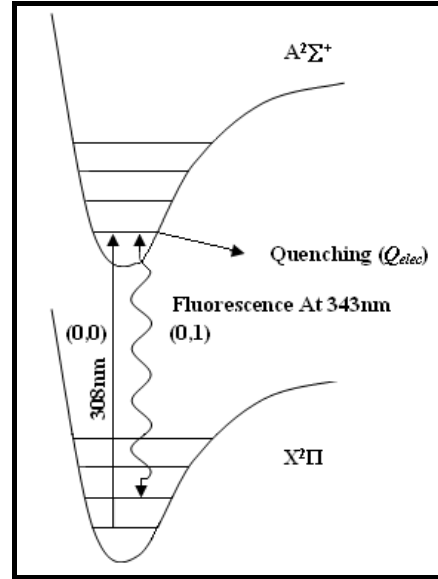


Figure 9.4: Energy Level Diagram for 308nm XeCl Line

Table 9.1 shows three other important excimers and corresponding wavelengths.

Excimer	Laser Wavelength (nm)
Argon Fluoride (ArF*)	193
Krypton Fluoride (KrF*)	248
Xenon Chloride (XeCl*)	351

Table 9.1: Common Excimers and Corresponding Wavelengths (Svelto, 1998)

Eq. 9.8 and Eq. 9.9 use spherical lens focal length, laser wavelength and initial beam width to calculate sheet thickness and length. Eq. 9.10 multiplies the ratio of cylindrical lens focal lengths by initial beam length to give sheet height. The inter-lens distance however is moved to suit experimental needs and this is primarily responsible for the discrepancy between the theoretical and measured sheet thickness.

$$t \approx \frac{4}{\pi} \sqrt{\frac{\ln 2}{2}} \frac{f_1 \lambda}{d_x} \approx 46 \mu m \quad \text{Eq. 9.8}$$

$$l \approx \frac{8}{\pi} \frac{\lambda f_1^2}{d_x^2} \approx 31 mm \quad \text{Eq. 9.9}$$

$$h \approx \frac{f_3}{f_2} d_y \approx 42 mm \quad \text{Eq. 9.10}$$

APPENDIX C

ENGINE OPERATING CONDITIONS

9.1 21AFR INJECTOR

Table 9.2 shows engine running conditions for the 21 AFR fuel injector.

	Engine Operating Condition		
	Ground Idle	Take-Off (1)	Take-Off (2)
T₃₀ (K)	530	891	891
P₃₀ (kPa)	615	1179	1179
AFR	60	41.4	47

Table 9.2: 21 AFR Engine Operating Conditions (Wynne, 1999)

9.2 BUILDS 34, 34C, 43, 45 AND 61

Table 9.3 shows RR scaled 5 Cell engine conditions for ANTLE Builds 34, 43, 45 and 61. 5 Cell is a single sector combustion test rig capable of 800K and 5 bar.

Engine Condition	T₃₀ (K)	AFR	P₃₀ (kPa)			
	All Builds		34	43	45	61
100% Take off (10:90)	800	22.5	336	321	314	354
85% Climb (10:90)	800	25.2	327	313	314	345
Cruise (10:90)	800	27.8	316	320	324	345
30% Approach (30:70)	691	43.75	420	414	416	450
24% Approach (0:100)	664	48.4	421	404	425	436
7% Idle (0:100)	557	63.6	400	407	407	432

Table 9.3: 5 Cell Engine Conditions for B34, 43, 45 and 61

Table 9.4 shows 18 Rig engine conditions for ANTLE Builds 34 and 34C. 18 Rig is a single sector combustion test rig but is capable of achieving 800K and 2MPa.

Engine Condition and Pilot:Main Fuel Splits	18 Rig Engine Conditions for Builds 34 and 34C		
	P₃₀ (kPa)	T₃₀ (K)	AFR
100% Take off (10:90)	2172	800	22.5
85% Climb (10:90)	2172	800	25.4
Cruise (10:90)	2172	749	35.6
30% Approach (30:70)	1827	708	43.8
24% Approach (0:100)	1358	664	48.4
7% Idle (0:100)	669	562	63.6

Table 9.4: 18 Rig Engine Conditions for B34 and 34C

Table 9.5 shows 18 Rig engine running conditions for ANTLE Build 61.

Engine Condition and Pilot:Main Fuel Splits	18 Rig Engine Conditions for Build 61		
	P₃₀ (kPa)	T₃₀ (K)	AFR
100% Take off (10:90)	2172	800	22.5
85% Climb (10:90)	2172	800	25.4
Cruise (10:90)	2172	760	34.3
30% Approach (30:70)	1827	691	43.8
24% Approach (0:100)	1358	645.4	48.4
7% Idle (0:100)	669	562	63.6

Table 9.5: 18 Rig Engine Conditions for B61

9.3 RR NO_x MEASUREMENTS

Table 9.6 shows the available EINO_x measurements for ANTLE Builds 34, 34C, 43, 45 and 61 taken from RR 18 Rig and 5 Cell combustion tests.

Engine Condition and Pilot:Main Fuel Splits	EINO_x Measurements for Each Build (g/kg)				
	34 (5 Cell)	34C (18 Rig)	43 (5 Cell)	45 (5 Cell)	61 (18 Rig)
100% Take off (10:90)	16.7	31.4	16.9	19.1	7.8
85% Climb (10:90)	14.7	20.5	12.3	14.5	3.9
Cruise (10:90)	10.2	1.90	7.4	11.2	2.2
30% Approach (30:70)	8.4	7.00	3.4	3.9	3.8
24% Approach (0:100)	11.1	11.4	9.4	9.7	7.8
7% Idle (0:100)	6.1	6.10	5.9	6.2	5.4

Table 9.6: RR NO_x Measurements

APPENDIX D

MSR OPERATING CONDITIONS

9.4 21 AFR INJECTOR

Table 9.7 shows scaled rig operating conditions for the RR 21 AFR fuel injector. The Ground Idle condition was only characterised to increase the experimental dataset although the main module would not be expected to operate at this condition. Scaling strategies conserved (a) injector pressure drop ($\Delta P/P$) and AFR and (b) $\Delta P/P$ and air to fuel momentum flux ratio. For experimental consistency, the air mass flow rate was held constant at 67.51g/s for all cases to give a $\Delta P/P$ of 4.37% of the upstream absolute static pressure. On average, the strategy that conserved air to fuel momentum flux ratio and $\Delta P/P$ performed ~64% better in terms $\Phi_{PS} = Re, Ma, Stk, We, p_D = 1$ in comparison to the other. This reflected its ability to reproduce key spray properties under atmospheric pressure conditions that corresponded better with actual engine operating conditions. Despite this, the fractional discrepancy under atmospheric pressure remained significantly large due to the error in Stk from the fuel momentum dominated pressure-swirl spray.

Injector Pressure Drop and AFR $\left(\frac{\Delta P}{P} \text{ and } AFR \right)$			
Engine Condition	$\left(\frac{\Delta P}{P} \right) (\%)$	Fuel (l/m)	$\Phi_{PS} (Re, Ma, Stk, p_D = 1)$
Ground Idle	4.37	0.08	26.3
Take-Off (1)	4.37	0.12	53.6
Take-Off (2)	4.37	0.11	53.6
Injector Pressure Drop and Air/Fuel Momentum Flux Ratio $\left(\frac{\Delta P}{P} \text{ and } \frac{P_a}{P_f} \right)$			
Engine Condition	$\left(\frac{\Delta P}{P} \right)$	Fuel (l/m)	$\Phi_{PS} (Re, Ma, Stk, p_D = 1)$
Ground Idle	4.37%	0.16	10
Take-Off (1)	4.37%	0.24	18.9
Take-Off (2)	4.37%	0.21	18.9

Table 9.7: MSR Conditions for 21 AFR

9.5 ANTLE WEAK MODULE BUILD 34

Table 9.8 shows MSR scaled operating conditions from 5 Cell for ANTLE Weak Module Build 34. Tested scaling strategies conserved (a) Global Air Velocity (U) and AFR and (b) $\Delta P/P$ and AFR.

$\left(\frac{\Delta P}{P}\right) = 3.3\%$ for both strategies							
(a) Global Air Velocity and AFR (U and AFR)							
Engine Condition and (Pilot:Main) Fuel Splits	P_{30} (kPa)	T_{30} (K)	AFR inj	Fuel (l/m)	Φ_A	Φ_{PS}	Φ_H
100% Take off (10:90)	336	800	22.5	0.72	1.62	2.11	2.66
85% Climb (10:90)	327	800	25.2	0.64	1.57	1.97	2.51
Cruise (10:90)	316	800	27.8	0.45	1.50	1.81	2.35
30% Approach (30:70)	420	691	43.75	0.34	2.57	5.12	5.73
24% Approach (0:100)	421	664	48.4	0.30	-	5.57	5.57
7% Idle (0:100)	400	557	63.6	0.21	-	7.02	7.02
(b) Injector Pressure Drop and AFR $\left(\frac{\Delta P}{P} \text{ and AFR}\right)$							
Engine Condition and (Pilot:Main) Fuel Splits	P_{30} (kPa)	T_{30} (K)	AFR inj	Fuel (l/m)	Φ_A	Φ_{PS}	Φ_H
100% Take off (10:90)	336	800	22.5	0.43	3.86	3.85	5.45
85% Climb (10:90)	327	800	25.2	0.38	3.70	3.57	5.14
Cruise (10:90)	316	800	27.8	0.27	3.49	3.25	4.77
30% Approach (30:70)	420	691	43.75	0.22	5.40	8.25	9.86
24% Approach (0:100)	421	664	48.4	0.20	-	8.75	8.75
7% Idle (0:100)	400	557	63.6	0.15	-	9.91	9.91

Table 9.8: MSR Conditions for B34

9.6 ANTLE WEAK MODULE BUILD 34C

Table 9.9 shows MSR scaled operating conditions from 18 Rig for ANTLE Weak Module Build 34C. The tested scaling strategy conserved global air velocity and AFR. Air Flow rate varied between and to give a maximum $\Delta P/P$ 3.4%.

$\left(\frac{\Delta P}{P}\right) = 3.4\%$							
Global Air Velocity and AFR (U and AFR)							
Engine Condition and Pilot:Main Fuel Splits	P_{30} (kPa)	T_{30} (K)	AFR inj	Fuel (l/m)	Φ_A	Φ_{PS}	Φ_H
100% Take-off (10:90)	2172	800	22.5	0.64	20.66	134.5	136.1
85% Climb (10:90)	2172	800	25.4	0.57	20.66	134.5	136.1
Cruise (10:90)	2172	749	35.6	0.39	21.43	148.9	150.5
30% Approach (30:70)	1827	708	43.8	0.31	18.46	115.5	116.9
24% Approach (0:100)	1358	664	48.4	0.27	0	70.52	70.52
7% Idle (0:100)	669	562	63.6	0.19	0	21.65	21.65

Table 9.9: MSR Conditions for B34C

9.7 ANTLE WEAK MODULE BUILD 43

Table 9.10 shows MSR scaled operating conditions from 5 Cell for ANTLE Weak Module Build 43. The tested scaling strategy conserved global air velocity and AFR. Air Flow rate varied between 171 and 211g/s to maintain $\Delta P/P$ at 2.9%.

$\left(\frac{\Delta P}{P}\right) = 2.9\%$							
Global Air Velocity and AFR (U and AFR)							
Engine Condition and Pilot:Main Fuel Splits	P_{30} (kPa)	T_{30} (K)	AFR inj	Fuel (l/m)	Φ_A	Φ_{PS}	Φ_H
100% Take off (10:90)	321	800	22.5	0.70	1.55	1.93	2.47
85% Climb (10:90)	313	800	25.2	0.62	1.51	1.82	2.36
Cruise (10:90)	320	800	27.8	0.56	1.55	1.92	2.46
30% Approach (30:70)	414	691	43.75	0.33	2.57	5.05	5.67
24% Approach (0:100)	404	664	48.4	0.29	0	5.15	5.15
7% Idle (0:100)	407	557	63.6	0.20	0	7.44	7.44

Table 9.10: MSR Conditions for B43

9.8 ANTLE WEAK MODULE BUILD 45

Table 9.11 shows MSR scaled operating conditions from 5 Cell for ANTLE Weak Module Build 45. The tested scaling strategy conserved global air velocity and AFR. Air Flow rate varied between 177 and 218g/s to maintain $\Delta P/P$ at 3.1%.

$\left(\frac{\Delta P}{P}\right) = 3.1\%$							
Global Air Velocity and AFR (U and AFR)							
Engine Condition and Pilot:Main Fuel Splits	P_{30} (kPa)	T_{30} (K)	AFR inj	Fuel (l/m)	Φ_A	Φ_{PS}	Φ_H
100% Take off (10:90)	314	800	22.5	0.72	1.504	1.802	2.35
85% Climb (10:90)	314	800	25.2	0.64	1.504	1.802	2.35
Cruise (10:90)	324	800	27.8	0.58	1.562	1.952	2.50
30% Approach (30:70)	414	691	43.75	0.34	2.56	5.05	5.66
24% Approach (0:100)	425	664	48.4	0.30	0	5.77	5.77
7% Idle (0:100)	407	557	63.6	0.21	0	7.37	7.37

Table 9.11: MSR Conditions for B45

APPENDIX E

BASIC LSD IMAGE PROCESSING FOR 21 AFR

Figure 9.5 shows basic LSD image processing for 21 AFR. A calibration image gives the spatial resolution, background level and co-ordinates of corresponding PLIF and Mie pixels. Individual PLIF and Mie data images are averaged, the background is subtracted and both images are separated, suspect regions are masked and the PLIF image is divided by ten to account for the ND 1.0 filter in the Mie channel. PLIF and Mie images are aligned so corresponding pixels in each image overlap. Finally, the PLIF image is divided by the Mie image to yield a two-dimensional map of SMD.

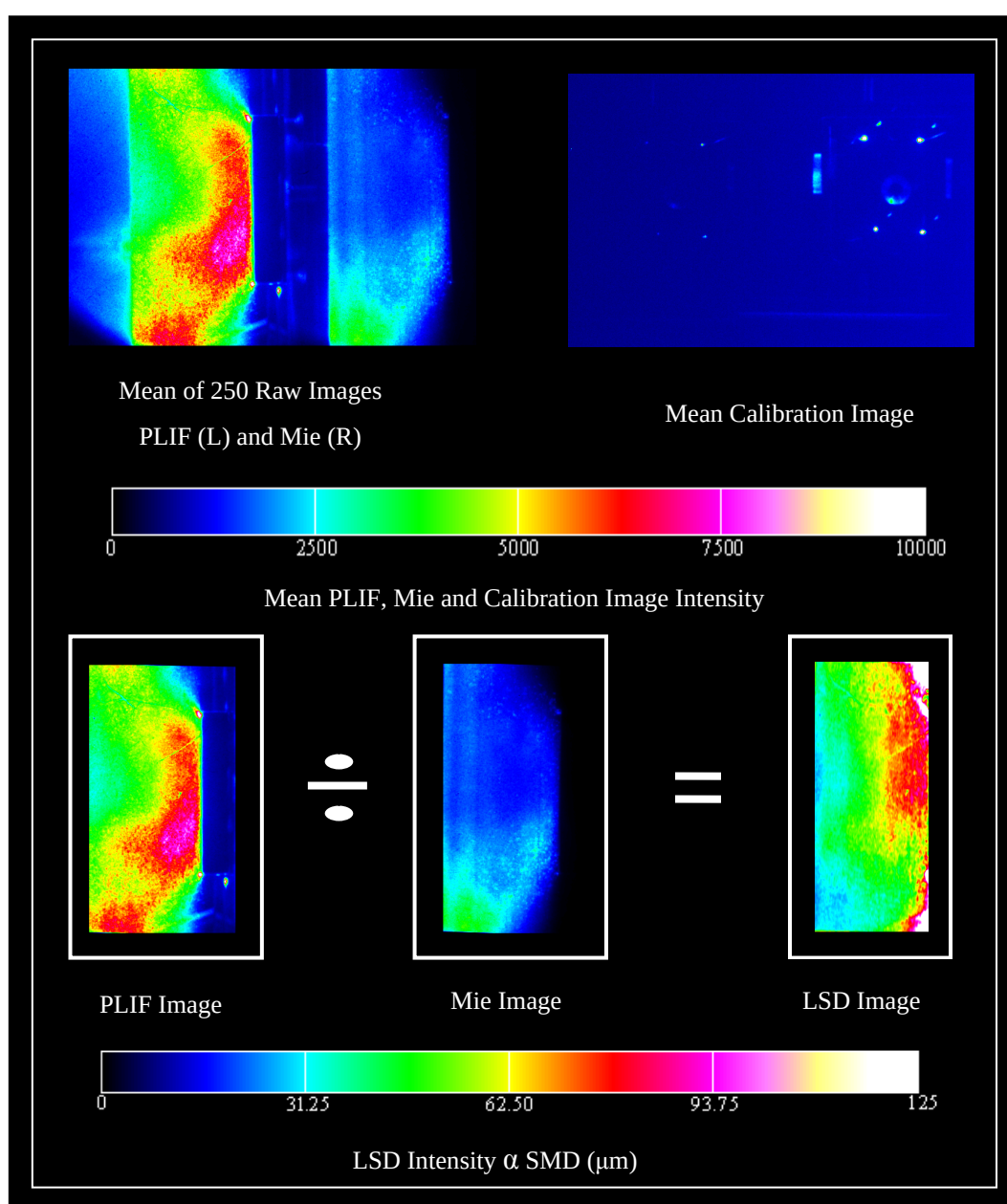


Figure 9.5: Basic LSD Image Processing for 21 AFR

APPENDIX F

PRELIMINARY CALIBRATION OF PLIF SIGNAL

The PLIF calibration constant, K_{PLIF} is found using the conservation of mass equation. Eq. 9.11 shows PLIF intensity in a pixel, I_j is related to the mass concentration of fuel in that pixel by a constant, K_{PLIF} . It assumes that K_{PLIF} is constant for each pixel in the image and there is no variation in the ICCD intensifier pixel response.

$$K_{PLIF} = K\rho_{ij} \quad \text{Eq. 9.11}$$

Figure 9.6 selects an area, A in the spray and Figure 9.7 shows pixels that coincide with one diameter of that area.

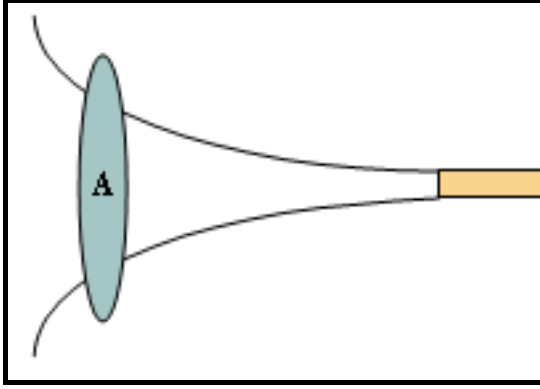


Figure 9.6: Selected Area in Fuel Spray

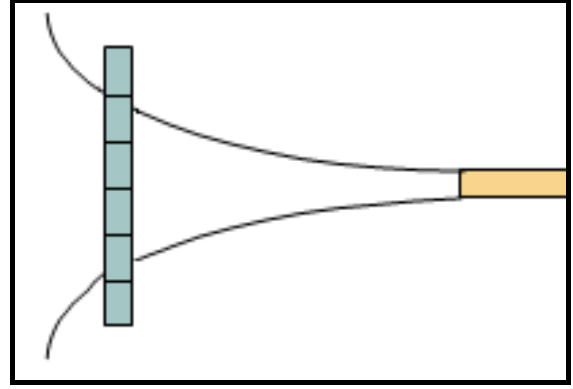


Figure 9.7: Pixels in One Diameter of Area

Eq. 9.12 rearranges the conservation of mass equation for ρ_{cal} that represents the average fuel density over A .

$$\rho_{cal} = \frac{\dot{m}_L}{AU_L} \quad \text{Eq. 9.12}$$

Since ρ_{cal} in the selected area is known, the PLIF intensities averaged over the same area, $I_{Averaged}$ is calculated to determine K_{PLIF} . Eq. 9.13 shows the relationship between $I_{Averaged}$ and ρ_{cal} in the selected area to calibrate the PLIF image.

$$K_{PLIF} = \frac{I_{averaged}}{\rho_{cal}} \quad \text{Eq. 9.13}$$

As pixels have width and height, a and the laser sheet has thickness, t ; Eq. 9.14 is used to calculate pixel volume

$$Vol_j = a^2 t \quad \text{Eq. 9.14}$$

Since the spray is axisymmetric Eq. 9.15 shows PLIF intensity, I_j per unit value.

$$I_{\text{unit value}} = \frac{I_j}{a^2 t} \quad \text{Eq. 9.15}$$

If pixels above and below the axis of symmetry are used in Figure 9.8, then Eq. 9.16 to calculate averaged PLIF intensity per unit value is divided by a factor of two.

$$I_{\text{averaged / unit value}} = \sum_{\text{All Annuli}} \frac{(r_{oj}^2 - r_{ij}^2) \times (I_j / Vol_j)}{r_{outer}^2} \quad \text{Eq. 9.16}$$

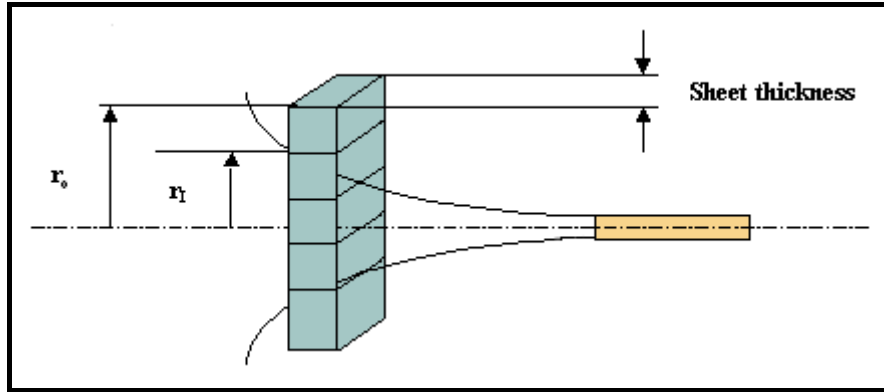


Figure 9.8: Sketch to Show Calculation of I_j Per Unit Value

Eq. 9.17 relates K_{PLIF} to the average intensity per unit value.

$$K_{PLIF} = \frac{I_{\text{averaged / unit value}}}{\rho_{cal}} \quad \text{Eq. 9.17}$$

Eq. 9.18 uses K_{PLIF} to calculate the fuel mass concentration in any pixel in the image.

$$\rho_{\text{fuel pixel}} = \frac{I_{\text{local}}}{Volume_{\text{pixel}} \times K_{PLIF}} \quad \text{Eq. 9.18}$$

Eq. 9.19 shows the mass of fuel in each pixel is the product of fuel density and pixel volume.

$$m_{fuel\ pixel} = \rho_{fuel\ pixel} \times Volume_{pixel} \quad \text{Eq. 9.19}$$

Eq. 9.20 shows volume fraction is the ratio of fuel and air density.

$$Volume\ Fraction = \frac{\rho_{fuel\ pixel}}{\rho_{bulk\ air}} \quad \text{Eq. 9.20}$$

Eq. 9.21 shows air mass flow is:

$$m_{air\ pixel} = \rho_{bulk\ air} \times Volume_{pixel} \times (1 - Volume\ Fraction_{fuel}) \quad \text{Eq. 9.21}$$

Eq. 9.22 calculates pixel fuel density.

$$\rho_{fuel\ pixel} = Volume\ Fraction \times \rho_{bulk\ fuel} \quad \text{Eq. 9.22}$$

Eq. 9.19 and Eq. 9.21 allow the calculation of the local AFR. However, K_{PLIF} will change if the laser ages or leak or if there are changes to the laser voltage; fluorophor concentration in the sprayed liquid; or to any of the signal collection optics. Application of K_{PLIF} is restricted for use in measurements using the same optical set-up. Any change to the experimental configuration may change the location of the correct pixel column to derive K_{PLIF} and therefore different pixel co-ordinates will be used. Although this method gave dubious AFR, it successfully tested spreadsheets, image processing macros and commercial codes to predict adiabatic flame temperatures and NO formation. The signal calibration method described in Chapter Four was subsequently developed and used to calibrate the sprays data presented in Chapters Seven and Eight.

APPENDIX G

UFR CHECKLIST FOR SPRAYS IMAGING

Before Closing UFR

- Dissolve 0.0118g/l of M-Terphenyl in Exxsol D80 and fill fuel tanks.
- Check absorbance is 2.7 to ensure cubic dependence of PLIF with diameter.
- Drain water traps on small compressor and all rig windows.
- Drain fuel from UFR and cyclones and store in labelled waste drums.
- Clean fuel filters downstream of fuel tanks and rig.
- Clean inner and outer surfaces of appropriate rig windows.
- Ensure window heater elements are installed and connected to the battery.
- Ensure adequate He supply for fuel and N₂ to cool camera.
- Lock the main door from inside and set interlock before switching on laser.
- At low power align sheet forming optics to give a non-diverging vertical sheet.
- Ensure there is a small flow of dry N₂ to the camera intensifier before turning on cooler. Ensure camera cooling water is flowing and check for leaks. Start with a low aperture (high *f*/number) and open up gradually. Do not expose the intensifier to bright light including full room light (e.g. intensifier on and pulsing but no lens fitted). Ensure camera has cooled to approximately -38°C.
- Check PLIF, Mie and ND filters and for signal breakthrough on each channel.
- Adjust camera field of view to obtain optimum spatial resolution.
- Acquire cross calibration image to determine spatial resolution and image manipulation factors for LSD image processing. Repeat after any change.
- Set up piezoelectric droplet generator in the UFR. Generate a monodisperse droplet stream. Apply PDA to measure droplet SMD for each stream and acquire corresponding LSD or PLIF images depending on the set-up.
- Do acetone fluorescence flatfielding experiment.
- Install injector in airbox. Ensure fuel sight tube and all fuel valves are closed and pressurise with He. Turn on fuel and check for all fuel connection points for fuel leaks to injector. Close airbox, attach simulated combustor geometry and install in UFR.
- Close the rig and ensure both control room pressure gauges read zero. If not recalibrate transducers.

After Closing UFR

- Wear laser goggles and ear defenders as appropriate. Adjust pneumatic traverse to locate injector exit in the camera field of view.
- Adjust airbox position via rear access window to ensure laser sheet enters and exits both slots in fake combustor walls into the beam-dump. Close window.
- Warm up camera electronics for ten minutes and check PG200 settings.
- Record laser power, gate delay, gate width, trigger level and gain.
- Record lens aperture and distance to filter and filters to window or rig centre.
- Record barometric pressure and air temperature inside rig after twenty minutes to recalculate scaled rig operating conditions.
- Contact technician to switch on industrial compressor and check for air leaks.

Prepare Image Acquisition

- Set, check and record $\Delta P/P$ and P_{Gauge} . Record $P_{Absolute}$ upstream of the UFR.
- For acoustic oscillation work set rotor speed.
- Input required delay to DG535 pulse generator depending on the phase angle under measurement.
- Acquire 100 background images to account for some of the background noise.
- Acquire 0° dataset every 22.5° in the sinusoidal cycle.
- Rotate airbox through 180° . Open isolation valve to obtain the same $P_{Absolute}$ to obtain the same standing waves in the air supply. Acquire a second dataset to correct laser attenuation through the spray in subsequent image processing.
- Take dynamic data with the rotor going and static data with the rotor stopped and open, and also stopped and closed.
- Repeat one condition for a repeatability check.
- Discard first 25 litres of fuel but recycle only once, providing it is clean.

To Close Down

- Switch off laser and camera but leave water and N_2 supply on.
- Turn off water and N_2 once chip reaches room temperature.
- Turn off fuel, window air purge; inlet air control valve; outlet air control valve, isolation valve, spill valve, small and main air compressors.
- Depressurise fuel tanks and close He gas bottle.
- Turn off all water supplies, electrics and clear gangways.
- Download all data onto CD for image processing.

Rotor/Siren

- Turn on rotor 3-phase supply.
- Press green button on control box.
- Adjust dial until desired rotational speed is achieved.
- Check output from rotor sensor.
- To close press red button on control.
- When 'Rdy' appears on display, turn off 3-phase supply.

Timing

- Rotor signal triggers all instrumentation.
- Plug rotor output BNC into DG535 Trigger Input.
- Connect BNC cable to AB output, and the other BNC to EXT Trig on DG535.
- Ensure rotor sensor amplifier circuit has power (5V DC amplifier).
- Press TRIG button and set to EXT.
- Press DELAY button and set $A = T + 0$ initially.
- Press DELAY button again and set $B = A + 0.00003$. This sets PG200 to have a pulse width of 3 microseconds.
- When running only adjust Delay $A = T + x$ depending on phase angle.
- Ensure A B in DG535 is connected to DG535 in connectors.
- Connect Camera Controller to Not Scan.
- Connect Delayed Trigger Out from PG200 to EXT SYNC of camera controller and to LAN of Laser.
- Select Trig Select to EXT.
- PG200 Settings.
- Delay 201ns; Gate Width 5 μ s; Delayed Trig 267ns; Trig Level 3.1V.

Camera

- Nitrogen supply to camera is at ~10 to camera.
- Turn on water supply to camera.
- Then turn on camera controller and set dial to -30 to 40°C.
- Only operate when status light is green.
- Ensure serial cable is connected from camera control to camera and GATE 1 OUT is connected to camera BNC.

APPENDIX H

UFR OPERATING CONDITIONS

9.9 BUILD 34

PLIF						
Air to Fuel Momentum Flux Ratio (q) and Injector Pressure Drop $\Delta P/P$ $\left(q \text{ and } \frac{\Delta P}{P} \right)$						
Engine Condition and Pilot:Main Fuel Splits	P_{Gauge} (kPa)	ΔP (kPa)	Fuel (l/m)	Φ_A	Φ_{PS}	Φ_H
100% Take off (10:90)	116	8.7	0.77	1.19	1.03	1.58
85% Climb (10:90)	114	8.5	0.67	1.19	1.04	1.58
Cruise (10:90)	162	10.6	0.77	1.19	1.00	1.56
30% Approach (30:70)	188	11.6	0.55	0.93	0.81	1.23
24% Approach (0:100)	175	11.1	0.50	-	0.73	0.73
7% Idle (0:100)	197	11.9	0.42	-	0.54	0.54
7% Idle Eng. (0:100)	378	19.2	0.67	-	0.54	0.54

Table 9.12: UFR Conditions for B34

9.10 BUILD 43

PLIF						
Air to Fuel Momentum Flux Ratio (q) and Injector Pressure Drop $\Delta P/P$ $\left(q \text{ and } \frac{\Delta P}{P} \right)$						
Engine Condition and Pilot:Main Fuel Splits	P_{Gauge} (kPa)	ΔP (kPa)	Fuel (l/m)	Φ_A	Φ_{PS}	Φ_H
100% Take off (10:90)	103	8.2	0.76	1.19	1.02	1.57
85% Climb (10:90)	98	8	0.67	1.19	1.02	1.57
Cruise (10:90)	105	8.2	0.62	1.19	1.03	1.58
30% Approach (30:70)	185	11.4	0.90	0.93	0.81	1.23
24% Approach (0:100)	165	10.6	0.50	-	0.73	0.73
7% Idle (0:100)	199	12	0.44	-	0.54	0.54

Table 9.13: UFR Conditions for B43

9.11 BUILD 61

PLIF, LSD and PDA						
Air to Fuel Momentum Flux Ratio (q) and Injector Pressure Drop $\Delta P/P$ $\left(q \text{ and } \frac{\Delta P}{P} \right)$						
Engine Condition and Pilot:Main Fuel Splits	P_{Gauge} (kPa)	ΔP (kPa)	Fuel (l/m)	Φ_A	Φ_{PS}	Φ_H
100% Take off (10:90)	126	9.1	0.76	1.19	1.04	1.57
85% Climb (10:90)	121	8.9	0.66	1.19	1.03	1.58
Cruise (10:90)	121	8.9	0.60	1.19	1.03	1.57
30% Approach (30:70)	209	12.4	0.55	0.93	0.81	1.23
24% Approach (0:100)	175	11.1	0.47	-	0.74	0.74
7% Idle (0:100)	218	12.8	0.42	-	0.54	0.54
7% Idle Eng. (0:100)	388	19.6	0.65	-	0.55	0.55

Table 9.14: UFR Conditions for B61

APPENDIX I

PDA DATASET FOR BUILD 61 AT 7% IDLE

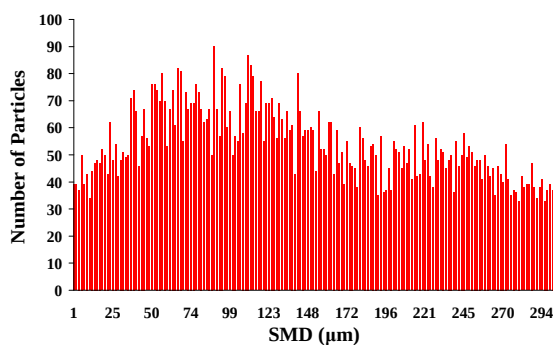


Figure 9.9: 7% Approach, $X = 2\text{mm}$

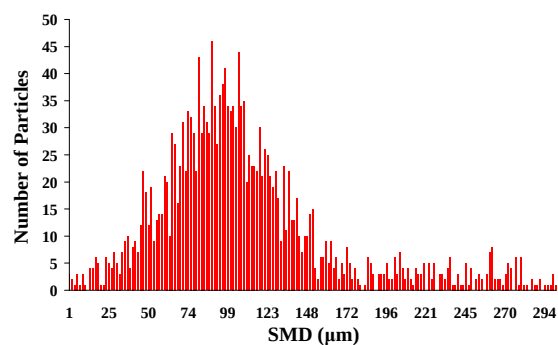


Figure 9.10: 7% Approach, $X = 10\text{mm}$

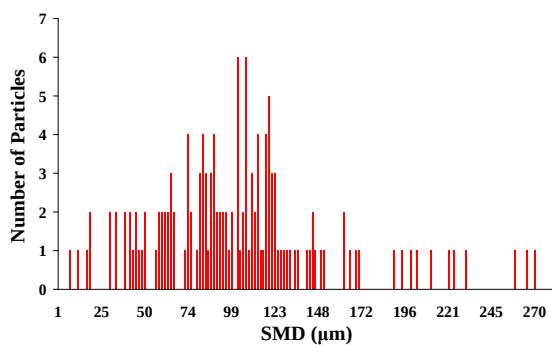


Figure 9.11: 7% Approach, $X = 20\text{mm}$

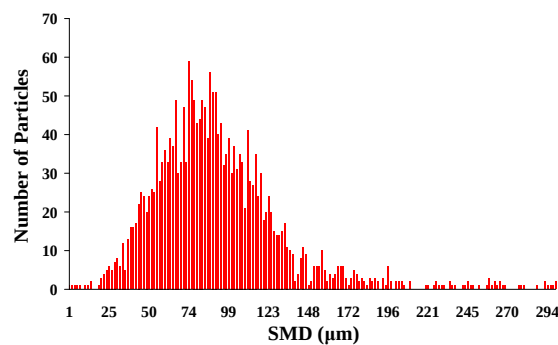


Figure 9.12: 7% Approach, $X = 30\text{mm}$

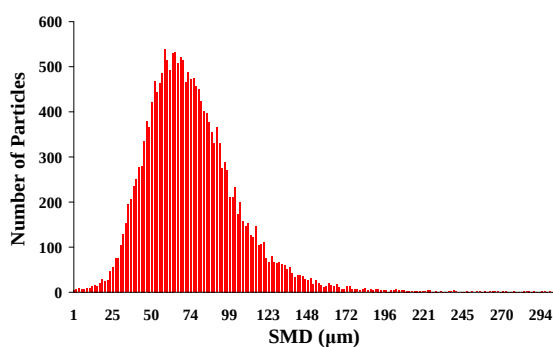


Figure 9.13: 7% Approach, $X = 40\text{mm}$

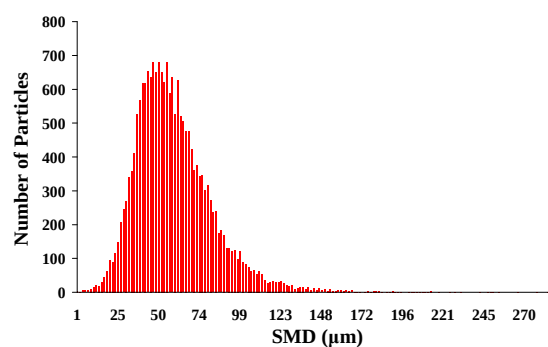


Figure 9.14: 7% Approach, $X = 50\text{mm}$

APPENDIX J

ACOUSTIC FORCING DATASET FOR BUILD 61

PRESSURE-SWIRL SPRAYS

Figure 9.15 to Figure 9.26 show phase-locked SMD and AFR images acquired at sixteen measurement points every 22.5° in the siren cycle at 12, 100 and 200Hz for Build 61 at the 7% Idle and 24% Approach conditions. Images are shown on a false colour scale. AFR images measure 163×190 pixels and correspond to a spray size of $43.5\text{mm} \times 50.7\text{mm}$. SMD images measure 41×120 pixels and represent a spray size of $10.9\text{mm} \times 32\text{mm}$. Figure 9.27 to Figure 9.30 plot AFR and SMD at the three frequencies in three radial planes perpendicular to the injector centreline. AFR plots are at a downstream distance of $X = 25\%$ (12.8mm), 50% (25.6mm) and 75% (38.5mm). SMD plots pertain to downstream distances of $X = 25\%$ (8.01mm), $X = 50\%$ (16.02mm) and $X = 75\%$ (24.03mm). Table 9.15 shows UFR operating conditions were $\Delta P/P$ of 7.05%; rig pressures of 215 – 247kPa absolute; fuel flow rates of 0.49 – 0.60l/m and injector AFRs of 49 – 64.

Case	$P_{Absolute}$ (kPa)	P_{Gauge} (kPa)	$\Delta P/P$ (7.05%)	Q (l/m)	Q (g/s)	T_a (K)	Φ_{PS}
7% Idle	247	147	0.17	0.49	6.59	316	0.77
24% App.	215	115	0.18	0.60	8.12	316	1.05
Geometry	Swirler 1 = -35°		Swirler 2 = 50°		Swirler 3 = 55°		

Table 9.15: UFR Conditions for B61 PS Atomiser and Geometry

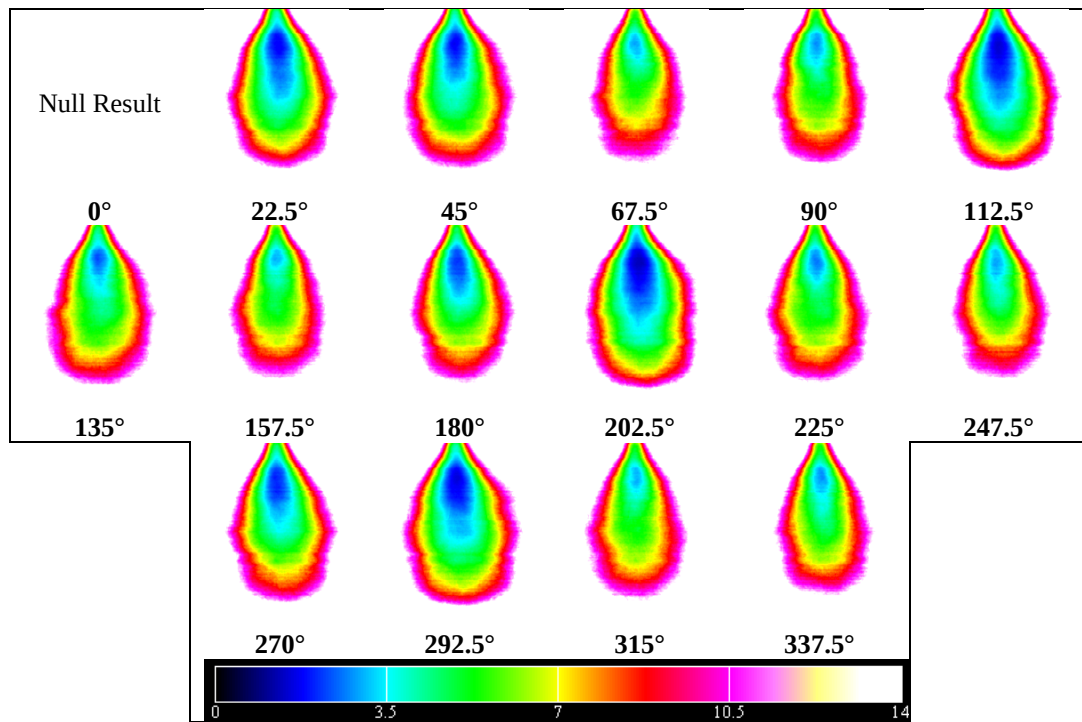


Figure 9.15: Seq. of AFR Images from B61 – 7% Idle at 12Hz

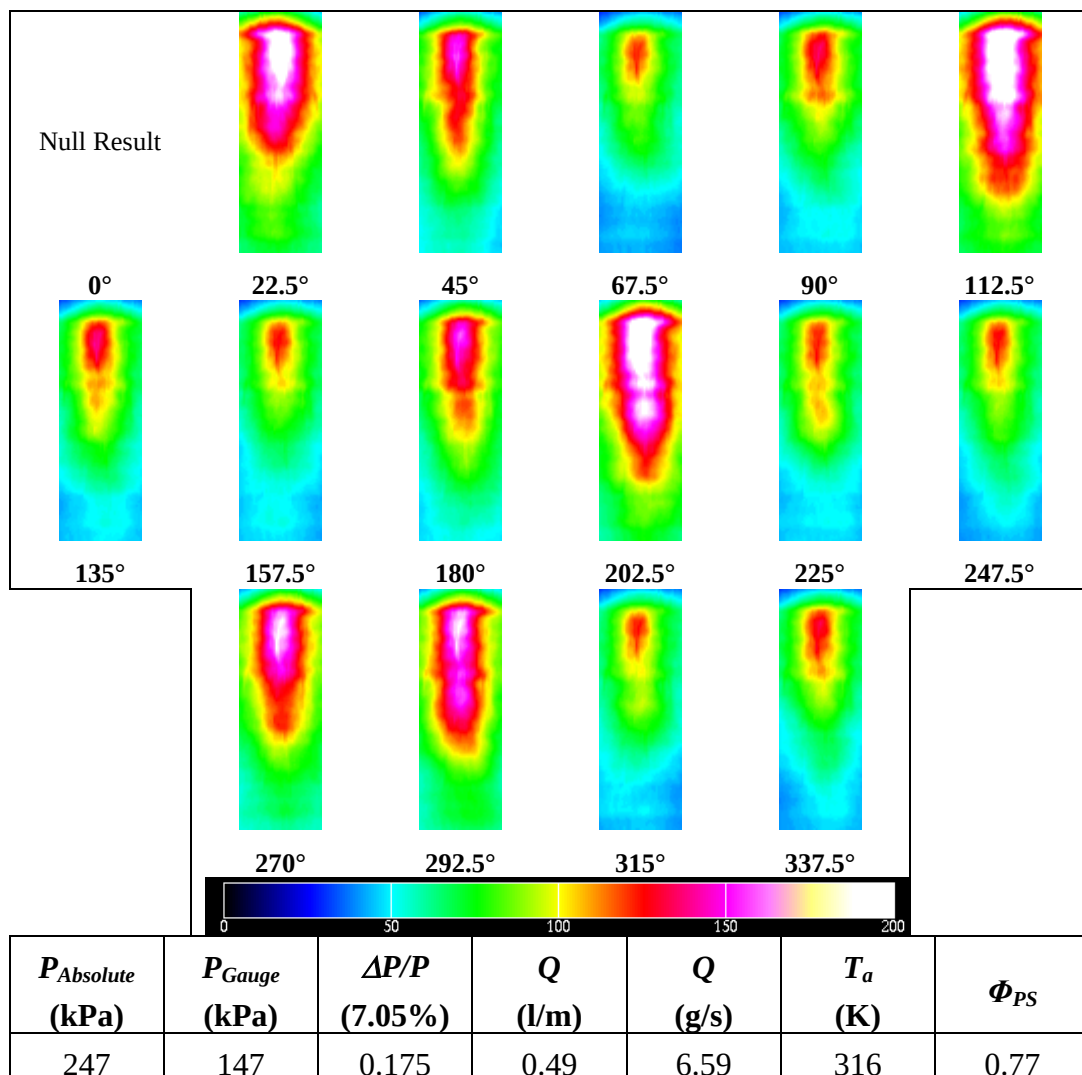


Figure 9.16: Seq. of SMD Images from B61 – 7% Idle at 12Hz

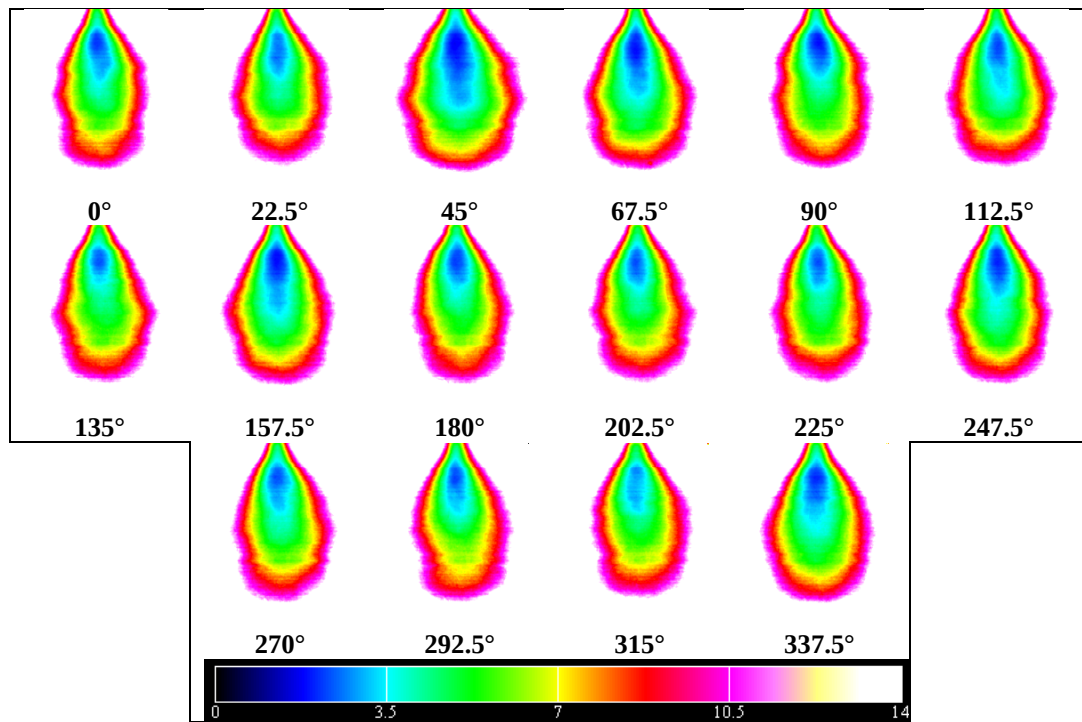
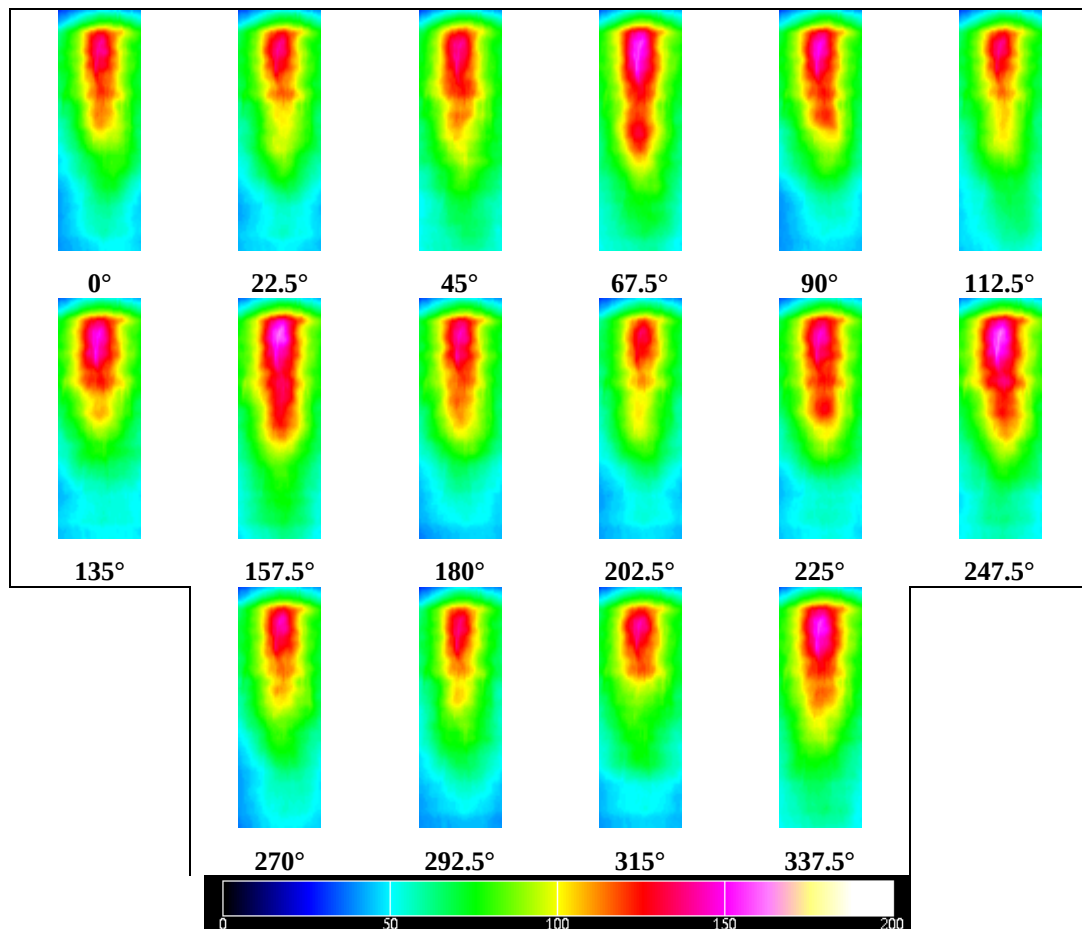


Figure 9.17: Seq. of AFR Images from B61 – 7% Idle at 100Hz



$P_{Absolute}$ (kPa)	P_{Gauge} (kPa)	$\Delta P/P$ (7.05%)	Q (l/m)	Q (g/s)	T_a (K)	Φ_{PS}
247	147	0.175	0.49	6.59	316	0.77

Figure 9.18: Seq. of SMD Images from B61 – 7% Idle at 100Hz

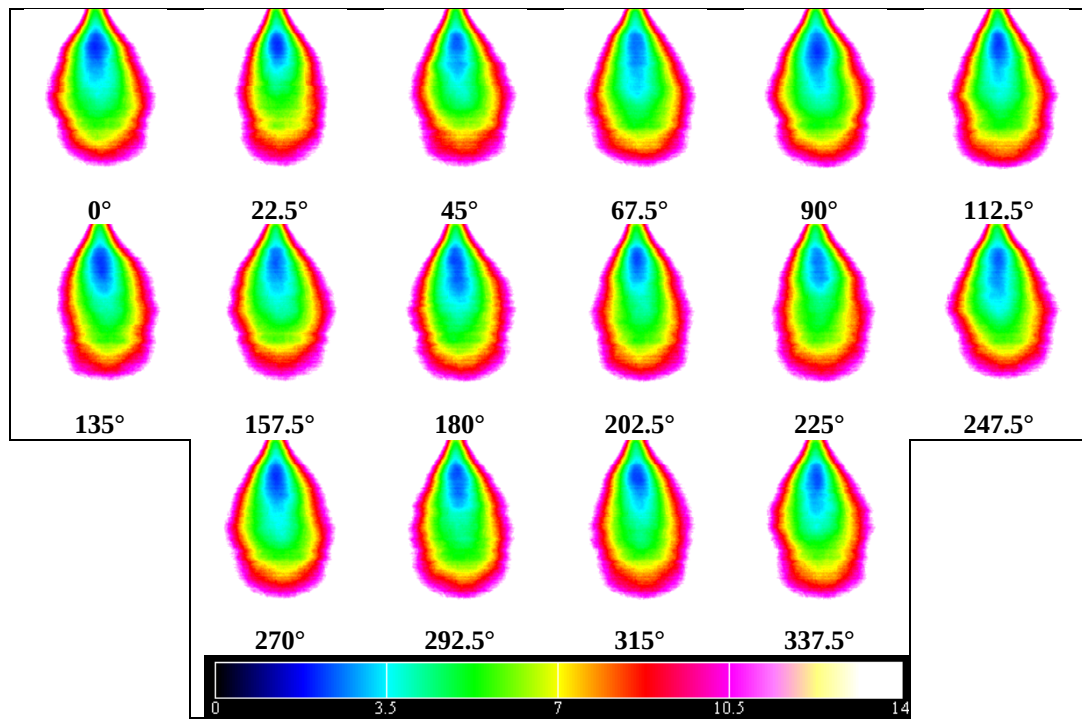
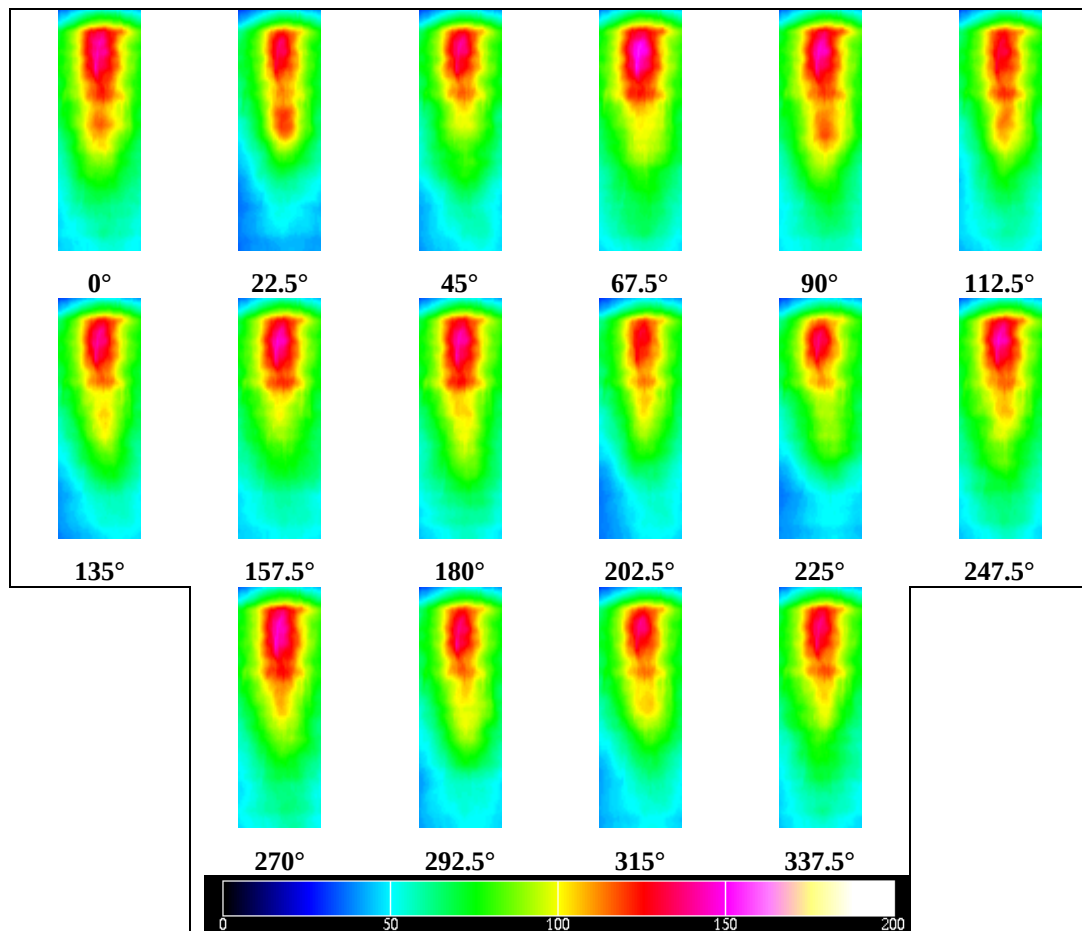


Figure 9.19: Seq. of AFR Images from B61 – 7% Idle at 200Hz



$P_{Absolute}$ (kPa)	P_{Gauge} (kPa)	$\Delta P/P$ (7.05%)	Q (l/m)	Q (g/s)	T_a (K)	Φ_{PS}
247	147	0.175	0.49	6.59	316	0.77

Figure 9.20: Seq. of SMD Images from B61 – 7% Idle at 200Hz

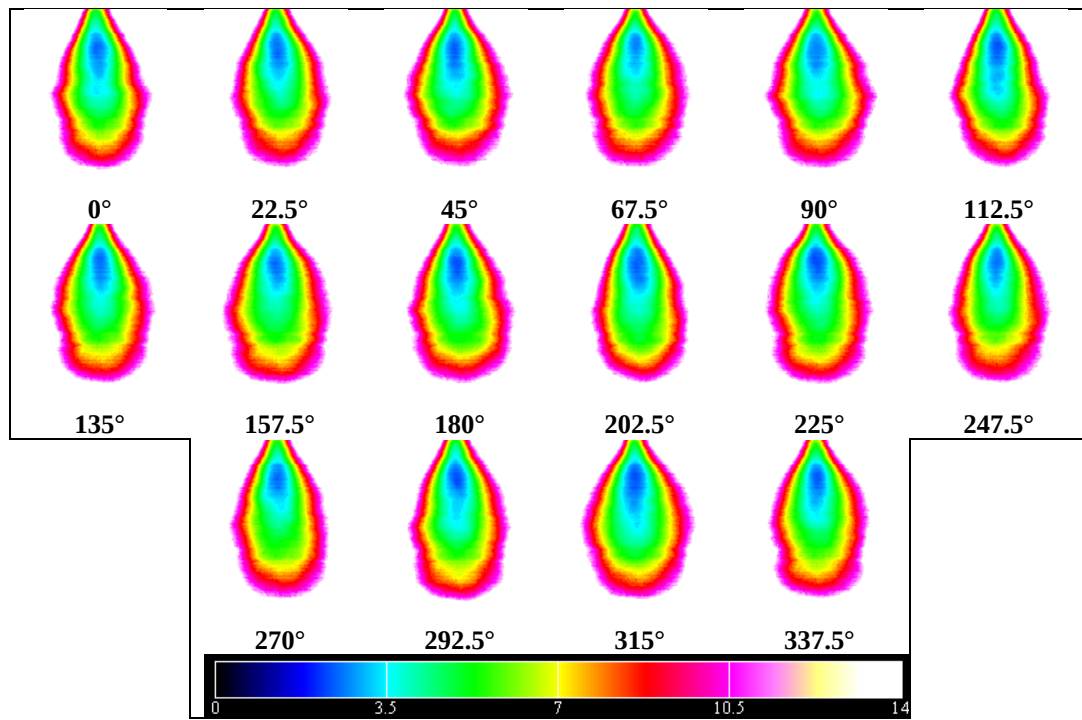
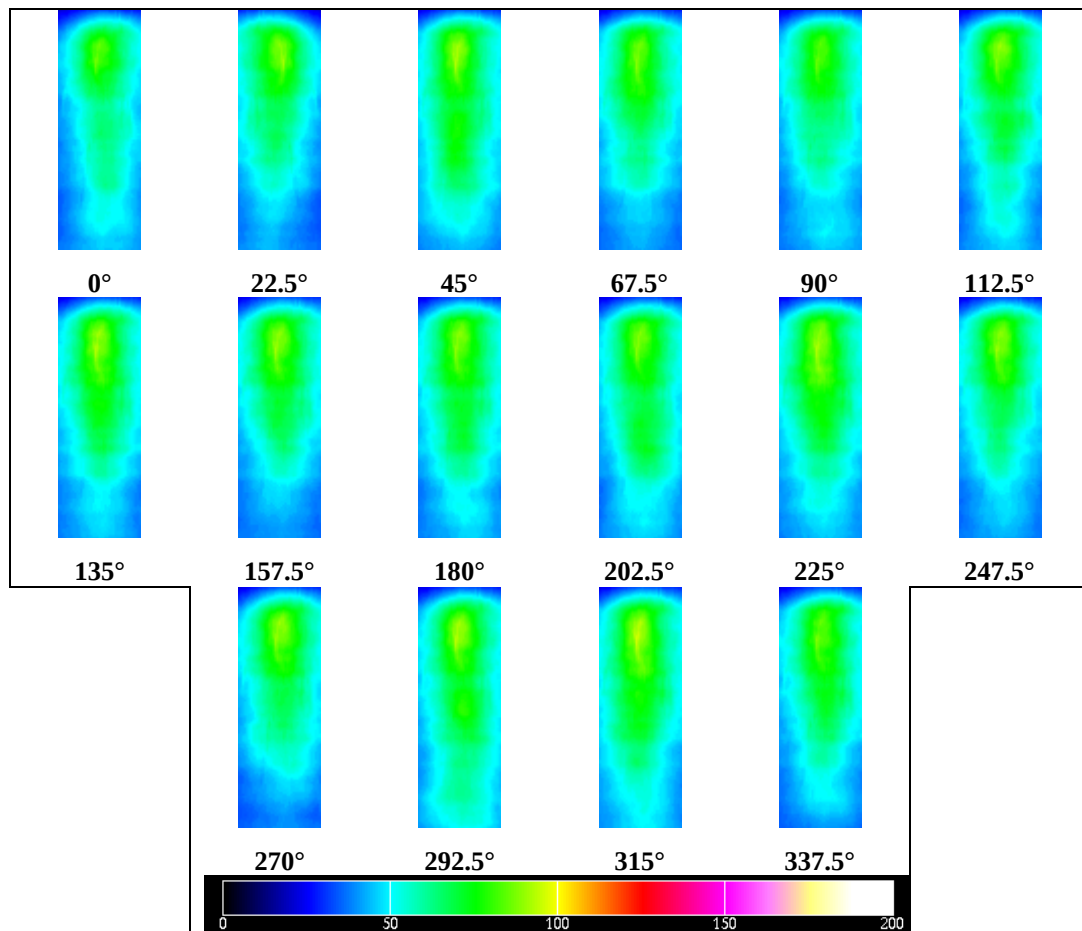


Figure 9.21: Seq. of AFR Images from B61 – 24% Approach at 12Hz



$P_{Absolute}$ (kPa)	P_{Gauge} (kPa)	$\Delta P/P$ (7.05%)	Q (l/m)	Q (g/s)	T_a (K)	Φ_{PS}
215	115	0.182	0.60	8.12	316	1.05

Figure 9.22: Seq. of SMD Images from B61 – 24% Approach at 12Hz

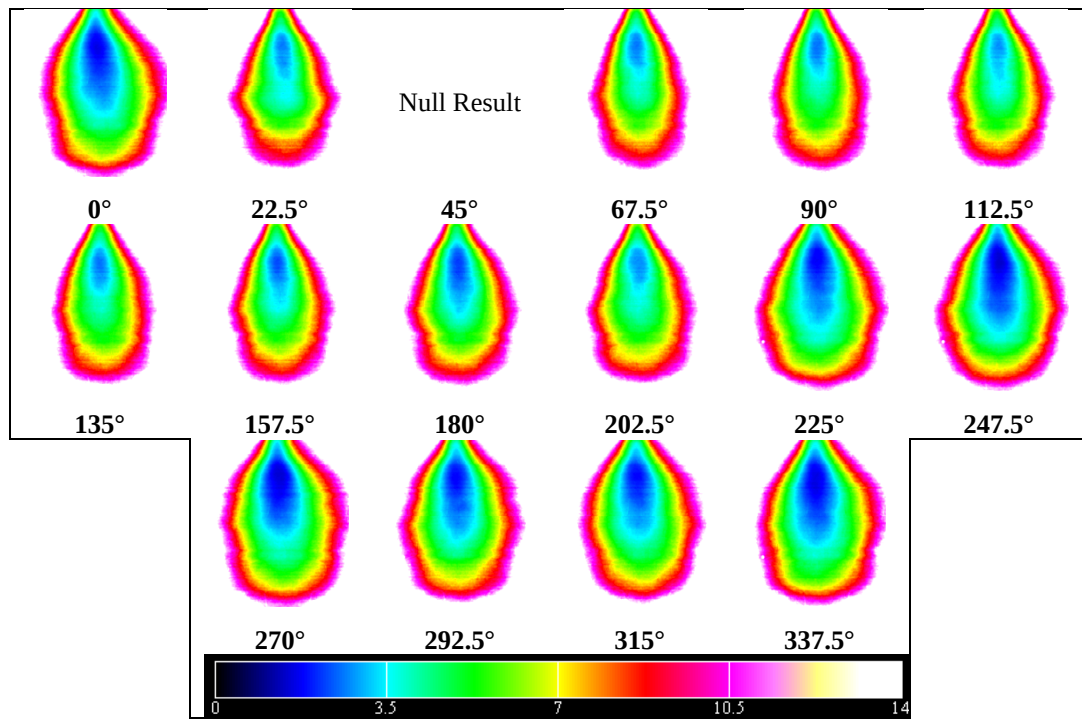


Figure 9.23: Seq. of AFR Images from B61 – 24% Approach at 100Hz

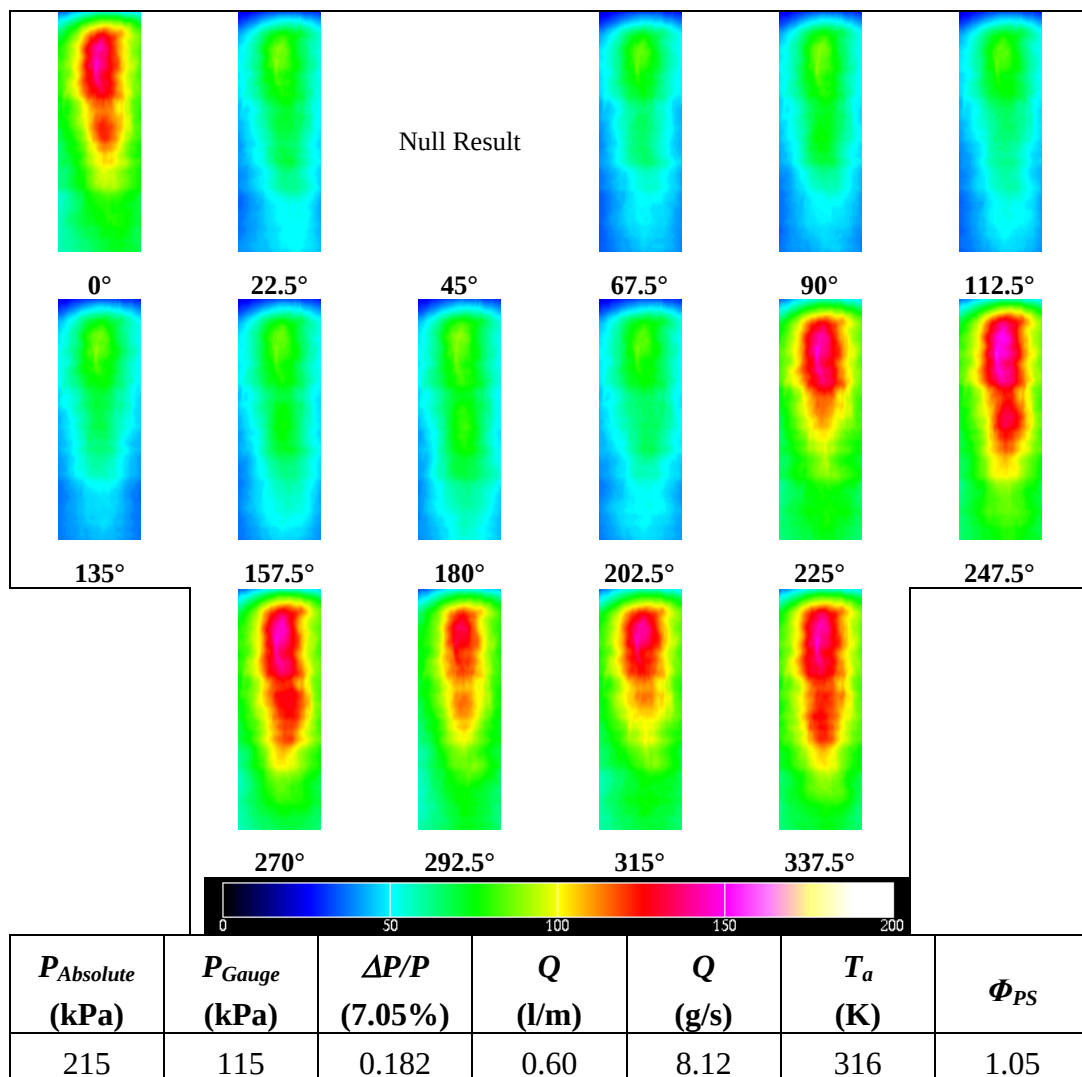


Figure 9.24: Seq. of SMD Images from B61 – 24% Approach at 100Hz

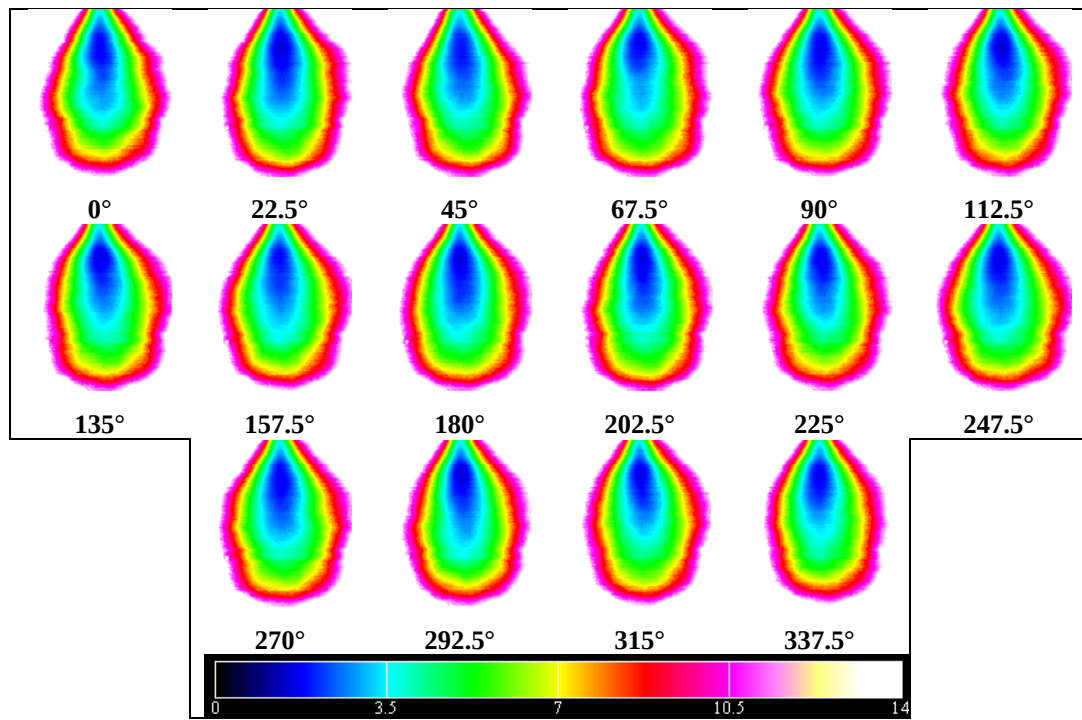
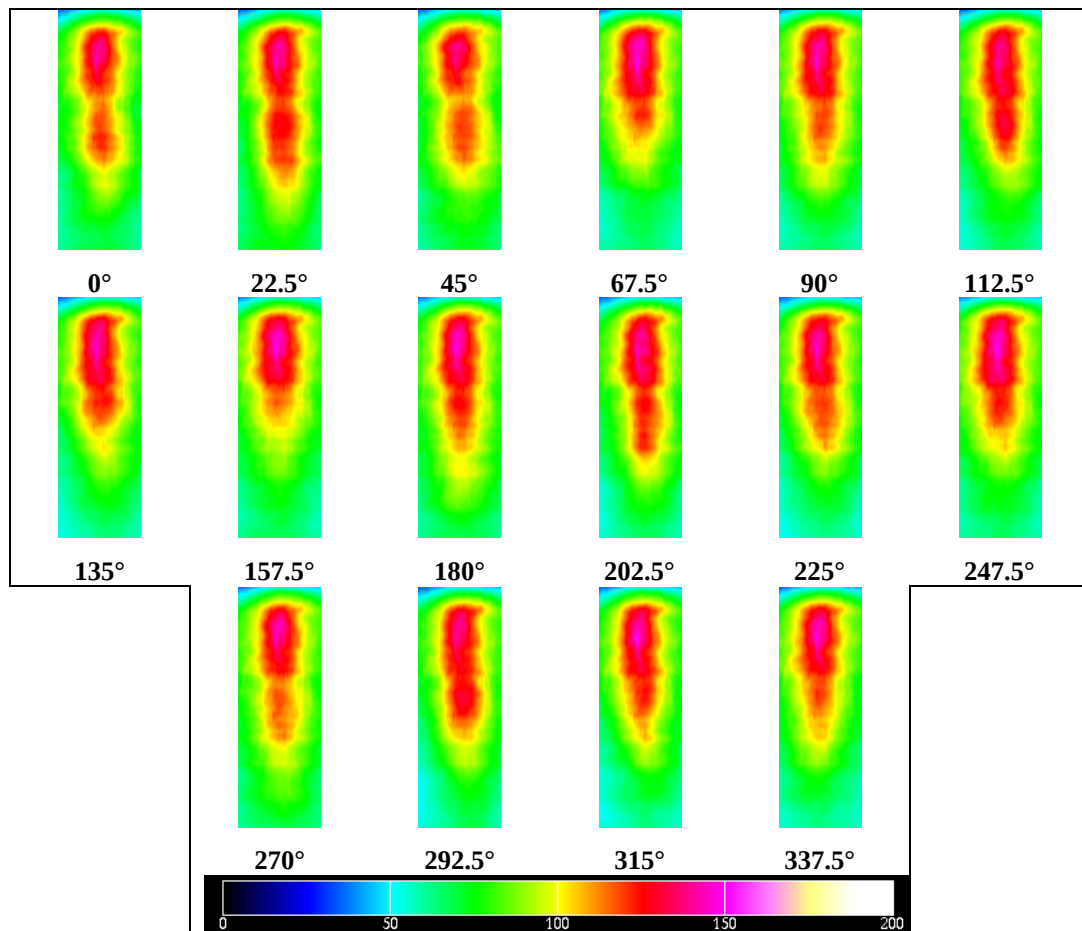
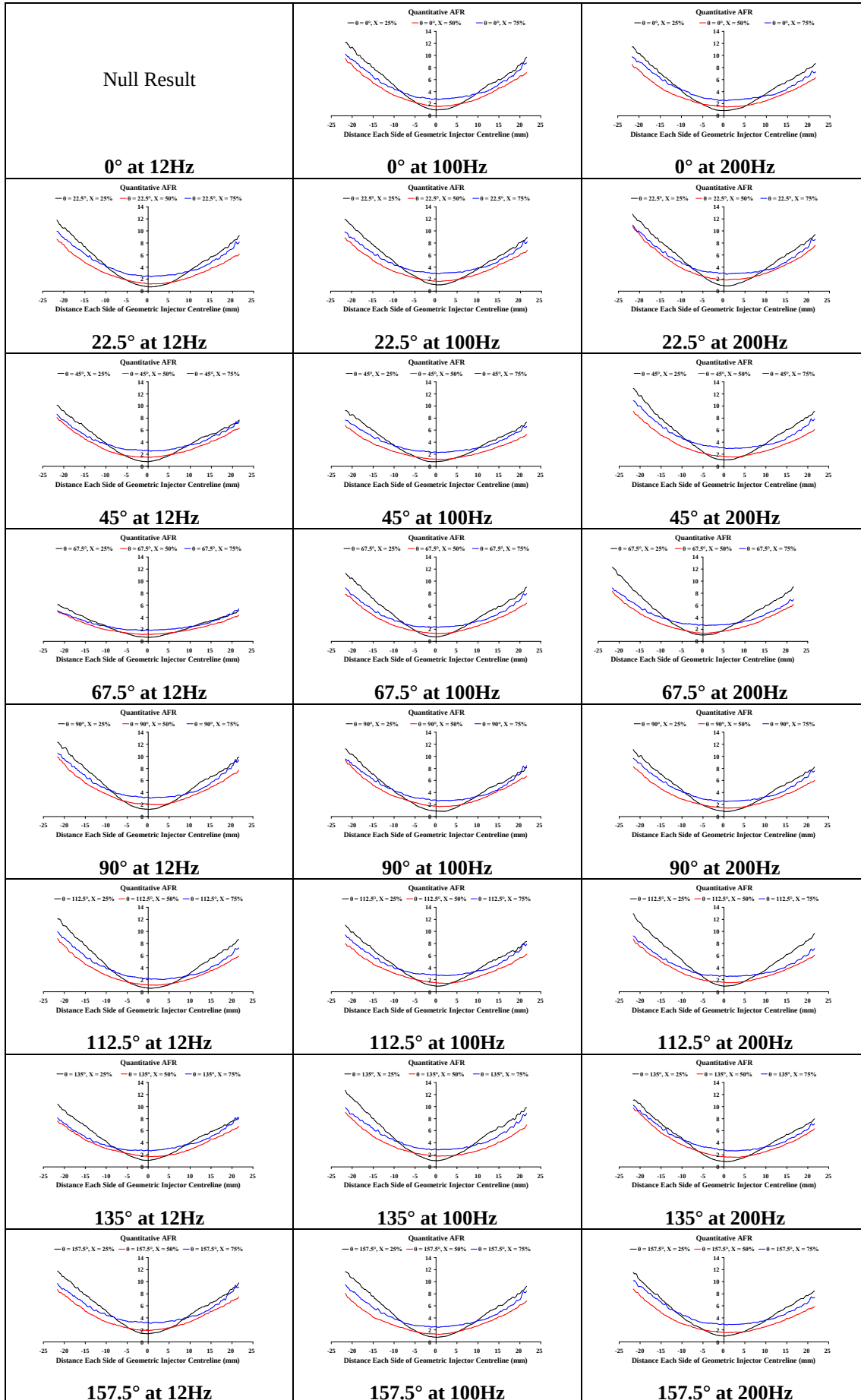


Figure 9.25: Seq. of AFR Images from B61 – 24% Approach at 200Hz



$P_{Absolute}$ (kPa)	P_{Gauge} (kPa)	$\Delta P/P$ (7.05%)	Q (l/m)	Q (g/s)	T_a (K)	Φ_{PS}
215	115	0.182	0.60	8.12	316	1.05

Figure 9.26: Seq. of SMD Images from B61 – 24% Approach at 200Hz



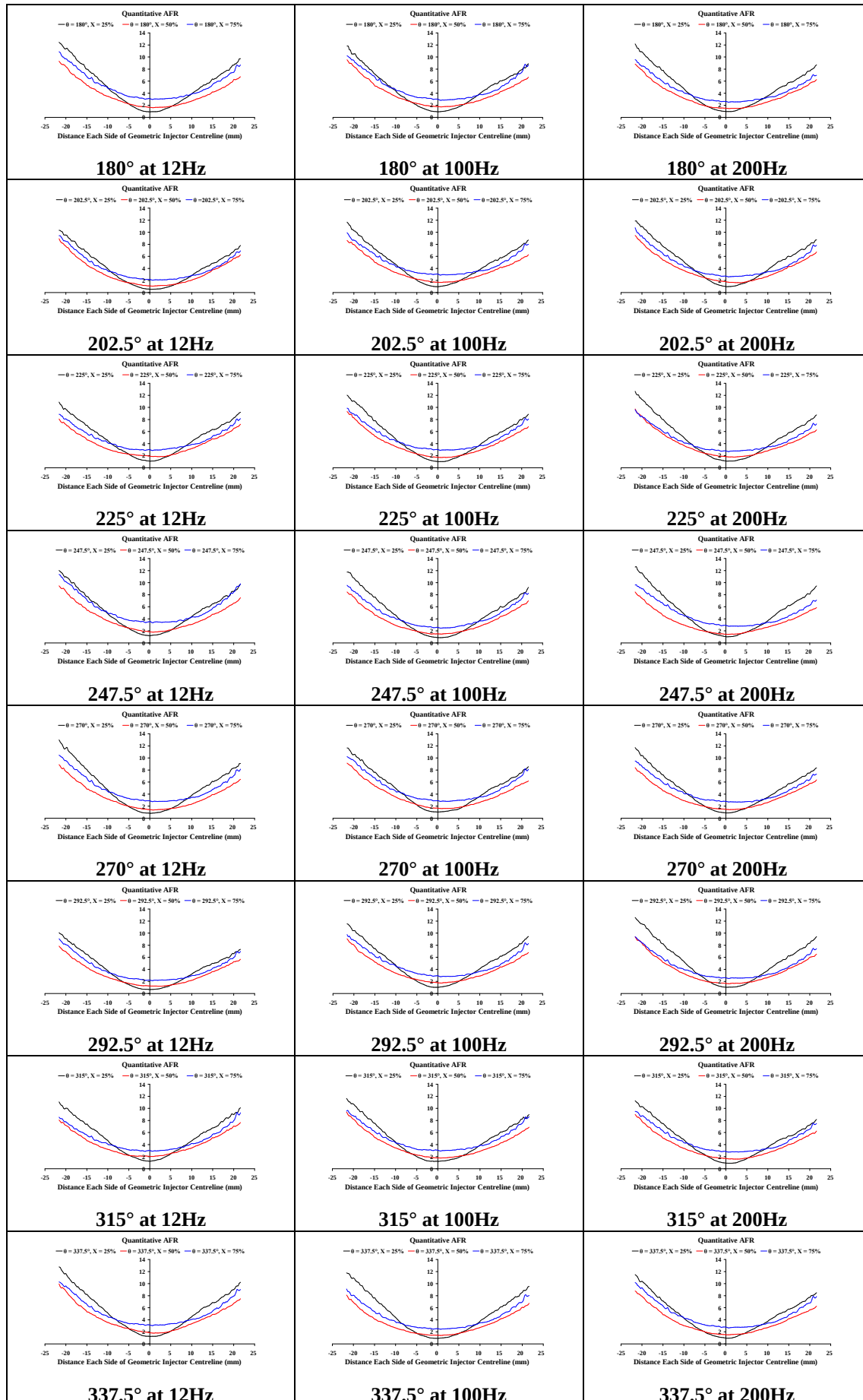
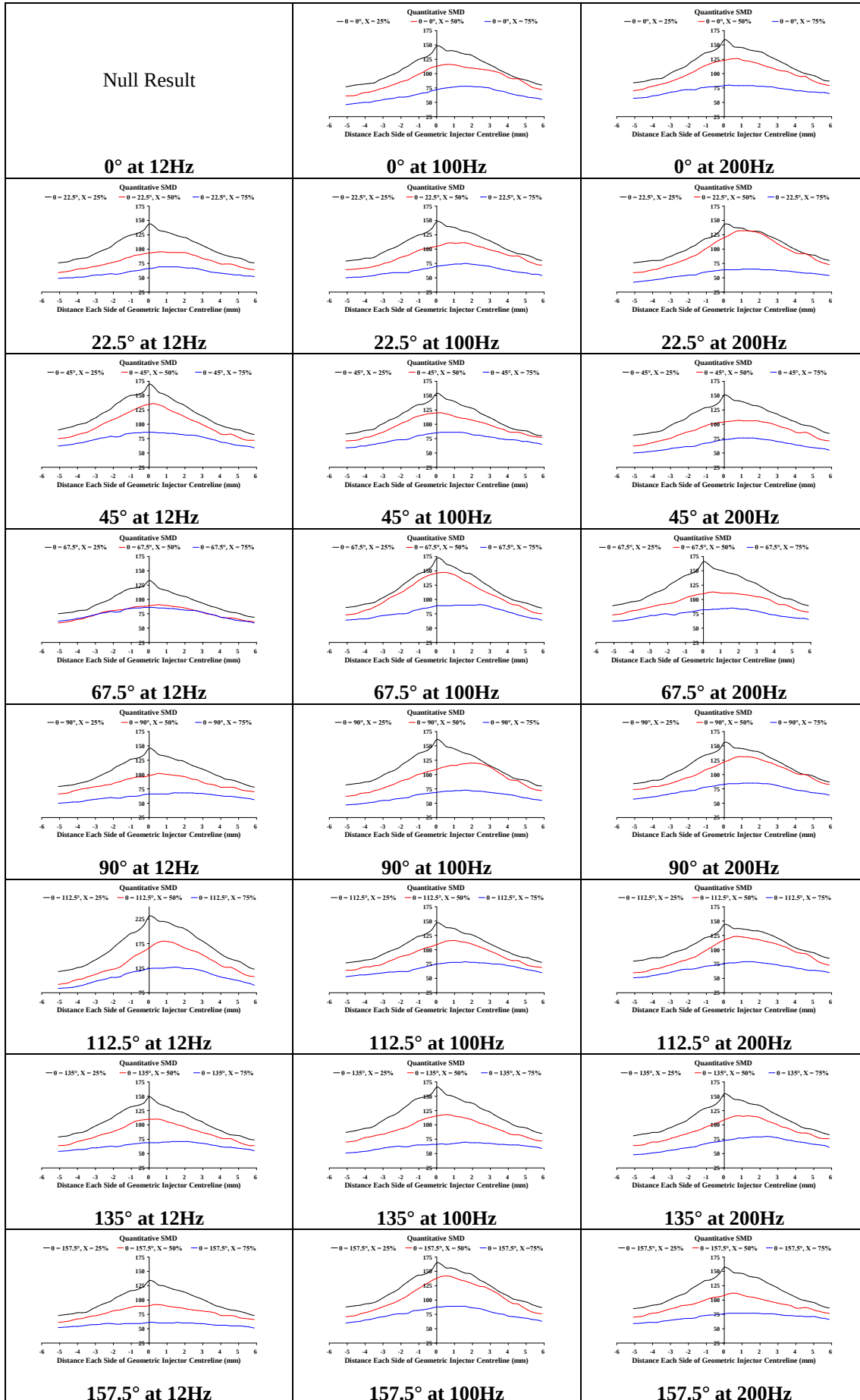
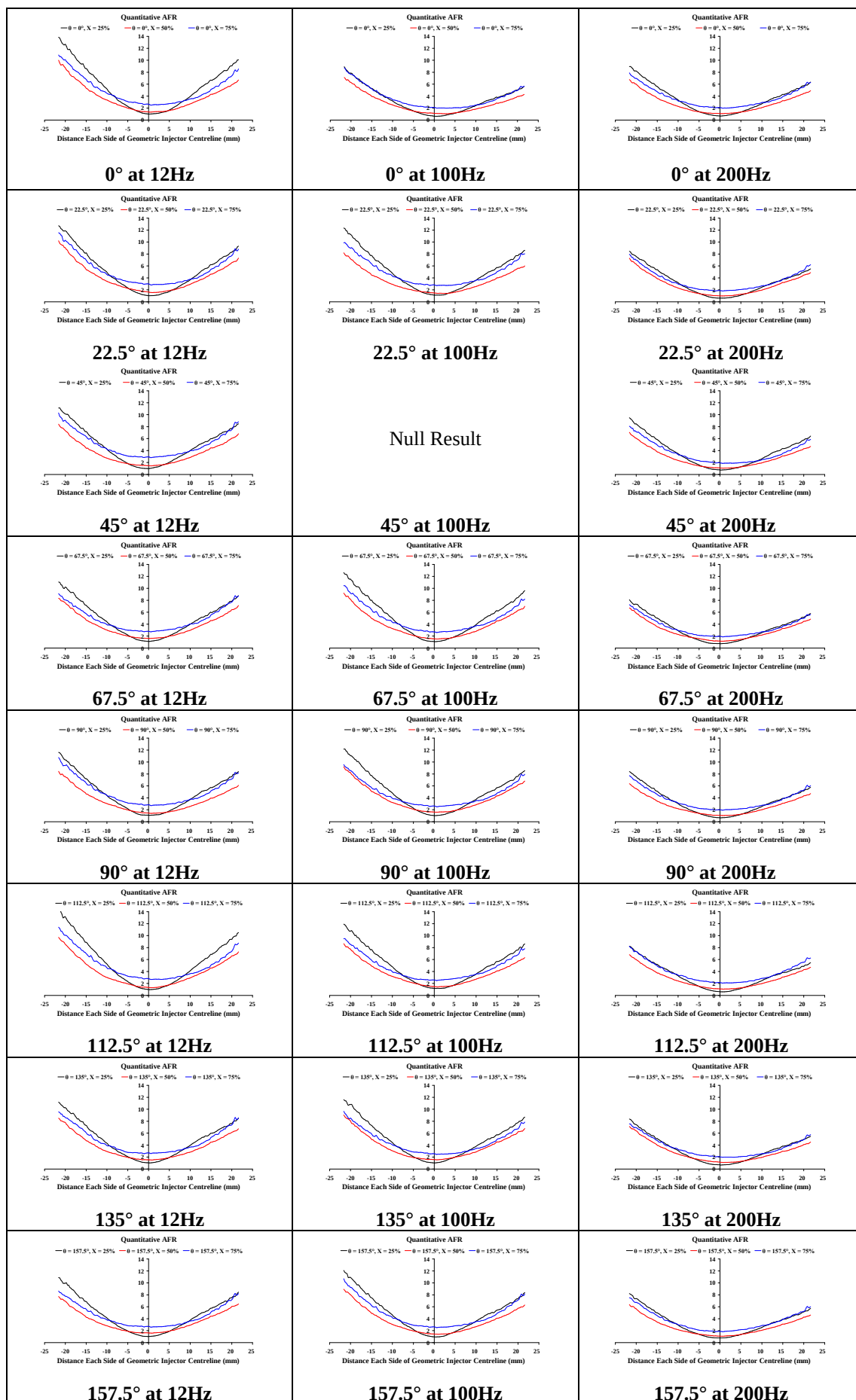


Figure 9.27: Seq. of AFR Plots from B61 – 7% Idle at 12, 100 and 200Hz







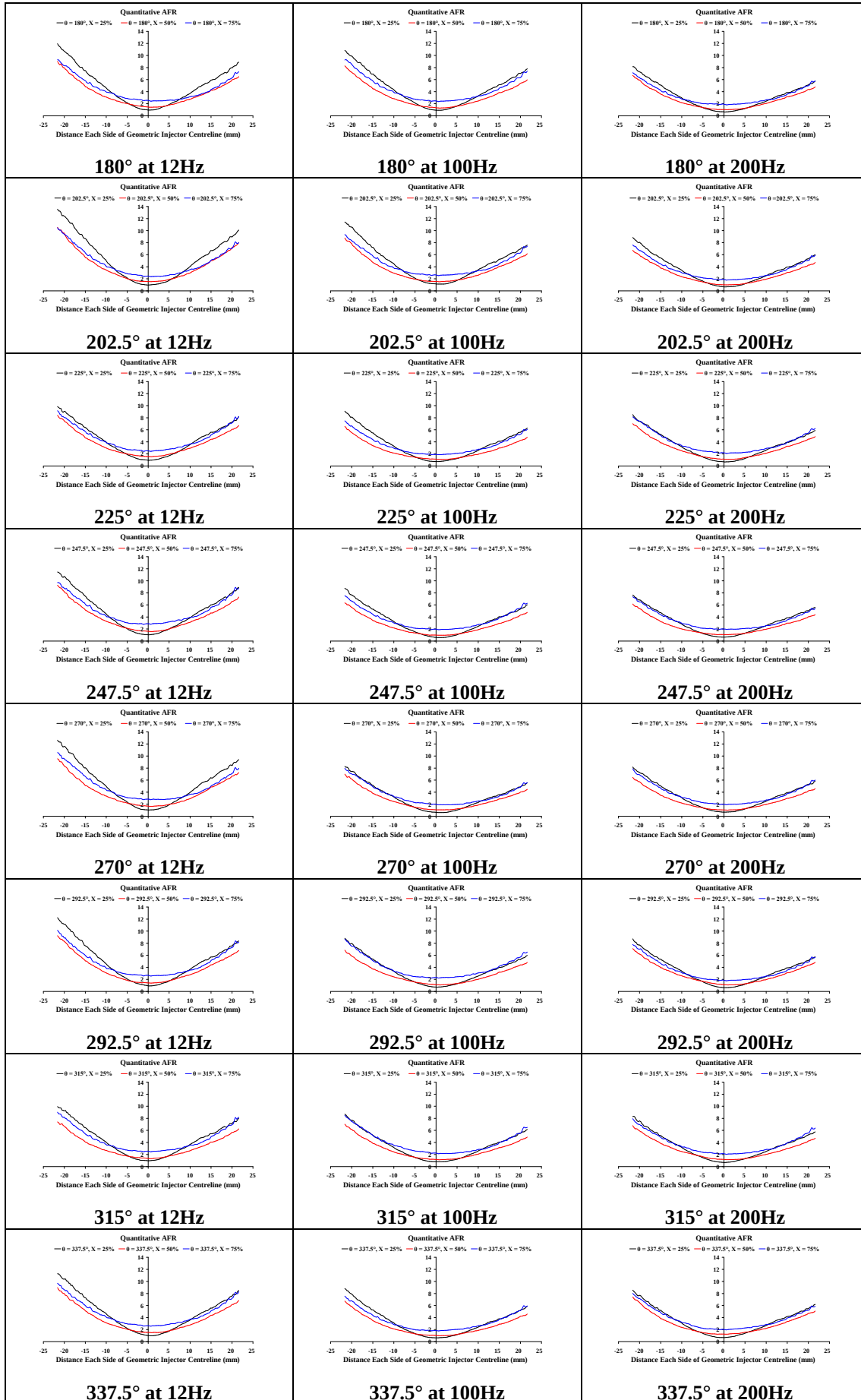
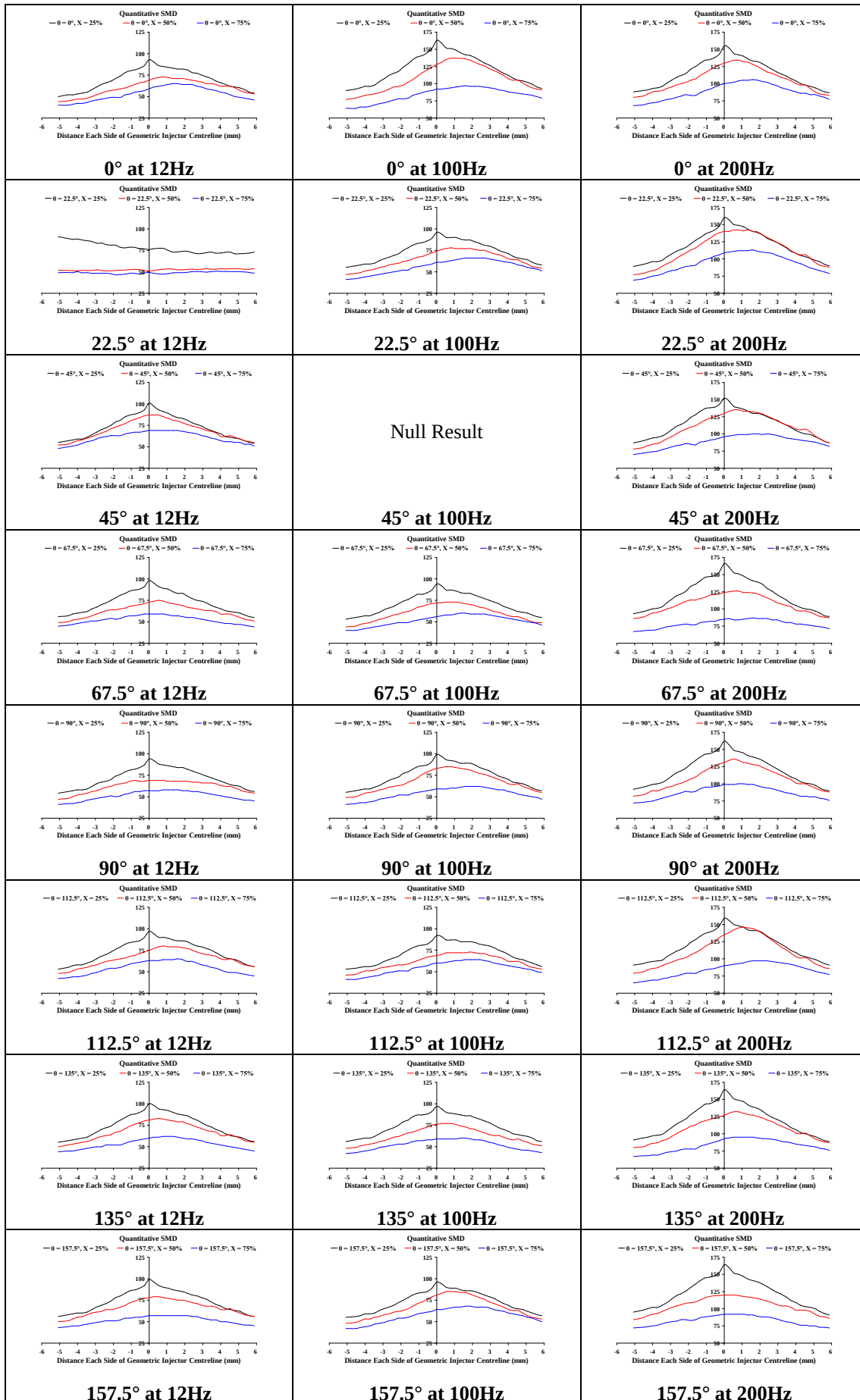


Figure 9.29: Seq. of AFR Plots from B61 – 24% Approach at 12, 100 and 200Hz



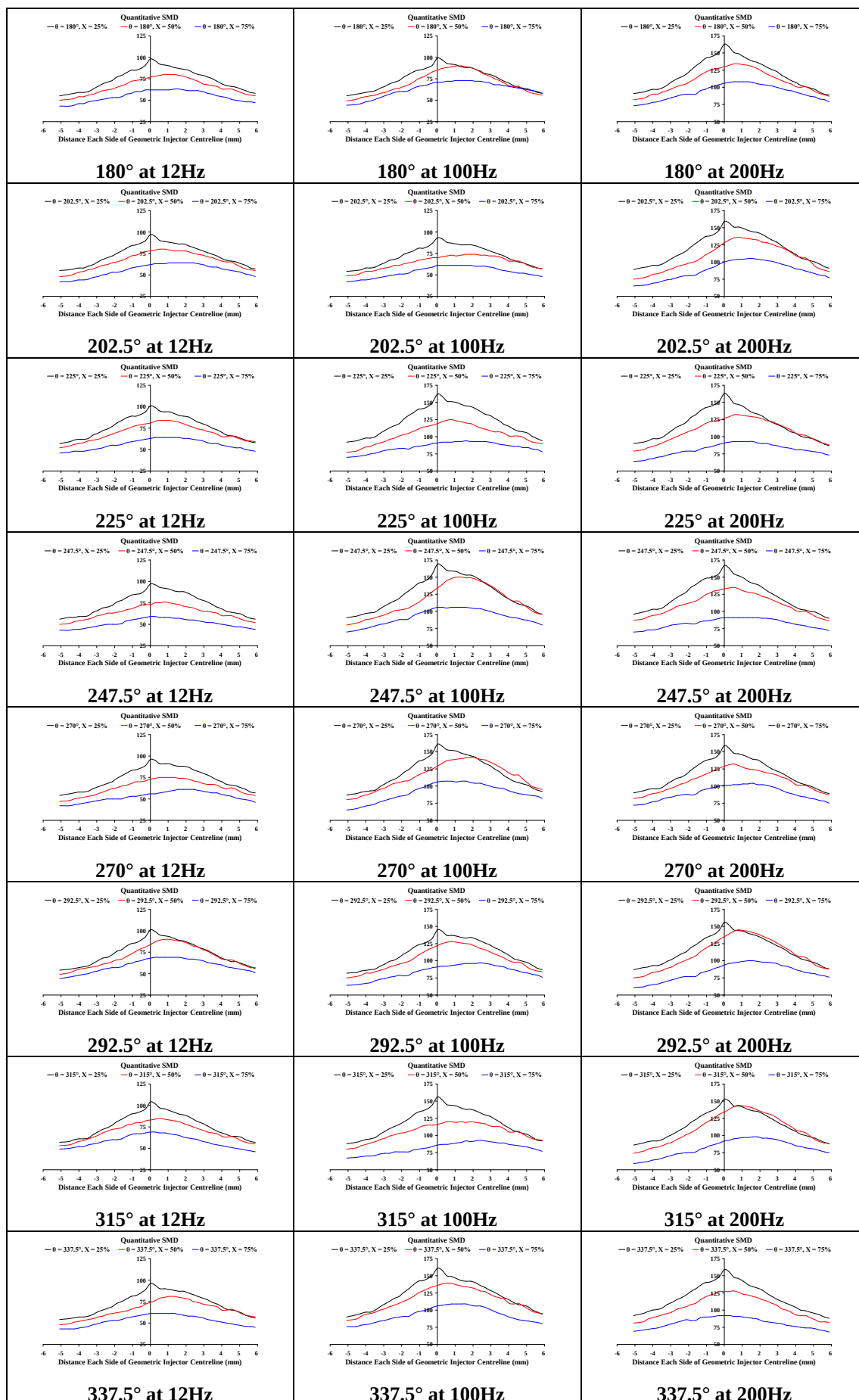


Figure 9.30: Seq. of SMD Plots from B61 – 24% Approach at 12, 100 and 200Hz