

CRANFIELD UNIVERSITY

David Alejandro Block Novelo

Application of Compressor Water Injection for the Reduction of Civil
Aircraft NO_x Emissions

School of Aerospace Transport and Manufacturing
Aerospace Propulsion

Ph.D.

Academic Year: 2016 - 2019

Supervisor: Dr. Uyioghosa Igie
Associate Supervisor: Dr. Devaiah Nalianda
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Abstract

Gas turbine Nitrogen Oxide (NO_x) emissions are directly proportional to combustion temperature. These contaminants are associated with respiratory diseases and damage to the local water quality and wildlife. Higher demand on civil aviation, coupled to high-pressure ratio (and thus, temperature-ratio) engines, have caused aviation-borne NO_x emissions to double since 1990. This is of concern around airports, at operations below 3,000 ft. where the concentration of air traffic is high and the population faces direct exposure to engine contaminants. This thesis explores the use of atomized water droplets into an engine compressor as a way of intercooling the cycle and in doing so reducing NO_x emissions. The use of water injection is proposed to be applied only during take-off and climb up to 3,000 ft. The analysis of water injection is firstly applied to common turbofan architectures (2 and 3-spool), under varied ambient conditions. The gas turbines are simulated by means of an in-house performance simulating tool, *Turbomatch*. The changes in cycle temperature when water injection is applied, are accounted for by means of a stand-alone analytical compressor model. The platform calculates the thermodynamic exchange between the gas path of the engine and the water droplets in the Lagrangian frame of reference. The engine models are then integrated into an in-house aircraft performance simulating tool, *Hermes*. Two types of aircraft, narrow and wide-body, are considered for operations with the water injection system. The performance benefits noted in the stand-alone engine section, are evaluated considering the extra system weight for different missions ranging from 500 to 11,000 km. The observed theoretical trends are then confirmed by means of an experiment performed on a stationary gas turbine. The test includes performance monitoring (pressures, temperatures, mass flows), water droplet measurements, and exhaust emissions analysis. The most optimistic case of water injection shows a reduction of NO_x emissions greater than 50%, for the period when water is used. This technology, when applied after the fan compressor, is effective at ambient temperatures as low as 5°C and is more promising in 3-spool engines. For the shortest mission considered, equivalent to a journey from London to Paris, the aircraft benefits from a small fuel saving, despite of the extra weight. For longer missions, there is a negligible fuel penalty (0.05%) derived from the extra payload. In all the cases Landing and Take-Off (LTO) emissions are estimated to be reduced by 42-43%. A reduction of NO_x emissions of 25% is achieved experimentally when injecting 2% water-to-air ratio. The study concludes that compressor water injection is a feasible solution that can significantly reduce the environmental footprint of aviation.

Keywords: Engine performance; NO_x reduction; Aircraft performance; Gas turbine; Experiment; Water Injection.

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I. Introduction

“We make our world significant by the courage of our questions and by the depth of our answers”

Carl Sagan

1.1 Background

This research forms part of the *Green Runways* project at Cranfield University, where different alternatives are being considered to promote a sustainable growth of the aviation industry. The solution studied here is the application of compressor water injection from within the aircraft with the purpose of reducing Nitrogen Oxide (NO_x) emissions during take-off.

According to The World Bank, in 2017, 3.9 billion people travelled by air, almost twice as many as in 2007 [1]. The International Civil Aviation Organization (ICAO), predicts a 20-year increase rate of all air traffic of 5.3% per year, suggesting that the number of aircraft could double again in the next 14 years [2]. In Europe, the rise in air transportation has been facilitated by low-cost carrier flights, which grew by 61% between 2007 and 2016, and today represent over 30% of Europe's air traffic [3]. This rapid growth promises a vibrant future for the industry but could have disastrous environmental consequences if it is not done in a sustainable way [4]. Airports are of special concern, as they are the places in which traffic concentrate and ground-level emissions have a direct effect on the surrounding population. Despite the increased air-traffic, between 2005 and 2014, the fuel- burn per passenger-kilometre was reduced by 19% as a direct consequence of more efficient flying [5]. Lighter airframe, implementation of winglets, or longer and thinner wings are some examples of the technological measures that facilitated this improvement. Advancements in the specific fuel consumption (SFC) of the engines have also been a big contributor. This has been achieved by increasing the propulsive efficiency of the power plants by means of higher bypass-ratio, as well as by improvements in the thermodynamic efficiency by raising the pressure-ratio of the engines. It is forecast, however, that even with these technological developments CO_2 emissions could still be 44% greater by 2035 compared to 2005 unless operational and market-based measures are implemented alongside future technological improvements.

The developments in gas turbine fuel efficiency have resulted in higher operating temperatures inside the core of the engine. Cumpsty [6] suggests that the innovations in materials have allowed the design turbine inlet temperature of modern engines to rise at a rate of 10 K per year. It has been known since the 1970s that NO_x emissions are directly proportional to the flame temperature and to a lower extent, to the air pressure [7]. The gains in fuel efficiency and carbon dioxide reductions have, thus, been penalized with an increase in Nitrogen Oxide emissions. In absolute terms, aviation NO_x emissions in Europe have doubled since 1990, and their share to total European NO_x emissions is four times larger than it was in that year [5]. These contaminants are predominately produced by aircraft engines during the take-off and early climb where the power requirement peaks [8]. Nitrogen Oxides are known to be detrimental to human health, as well as contaminating water reservoirs, and affecting the local vegetation and wildlife[5,9]. Air pollution has now become the fourth-leading cause of premature death in the world,

causing one in ten deaths in 2013 [10]. In the United Kingdom alone, it is estimated that every year 110 people die prematurely because of airport-related emissions [11].

The positive association between exposure to air pollutants (like NO_x) and respiratory diseases, has driven the ICAO to set long-term goals (2026) of cutting NO_x emissions by 60% compared to 2005 levels [2]. This project analyses one of many solutions focused on improving the air quality at and around airports. The study implements evaporative cooling technology inside the engine's compressor to lower the operating temperature of the core gas and thus reduce NO_x emissions. Compressor water injection has been applied before for power augmentation of land-based gas turbines or thrust increase in early aircraft. In this study, the technology is adapted to civilian- aircraft, by analysing the implications that it would have in terms of emissions, engine performance, fuel burn, and extra weight. It is shown that compressor water injection is an alternative that promises high reductions in Nitrogen Oxide emissions (>50%) and can be more readily implemented, compared to other alternatives. The investigation includes analysis at a compressor, engine, and aircraft level, and the trends obtained theoretically are confirmed by means of an experiment performed on a single-shaft gas turbine.

1.2 Objectives

Compressor and Gas Turbine:

1. Compare Water Injection to other alternatives focused on reducing airport air pollutants.
2. Develop an analytical evaporation model to simulate compressor water injection. Quantify the effects of droplet size, water quantity and injecting position.
3. Extend the model to typical configurations of aero-engine compressors: 2 and 3-spool. Evaluate the effects of ambient conditions and injection properties: droplet diameter, water quantity, location of the nozzles.
4. Develop engine models representative of two and tree-spool modern turbofan engines and incorporate point 2 into the models. Evaluate the effects of ambient conditions and injection properties. Quantify the overall changes in performance and exhaust emissions.

Aircraft

5. Develop aircraft models representative of narrow and wide-bodied aircraft, incorporate point 4 to the models.
6. Evaluate the effects of the added weight for different range missions and quantify changes in aircraft performance and emissions.

Experimental Study

7. Test different types of nozzles and identify the appropriate nozzle to be used based on flow delivery and droplet size
8. Test the effects that pressure, water composition, water temperature, and measuring position have on droplet size for the selected nozzle.
9. Inject different water quantities into the intake of an engine. Simultaneously record droplet size, engine performance parameters, and emissions.

1.3 Contribution to Knowledge

For the first time,

Water injection was considered alongside other alternatives aimed at reducing airport-related emissions (Obj. 1). It was observed that this technology can be more readily applicable than other solutions, and it is unique in the potential it has to tackle NO_x emissions.

The application of water injection into different engine architectures was evaluated on a compressor and engine level (Obj. 2-4). The three-spool engine was seen to benefit more from water injection, due to the higher-pressure ratio of the intermediate pressure compressor, which enhances evaporation. The higher cooling capacity noted in the three-spool engine, allowed for higher temperature, fuel, and NO_x reductions, compared to the two-spool engine.

Water injection was considered to be applied between the fan and the intermediate pressure compressor (Obj. 2-4). It was noted that this location was specifically beneficial, as the water is injected into a hot and dry medium. This allows for the application of water injection to be extended to cold and/or humid ambient conditions. For this injecting position, the ambient temperature has little influence on the reductions of NO_x emissions, as a percentage of the “dry” value. For example, it can be stated that a two-spool engine like the one analysed here can have a reduction in NO_x emissions of close to 50% when 2% of water is injected into the core of the engine (with droplets of 5-10 µm in diameter), irrespective of the ambient temperature at which this is applied.

The implications of the added weight were accounted for and the associated fuel penalties were compared against the fuel savings seen while the water was applied (Obj.5,6). This was analysed for different mission lengths. For the shortest mission considered, the fuel savings obtained while the water is being used (during take-off and early climb) outweigh the fuel penalties derived from carrying the extra weight. For the longest mission, corresponding to the maximum-payload range, an insignificant fuel penalty was noted as a consequence of the extended cruise time in which the system weight is being carried.

An experimental test was performed in which engine temperatures, pressures, fuel flow, air flow and exhaust emissions, along with water quantity and droplet size were simultaneously monitored (Obj. 7-9). This presents a step further from previous studies which only focus on one of the following aspects: fogging sprays, compressor performance, emissions or thermodynamics, but do not present an integrated analysis. A reduction in NO_x emissions of up to 25% was achieved when applying water to the single-shaft stationary gas turbine.

1.4 Thesis Structure

This thesis is presented in the format of a “thesis by publication”. Each chapter represents an individual study that has been published or submitted for publication prior to the delivery of the thesis. The chapters/papers follow a sequence from the simulation of a single compressor through the modelling of an entire aircraft and finish by presenting experimental results for the predicted trends. All the papers presented have been written by the first author and edited by Dr. Uyioghosa Igie who also provided constant technical support and guidance. Paper 5 was written with the contribution of Dr. Devaiah Nalianda, who provided technical assistance related to aircraft modelling. Paper 6 includes the contribution of Mr. Vinod Prakash who assisted with the experimental testing as part of his MSc. studies, and of Dr. Artur Szymanski, who proofread the manuscript and contributed by giving advice about the experimental procedure and post-processing of the data. A summary of the chapters, with some details about the publication status, is given below, followed by a brief description of each thesis section.

Chapter number	Objective Addressed	Publisher	Focus	status
II	1	ASME Turbo Expo: Power for Land Sea and Air	Literature Review	Published
III	2	Revista Internacional de Investigación e Innovación Tecnológica	Water Injection: Temperature & humidity effects on 2-S engine	Published
IV	3	Energy	Compressor model with water injection 2, 3-S	Published
V	3, 4	Energy	Engine model with water injection 2, 3-S	Published
VI	5,6	Journal of Transportation Research Part D: Transport and the Environment	Aircraft model with water injection. NBA and WBA	Published
VII	7-9	Energy	Experiment	Accepted
VIII	1-9	-	Discussion and Conclusions	-
Annex	2,3,9	-	Input files for Simulations	-

II. Paper 1 explains the necessity to investigate means of reducing airport emissions. Eight approaches are analysed and classified into operational changes, technological implementations or a mix of both. These solutions are then applied to 11 aero-engines of varying technological level and architecture to evaluate their potential in reducing Nitrogen Oxides, Carbon Monoxide, and Unburned Hydrocarbons, the three emissions regulated by the ICAO. Compressor Water Injection is then identified as a promising solution that can be implemented with lower costs or development time, as compared to the other approaches. The promise and challenges in the implementation of this technology are mentioned.

III. Paper 2 presents a method for modelling water injection into a compressor. The methodology is compared to other analytical publications. The study identifies that compressor water injection has two main effects: The increase of the air humidity inside the gas path and the reduced gas temperature. Both effects are isolated and analysed to account for the overall impact that this technology has on engine performance. The analysis is done on one of the 11 engines presented in *paper 1*, which is representative of most of the current active engine fleet. This chapter uses a model to simulate water injection that assumes equilibrium evaporation. It does not consider the effect of compressor polytropic efficiency, and assumes that saturation conditions are present in the flow.

VI. Paper 3 Improves the compressor analytical model from *paper 2* and applies it to two different compressor architectures corresponding to 2 and 3-spool compressors, both representative of modern aero-engines. In this chapter, non-equilibrium evaporation is considered, and the expression used to model wet compression accounts for the entropy generation of a polytropic compression. The effects of Water Injection are evaluated under different ambient conditions for both cases, as well as for different water quantities and water droplet diameters. The physics behind the cooling of the compressor, as well as the potential and limitations of evaporative cooling, are thoroughly explained. For the case of the 3-spool compressor, injection is considered at two positions inside the engine. The paper concludes that 3-spool compressors, due to the longer and higher pressure-ratio intermediate compressor, present superior benefits in terms of cooling than 2-spool compressors when injected with the same relative water quantity.

V. Paper 4 is a continuation of *paper 3* and incorporates the two compressor models into complete gas-turbines. The paper presents the performance changes of 2 and 3-spool high-bypass-ratio turbofan engines when they operate under “wet compression”. The effects of humidity and temperature observed in *paper 2* are considered for the analysis. Water Injection is evaluated under different ambient conditions, water quantities, and droplet sizes. It is demonstrated that the effects of water injection are independent of the ambient conditions when water is injected between the Fan Compressor and the Intermediate Pressure Compressor. Important reductions in NO_x emissions are noticed (50-60%), coupled with fuel reductions (4-7%) and lower turbine temperature operation

(160- 240 K). All the calculations for this chapter are assuming an uninstalled engine operating at take-off conditions.

VI. Paper 5 integrates the engines analysed in *paper 4* into two civil aircraft representatives of narrow and wide-body configurations. The investigation weighs the fuel benefits seen on *paper 4* against the fuel penalties expected from carrying the system and the water on board the aircraft. The analysis is done for different range missions going from 500 to 11,000 km. The study concludes that water injection is more promising in short-haul missions and that even on the longest-range missions analysed, the fuel penalties would not be considerable, especially considering the important reductions in LTO NO_x emissions observed for both aircraft, estimated in about 43%. The performance changes due to water injection are compared against those from reduced-thrust-take-off operations. The engine simulations corresponding to this chapter are for many different points other than take-off, including climb up to 3,000 ft.

VII. Paper 6 presents experimental results for gas turbine compressor water injection. The first part of the paper presents tests of the fogging nozzles under still air conditions. The influence of water chemistry, temperature and delivery pressure are analysed to determine the configuration that gives the smaller droplet diameter. The change in droplet size as the plume travels away from the nozzle was also evaluated by moving the measuring point away from the nozzle tip. In the second part, an array of nozzles was then installed at the intake of a single-spool gas turbine. The performance and emissions of the engine were monitored for different water quantities going from 0.5% to 2% of the inlet air mass flow. Reductions in NO_x emissions of up to 25% were achieved, coupled to a 7% decrease in cycle operating temperature for the highest amount of water injected with droplets of a maximum size of 37 µm.

Thesis Appendix: Additional Information, Is an annex to the thesis where the input files for all the engine and aircraft performance simulations are resented.

References

1. World Bank. Air transport, passengers carried. 2017. Available at: <https://data.worldbank.org/indicator/is.air.psgv> (Accessed: 26 September 2018)
2. ICAO. ICAO Environmental Report 2016- Aviation and Climate Change. 2016.
3. Eurocontrol. The rapid Rise of Low-Cost Airlines. 2017. Available at: <https://www.eurocontrol.int/news/rapid-rise-low-cost-carriers> (Accessed: 26 September 2018)
4. Nilsson JH. Low Cost Aviation. In: Gossling S, Upham P (eds.) Climate Change and Aviation. 1st edn. London: Earthscan; 2009. pp. 113–129.
5. EEA (European Environment Agency). European Aviation Environmental Report 2016. 2016. Available at: DOI:10.2822/385503
6. Cumpsty N. Jet Propulsion a Simple Guide to the Aerodynamic and Thermodynamic Design and Performance of Jet Engines. 1st edn. Cambridge: Cambridge University Press; 1997. 279 p.
7. Lipfert FW. Correlation of Gas Turbine Emissions Data. The American Society of Mechanical Engineers. 1973; 72 GT 60.
8. Lefebvre AH., Dilip RB. Gas Turbine Combustion Alternative Fuels and Emissions. 3rd edn. New York: CRC Press; 2010. 560 p.
9. EEA (European Environment Agency). Nitrogen Oxides (NO_x) Emissions. 2016.
10. World Bank Group. The Cost of Air Pollution. The World Bank. 2016. Available at: DOI:10.1080/000368497326688
11. Yim SHL., Stettler MEJ., Barrett SRH. Air quality and public health impacts of UK airports . Part II : Impacts and policy assessment. 2013; 67: 184–192.

II. Paper 1

Literature Review

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Case for Exploring Compressor Water Injection for Airport Emission Reduction

David Alejandro Block Novelo and Uyioghosa Igie

School of Aerospace Transport and Manufacturing, Cranfield University, Cranfield,
UK

Abstract

The increasing world population, higher accessibility to air transportation, coupled with new low-cost airline models has resulted in an unprecedented increase in demand for civil aviation. The industry is currently experiencing a global increase in operational civil aircraft at a rate of 5-6% annually. This growth suggests a vibrant future for the industry, however, the environmental implications and the footprint is worth considerable attention given the expected scale of growth of this sector and the possible side effects to human health. The stakeholders involved, some of which include: airports and airline operators, jet engine and airframe manufacturers and various government bodies, are introducing measures in order to mitigate the increase in certain emissions and hence their impact.

This study focuses on one of the many existing approaches targeting the reduction of gaseous emissions, predominantly nitrogen oxides (NO_x). This is through compressor water injection that is estimated to reduce NO_x emissions by almost half under certain ambient conditions and water-to-air ratio. Apart from reviewing this technology, the study, more importantly, presents the ideas in relation to other major existing approaches/concepts.

It would be observed that compressor water injection can be more readily applied to the existing infrastructure when compared to other approaches. This technique is one of the most promising methods for reducing NO_x emissions, an area of particular importance given that modern engines, though more thermally efficient, operate at higher pressure ratios and flame temperature, both of which enhance nitrogen oxides formation.

One of the main contributions of this paper is the categorisation of existing approaches focused on reducing aircraft-borne airport emissions. Different technologies and operational changes are classified according to the key pollutants that they target with respect to the landing and take-off cycle based on 11 different engine types. These gaseous-emissions mitigating approaches are analyzed based on their individual merits, limitations and feasibilities. Compressor water injection is re-introduced here as a more readily applicable solution despite its technological challenges, many of which can be better resolved with today's knowledge.

Key Words: Airport Pollution, Emissions mitigation, NO_x Emissions, Water Injection.

1- Introduction

Civil aviation accounts for 13% of transportation greenhouse gas emissions in Europe [1,2] and 7% of total European NO_x emissions [3]. At Heathrow airport and surrounding areas, 53% of air pollutants come from air traffic [4], and evidence reveals that this number can be in the order of 60% - 80% in other airports around the world [5,6]. Aircraft-related contaminants are likely to overtake motor vehicle pollutants in the near future [7]. Currently, around 3% of the overall carbon dioxide (CO₂) production by man-made activities comes from civilian jet fuel burn and that number is likely to increase with increasing air travel demand. Macintosh [8] indicates that international aviation carbon dioxide emissions could increase by more than 110% between 2005 and 2025 despite technological developments. Air transportation in North America, Europe, Asia, and the Middle East is bound to increase by 5.7%, 5.0%, 8.8% and 10% respectively every year [9]. Experts predict a worldwide rise in demand of over 5% for international travel and 4.4% for domestic traffic, suggesting that passenger air traffic will double every 14 years [3,10]. In terms of passenger flow, civil aviation transports more people than ever before and around 2 billion passengers fly on scheduled flights annually with predictions of a rise of up to 7 billion by 2034 [11]; some sources predict 9 billion passengers by 2025 [12]. Sgouridis et al. [9] estimate that aviation contribution to total European Union emissions could reach anywhere between 10% to 50% by 2050.

Aircraft-related ground gaseous emissions have received considerable attention in previous years, especially for NO_x emissions. Modern aircraft engines, despite being more thermally efficient, tend to produce more NO_x due to the dependency of this emission on Combustion Chamber (CC) exit temperature[13,14]. The trend of engines that produce high levels of NO_x is reduced by newer CC designs, but not sufficiently, considering the high rise in aviation demand[3]. The environmental implications of aircraft pollutants and effects on the human health and the environment can be found in [6,10,15–18], and include respiratory illness, acidification of freshwater reservoirs and damage to the local vegetation and wildlife.

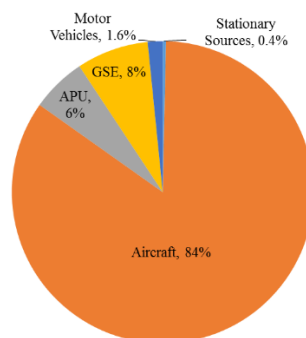


Figure 1 Source of NO_x emissions in Atlanta International Airport [19]

ICAO [3] has identified aircraft engines to be the dominant airport-related source of air contaminants. In the busiest airport in the world: Hartsfield-Jackson international airport in Atlanta, jet fuel burn accounts for 84.5% of the total airport NO_x emissions [19] as shown in Fig. 1 with Ground Support Equipment (GSE) and Auxiliary Power Units (APU) representing only 8 and 6% of the emissions, respectively. Figure 2 shows the sources of air pollution at Heathrow airport (left) as well as the aircraft emissions distribution per segment/activity (right). Over half of the total airport pollutants come from aero-engines, of which almost 50% is produced during the take-off roll. Based on the experimental data taken at 8 locations around Heathrow airport, Carlsaw et al. [20] indicate that the airport is responsible for 23% of the NO_x in the air around the area, while the Heathrow study indicates that this number could be about 50% [4].

Stettler et al. [6] taking into account 20 of the busiest airports in the UK, concluded that around 72% of NO_x emissions are produced at take-off and climb (10% at taxi and 18% at landing). Daggett et al. [21] estimate similar emission inventories taking into account taxi, climb, take-off and landing as shown in Fig. 3. The opposite is the case for other contaminants like CO, where the highest levels are found at low power settings like taxiing.

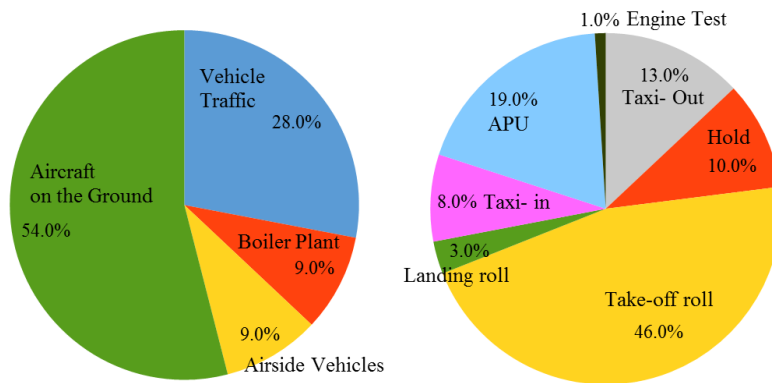


Figure 2 Heathrow airport NO_x emissions by source and aircraft activity [4]

Some of the main aviation pollutants have been mentioned (CO, CO₂, and NO_x) and others include Unburned Hydrocarbons (UHC), Particulate Matter (C) and Oxides of Sulfur (SO_x). An extensive review of airport-related pollutants and their sources can be found in [22]. Figure 4 presents a general overview of some of the key aero-engine pollutant emissions as a function of engine power setting. CO which is produced as a result of unburned hydrocarbons due to inadequate mixing of fuel and air, quenching of post-flame products or CO₂ dissociation [23], is higher at low power settings (taxiing and idle). Lefebvre [7] notes that most modern combustor designs can already achieve 99%

combustion efficiency at design point (typically cruise – around 20 to 30% of take-off thrust), and thus the CO production at this flight stage will be minimum. NO_x is a combination of Nitrogen Oxide (NO) and Nitrogen Dioxide (NO₂) and can be formed by either endothermic reactions in the combustion chamber, oxide mechanisms, prompt NO or fuel NO [24].

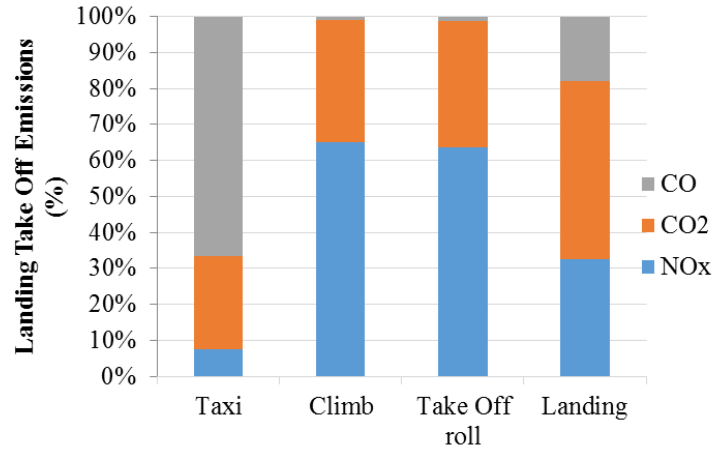


Figure 3 Airport emissions by type and activity [21]

As indicated in Fig. 4, NO_x increases with increasing power thus its production rate is highest during the take-off and climb flight phases. The reason being that NO_x emissions increase with gas pressure and temperature, as well as residence time. Following the smoke crisis in Los Angeles in the 1970s, Lipfert [25] conducted studies correlating NO_x production with combustor inlet temperature for different engine models. From the work done by Lipfert [25], Maughan et al. [26] proposed correlations of NO_x formations as a function of combustion pressure and temperature. Lefebvre [7] also proposes a mathematical relationship between NO_x and pressure ratio. This indicates that aero-engines with higher pressure ratios or operating at higher temperatures will produce more NO_x emissions.

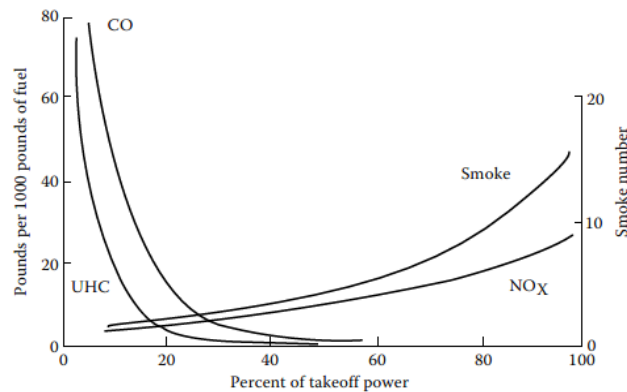


Figure 4 Different Emissions as a percent of take-off power [7]

CO₂ is produced as a consequence of the complete burn of any fuel containing carbon [23]; as long as there is combustion there will be CO₂. A reduction of aviation CO₂ can be achieved by increasing the thermodynamic efficiency of the engines, shorter waiting times or improving the operations of the aircraft, all of which lead to reduced fuel burn.

2- Measures for Mitigating Airport-Related Emissions

Current measures in tackling airport-related air pollutants can be broadly classified as operational, technological or a mixture of both. Operational solutions are defined here as those approaches in which there are no fundamental changes to the aircraft or the engines, and thus require very little investment and developing time. This category is on the left-hand side of Fig. 5 and can be implemented by modifying the management of the aircraft. Most of the operational changes proposed in the open literature are based on reducing the time the engines run at low power settings such as idling or taxi as indicated in Fig. 5 which highlights technologies/approaches addressing these activities with a surrounding dashed line. These alternatives have great potential for CO and HC reductions (applicable to operations on the left-hand side in Figure 4) but do little to reduce NO_x. Nevertheless, the reductions in emissions during idle/taxi are important, given the typical length of the time duration of a Landing and Take-Off (LTO) cycle as indicated in Table 1 Landing/Take-Off Cycle (ICAO) [27].

On the other hand, technological solutions are indicated on the right-hand side of Figure 5. These are those approaches for which considerable alterations to the aircraft are necessary. They often involve very lengthy times in development and certification, usually requiring modifications of aircraft and airport infrastructure to accommodate for the changes. As a result, they are capital intensive for the respective stakeholders involved. From Figure 5 it can be observed that in the classification, technological approaches can involve reductions during take-off or taxi mode operation

Between these two extremes in the classification, are approaches that consist of both features. This category is effectively technological, but require less transformation to the engines or the airframe as compared to the purely technological approach. As a result, these initiatives require minor operational adaptations.

Table 1 Landing/Take-Off Cycle (ICAO) [27]

Mode	Time (min)	Thrust
Take-off	0.7	100%
Climb	2.2	85%
Approach	4.0	30%
Idle/taxi	26.0	7%

Each pie chart in Figure 5 represents a different airport emission-mitigating approach. The impact on HC, CO, and NO_x is based on the ICAO engine emission data bank [28]. The size of each pie chart relates to the impact on the main tackled emission reduction. Further details of the calculations can be found in the [Appendix](#). The relative proportion of each segment of the pie chart shown in different colour indicates the pollutant that is mainly targeted. For example, in accordance with Balakrishnan and Hansman [29], Towing Aircraft to Runway with a gasoline vehicle (TAR, G) reduces aircraft related pollutants. However, this increases ground support emissions, leading to a total reduction of NO_x during taxiing of 10%. This impact is nevertheless small compared to any other individual technology or approach indicated in Figure 5.

This average estimate is based on calculations for 11 different engines, accounting for different gas turbine architecture and size as shown in the [Appendix](#). The measurement of emissions is considered during the LTO cycle that consists of descent and ascent as shown in Tab.1. Descent includes approach from 3,000 ft., taxiing/idle, while ascent is taxiing/idle, take-off and climb to 3,000 ft. Although actual operations differ from the LTO cycle, this standardization enables the comparison of different technologies [30]. As such, it is a convenient method for the purpose of this study. More detailed techniques for emission inventories based on actual aircraft operations can be found in [7,30,31].

The emissions reduction effects of each technology have been obtained from Daggett et al. [32], Brown [33], and Balakrishnan et al. [29,34]. These have been adapted to indicate the classification, type of emission targeted, impact, and mode of operation. Subsequent subsections discuss the respective approaches in further details, to provide a context. More emphasis on Engine Water Injection (EWI) has been made in the latter part¹.

2.1 Operational Approaches

Single Engine Taxiing (SET) - A world-wide effort in reducing the levels of emission at and around airports is in place. India is one of the countries with the highest growth in air transport demand, with about 25% growth in 2015 [35]. Such growth has brought about SET operation, as encouraged by the civil aviation authority, to reduce emissions, fuel burn and power output [36]. SET consists of using only one engine from pushback to runway approach. Studies suggest that implementation of SET can potentially reduce 25% - 40% of taxi-out fuel burn [34]. During taxiing -since the engines operate on low power settings- the primary pollutant emissions are CO and HC (Figure 3, Figure 4), therefore SET is well suited to target reduction in these specific emissions. The Heathrow airport management plan for emissions reduction is also encouraging airlines to turn-off

¹ [Chapter VI](#) (Aircraft analysis) also compares compressor water injection to reduced thrust take-off.

one or more engines during taxiing, as well as an investment in infrastructure to reduce the use of APU's whilst the aircraft is at the gate [37].

Airport Traffic Management (ATM)- ATM is an avenue for reducing gaseous emissions investigated in Torres and Chaptal [1] and Balakrishnan and Deonandan [34] focused on reducing queues at the runway. The latter study shows a reduction in taxi-out emissions of up to 60% by correctly managing queues, and dispatching one aircraft at a time directly from the gate to the runway. This approach, although attractive, is restricted by the airport throughput and could result in increased overall delays. The Single European Sky (SES) and Airways [38] are initiatives that consist of optimising routes and networks. Flight inefficiencies in Europe dropped from 5.42% (2009) to 4.9% (2014), and the ultimate goal is for the pilots to fly in straight lines between destinations to minimise flight time and fuel consumption [39]. Flight trajectory optimisation measures are intended to reduce aircraft emissions during flight but do little to mitigate airport-related emissions.

Towing Aircraft to Runway (TAR)- Taxibot [40] is a towing vehicle controlled and operated by the pilot from the cockpit. Taxibot guides the aircraft to the departing runway while the engines are turned off and is subsequently driven back to the gate by a safety driver. The use of Taxibot or other towing vehicles is restricted to the landing gear loads and cycles, as they are currently not designed for long duration, high-speed towing [34]. Balakrishnan and Deonandan [34] also covers dispatch towing. The study claims that certain pollutants can, in fact, increase while using the towing truck, depending on the engine type and hence fuel type utilised in running the vehicle. It is suggested that the use of Diesel fuel might increase NO_x emissions while gasoline fuel comparatively produces more CO. The ICAO Airport Air Quality Manual [30] also comments on this issue suggesting that NO_x emissions from a Diesel aircraft handling vehicle are 5 times higher than for a gasoline one, and CO emissions are 75 times lower. Nevertheless, they both bring about a reduction in the use of jet fuel and hence CO₂. Efforts are also being made at replacing ground support vehicles from internal combustion engines to hybrid or electric vehicles [41]. For this reason, TAR-D on the figure, shows only a reduction of CO and HC, as in this case the NO_x emissions could rise or remain unchanged.

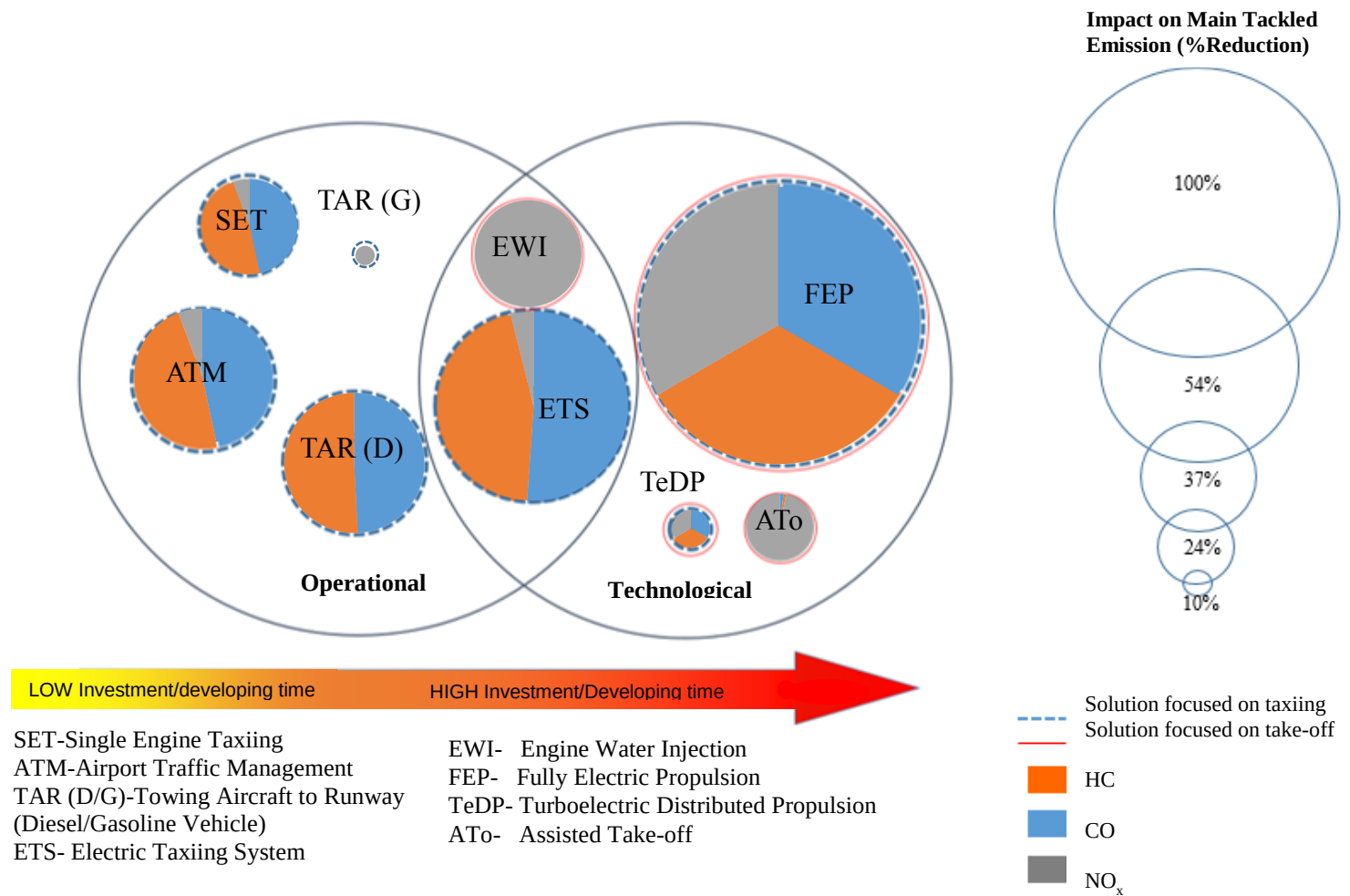


Figure 5 Airport Emissions Mitigating Measures by Type, Impact, development time/cost and pollutant

2.2 Technological Approaches

Assisted Take-Off (ATo)- In 2012 Airbus introduced a concept that promises to be more environmentally friendly through ATo [42]. This idea dubbed “Eco-Climb” is a part of their “Smarter Skies” initiative for 2050 and beyond. ATo includes an electrically driven platform that propels the aircraft out of the airport, reducing the need for aircraft propulsion at take-off. ATo would considerably reduce emissions at the take-off roll. The impact of this technology shown in Figure 5 is calculated by replacing the levels of emissions at take-off – from full power setting (100%) to idling (7%), and subsequently comparing the emissions to the normal LTO cycle. For the implementation of this technology, the operations, infrastructure and design of both aircraft and airports would have to change considerably.

Turbo Electric Distributed Propulsion (TeDP)- The turboelectric distributed propulsion system has been proposed by NASA in conjunction with several collaborations with universities [33,43,44]. The NASA N3-X concept of Turbo-electric Distributed Propulsion (TeDP) on a Blended Wing Body (BWB) airframe involves a low drag shaped aircraft propelled by electric fans powered by the electricity generated by a gas turbine. The fuel burn benefits from this concept come from the higher By-Pass Ratio (BPR) of the electric fans, which produce a higher propulsive efficiency as well as from the boundary layer ingestion which reduces the overall drag [33]. These benefits, however, are counteracted by the weight of the components and inefficiencies of the system. The net impact, evaluated by Brown [33] could translate into a 10% fuel saving. Other challenges of the technology include the positioning of the electric engines, cooling of the superconductors and weight of the components that have been evaluated and presented in Gibson et al. [45] for a conceptual subsonic passenger aircraft. According to NASA, electric distributive propulsion will be the future of flight but we are still a long way away from that [46]. TeDP is accounted for in Figure 5, taking into consideration a 10% reduction in emissions throughout the LTO cycle and for all the pollutants under consideration (CO, HC, NO_x) representative of the overall fuel saving.



Figure 6 TeDP on a blended wing body airframe [47]

Fully Electric Propulsion (FEP) -The first fully electric-solar powered aircraft – Solar Impulse landed at Dubai International Airport on the 26th of July, 2016, completing the first ever round-the-world, zero-emission flight [48]. Although this solar-powered solution demonstrated in the experimental vehicle (Figure 7) is attractive in eliminating aircraft emissions, the technological challenges to achieve this on a large scale for international air travel are considerable.



Figure 7 Solar Impulse concept aircraft: [49]

In Figure 5, FEP is represented as the biggest pie chart and it is divided equally into three parts, indicating that it has the biggest impact of all the technologies and it would significantly reduce all the respective pollutants.

Moore [50] evaluates different solutions for distributive propulsive aircraft and mentions the technological challenges associated with them. These challenges include battery development, and weight (estimated to be 25% of the aircraft weight) system reliability, superconductor technology improvement and propulsion integration.

Use of Alternative Fuels- The use of alternative fuels to reduce emissions is being evaluated all around the world [9,51–53]. Kivits et al. [53] conclude that the use of alternative fuels like liquid hydrogen, although promising, is still a distant idea. To achieve this practically, a considerable change in infrastructure would be needed, from airports (storage of the LH₂, vehicles to supply it, extra energy required to keep it at a low temperature etc.) to the airlines, and aircraft design. Allen [51] estimates the increase in an airport facility to be able to do this, and the amount of electricity required, which would have to come from a Carbon-free source. The study also highlights the changes that aircraft would have to undertake to implement this technology. LH₂ has a lower volume power density than current hydrocarbon fuels, meaning that for the same aircraft to fly the same long-haul mission, the fuel tanks would have to be considerably larger, or external tanks would have to be fitted on the aircraft.

The use of Biofuels has been widely used by several airlines for test purposes or on specific routes. In 2008 Air New Zealand successfully completed the first flight powered by a 50-50 mix of kerosene and a second-generation biofuel. Following this, KLM flew Amsterdam to Paris in 2011 with a fuel based on cooking oil. Lufthansa has operated a Frankfurt to Berlin route using a 10% blend based on Sugarcane. Although “drop-in” biofuels have the potential of reducing emissions by up to 80%, this reduction happens mostly at the time of manufacture of the fuel and not during the flight or LTO cycle [36].

2.3 Technological/ Operational Approaches

Electric Taxiing Systems (ETS)- A study on efficient taxiing systems presented in Re [54], highlights the potential emissions reduction at the airport during taxiing. Examples of ETS includes that of Wheeltug [55] that involves the use of a small electric motor installed at the nose landing gear and powered by the APU. This also eliminates the use of the engines during taxing as well as the need for a towing/tug vehicle or any ground support equipment. A similar approach is also implemented by MagnetMotor [56] currently involving the use of permanent magnet electric wheel drives on the rims, also in the main landing gear

A competing solution developed by Honeywell and Safran [57], referred to as the Electric Green Taxiing System (EGTS), has received special interest from EasyJet, that has been involved in exploratory trials. The airline claims that 4% of their annual fuel consumption comes from ground operations, accounting for a travel of 3.5 million miles a year [58]. The system currently involves not only using the APU to power the electric motors at the wheels but using regenerative braking at landing to store the power into batteries. Galea et al. [59] propose a conceptual design for a wheel actuator that can be used in any of these applications and estimate a 4-5% reduction in fuel burning and carbon emissions.

The implementation of ETS would involve operational changes, like the redundancy of towing vehicles, and the re-positioning of fire crews at the airport, which at the moment are close to the main buildings where the engines are turned on [54]. Another challenge is the engine warm-up time that can be as long as 5 minutes in some cases [29]. In conventional taxiing, this requirement is fulfilled within the taxiing period, however, if any of these measures were implemented they would mainly be beneficial for operations where taxing times are normally above the engine warm-up time.

The impact of ETS was evaluated in this review based on the LTO cycle, by reducing the idling time from 26 to 5 minutes and comparing the total emissions to that of a standard LTO operation. It is important to reiterate that these measures that mainly target taxiing would only have a significant impact on CO and HC pollutants that are more dominant in low power aircraft flight phases like idle or taxiing.

Despite the efforts to reduce emissions based on better operation, better design, new technologies, and more stringent regulations, not one of these solutions on their own would be enough to keep emissions at an acceptable level if the demand keeps growing at the rate foreseen, and considering the long development and certification times associated with the aviation industry [9,15].

Jet Engine Water Injection (EWI)-Engine Water injection provides a way of achieving reductions in gas turbine emissions, especially NO_x . The studies reported in references [21,60] suggest that if 2% of the total engine mass flow is injected as water into the compressor, the NO_x emissions can be potentially reduced by the order of 47%. The implementation of EWI does not demand or necessitate the significant changes in infrastructure or hardware that other technologies may require. Decreasing NO_x was not the initial aim of water injection; six years after the first Whittle turbojet engine flew, Wilcox and Trout [61] conducted experiments on gas turbine performance with water injection for thrust augmentation. The outcome of the study concluded that the effect is more beneficial at low altitudes, high temperatures, and low humidities, mainly for take-off conditions. This method has since been widely studied and applied for over 1,000 industrial gas turbines around the world. A comprehensive review of the injection methods, benefits, and types of injection is presented in Bhargava et al. [62–64].

EWI technological challenges are minor compared to solutions like FEP or the use of alternative fuels (hydrogen or biofuels). Many alternatives intended for reduction of airport-related contaminants target operations at taxiing. Although these measures are necessary it has been seen that taxi at Heathrow accounts for 21% of air pollutants, while take-off accounts for 46% [4]. Moreover, implementing solutions targeted at taxiing would reduce CO and CO_2 emissions but would have little or no effect on NO_x . Considering that the CAEP regulations are focused on NO_x emissions restrictions, it is fundamental to develop technologies that could reach the goals of ICAO of 60% reduction in NO_x by 2026 (compared to the certification CAEP/6) [27]. Water injection at take-off and climb is therefore suggested to complement other operational and technological approaches. This could further reduce the environmental footprint of aviation: dominant carbon pollutants at taxiing, and dominant NO_x pollutants at take-off and climb.

Water injection for gas turbine engines has been historically applied to the combustor or compressor. The following section provides a review of the different methods and impacts on engine performance based on studies from the open literature.

Combustion Chamber (CC) water injection- When water is injected into the combustion chamber, additional energy is required from the fuel to evaporate the water, increasing the fuel consumption and lowering the thermal efficiency [65]. Typical figures for NO_x reductions into the combustor are in the order of 80% reduction for 1:1 water-to-fuel ratio [66].

Bahr and Lyon [66] suggest an expression to relate NO_x abatement to fuel heating value, water and fuel flow rates. The investigation shows an increase in CO with rising levels of water-to-fuel ratio for engines with low-pressure ratio, but a steady production of CO

with high-pressure ratio compressors; suggesting that modern engines with higher pressure ratios will have more favourable combustion conditions with water injection. The production of CO depends on the efficiency of the combustor, as mentioned previously. Bahr et al. [66] indicate that this value decreases by 0.1% when water is injected into the CC.

Findings of Roumeliotis and Mathioudakis [67] agree with Bahr and Lyon [66] in that the potential of NO_x reduction by injecting water into the combustion chamber has the drawback of a marked decrease in thermal efficiency. Though CC water injection has shown to be more effective at reducing NO_x emissions, there are other technological challenges associated with injecting water into this part of the engine. Daggett et al.[21] Indicate some of the historical problems in the early Boeing 747 aircraft powered by Pratt and Whitney JT9D engines. Some of this included non-uniform distribution of water resulting in poor temperature distribution in the HP turbine (injection prior to combustor). Thermal stressing on HP turbine due to sudden introduction of cool water that impinged on hot metal surfaces was also reported as a potential problem [68,69]. Spraying water in the combustor proved even better with steam however only practical for the stationary engines due to the relatively large volume of water needed and steam generating requirements[70]. If water is injected into a hot medium and it is fully evaporated, the temperature reduction will be higher (at the injection point) than if it is injected in a cooler medium. This suggests that combustion chamber water injection will achieve higher temperature reductions than compressor water injection. However, in the compressor case, the air is precooled and then compressed. Although the initial temperature drop will be lower than that seen in the combustor, once the cooler air gets compressed, this initial cooling effect will be multiplied. The end result will be a higher temperature reduction at the combustor than what would be achieved if the water was injected directly into the CC. With Compressor water injection, the inlet cooling and intercooling effect will also reduce the specific work of the stages. This effect is lost when water is injected into the combustion chamber.

3- Compressor Water Injection (CWI)

When water is injected into the compressor typically at hot and dry ambient conditions, it reduces the air temperature, increasing the mass flow, thereby reducing the work required by the turbine to drive the compressor in order to generate thrust or shaft power. Utamura [71] concludes that this reduction in compressor work contributes to a rise in cycle thermal efficiency. This increase in thermal efficiency for stationary gas turbine engines could be achieved at constant power output operation, as well as augmented power operation. The latter involves maintaining the firing temperature or heat input. Cumpsty [72] notes that cycle efficiency depends on the ratio of TIT to Compressor Inlet

Temperature (CIT), and that reducing CIT has the same effect of increased efficiency as rising TIT, especially for high-pressure ratio engines.

Water injection consists of two approaches for which the impact and classification are determined by the thermodynamic state of the ambient air. One approach is referred to as inlet fogging/misting which involves the addition of sufficient amount of water at the intake of the engine, so as to cool and saturate (or achieve 100% relative humidity) the inlet air. The other approach is known as wet compression or overspray. The main objective of the latter is to allow for continuous evaporation of water droplets through the compressor. This permits a bigger drop in the compressor outlet temperature due to the intercooling effect, thereby tending towards isothermal compression [70,71]. This method is widely used in industrial gas turbine applications in predominantly hot and dry climates when the demand for energy increases partly due to increased use of air-conditioning. The P-V and T-S diagrams for wet compression are shown in Figure 8. The points i, wi, s, and n corresponds to isothermal, water injection, isentropic and polytropic process respectively (Fig.8- Right). The corresponding final entropies of the different compression processes are labelled as w, x, y, and z, respectively.

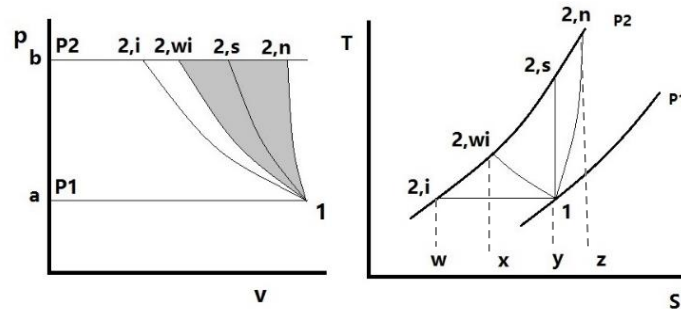


Figure 8 P-V and T-S diagram for wet compression [73,74]

The work corresponding to dry polytropic compression can be calculated from the area 1-2n-b-a-1 on the P-V diagram. The compressor exit entropy and temperature of the gas would be that corresponding to point z, 2,n on the T-S diagram. For an isothermal compression process to take place between P_1 and P_2 , the temperature would remain the same (1-2i) and the gas entropy would decrease to w (although in reality, no process can occur with a reduction in entropy, so the overall entropy of the system would indeed increase, but would be comparatively less). The work required for this operation (PV diagram) would be 1-2i-b-a-1. The wet compression process is benefited from a negative heat transfer (from the air to the water droplets) and would lie between the polytropic and isothermal compression. The compression work would be 1-2wi-b-a-1, and the entropy of the gas would decrease to x, as compared to the polytropic case. The difference in

compressor delivery temperature is $2n - 2w_i$ and the difference in compressor work would be the grey area $1-2w_i-n2-1$ on the PV diagram. Note that the diagrams are representative of a process and are not to scale.

Inter-stage high fogging has been investigated by several authors including Wang and Khan [75], Roumeliotis and Mathioudakis [76], Wang et al. [77] Bagnolli [78] and Sun [74]. The main advantage of injecting between the stages and not just at the entrance of the compressor is the insensitiveness to ambient conditions and ease of control that could be achieved. However, the effectiveness is less pronounced when water is injected into the HPC as compared to LPC. Daggett et al. [21] have reported that a double reduction in SFC can be achieved when injecting into the LPC, as well as a further 3% reduction in NO_x and TIT compared to HPC injection.

Water droplet diameter and residence time are amongst the most important variables dominating evaporation time within the compressor [79]. Reducing the droplet residence time in the compressor by injecting the water as early as possible is of great importance as this ensures that the water is completely evaporated at the end of the compression process, and will reduce the possibilities for blade impact and blade erosion. White [80] suggests the use of droplet diameters below $5\text{ }\mu\text{m}$ to ensure that they follow the flow path, as well as avoid them being centrifuged towards the compressor casing, or impacting on the blades.

Low-pressure compressor (LPC) water injection poses the biggest overall advantages. Utamura et al. [71], Wang et al. [77], Roumeliotis and Mathioudakis [76] and Balepin et al. [81], agree that the most effective location for water injection is at the inlet of the LPC. The main advantage of injecting water into the compressor is the reduction in compressor exit temperature (CET) that ensures a lower flame temperature, which reduces the amount of NO_x . The reduced TIT also causes an extension in the creep life of the turbine, which translates into potential maintenance costs savings.

The polytropic coefficient of wet compression differs from the dry case. The ideal compression will no longer be adiabatic but will be affected by heat transfer to and from the water droplets, approaching a curve that will lie between the isothermal and adiabatic processes [80,82] as shown in Figure 8. When water injection is applied to maintain the same thrust, at reduced throttle setting, the fuel flow is reduced, decreasing the specific fuel consumption (SFC) [32]. Burning less fuel will have an effect in reducing CO_2 , at a level proportional to the SFC decrease ($\sim 4\%$).

Specialists from engine and aircraft manufacturing companies (Rolls-Royce, Pratt & Whitney, Boeing, NASA) commented on the findings in Daggett et al. [21] that is also available in this study. The comments outline that the water injection maintenance issues

presented on the early Boeing 747 & 707 could easily be overcome by today's techniques and technologies. The benefit of reducing TIT is emphasised, suggesting that such reductions (around 220K) could double the life of the hot components of the engine. Askeland et al. [83] show the impact of temperature on rupture life due to creep, also showing that a very small change in temperature can have a significant effect on hot component life. Daggett [68] estimate that a gas turbine could have its life increased by 46% if water injection is implemented.

One of the biggest drawbacks of this approach is the installation on the aircraft and the additional weight of water, tanks and delivery system. Daggett [68] evaluates an increase in weight of about 1,540kg for LPC water injection on a Boeing 747. According to the FAA [84], this could translate to a reduced payload between 13 to 18 passengers depending on their weight and luggage, which for a 747-400 aircraft represents 5% of the passenger capacity [85].

4- Conclusion

This review has highlighted the existing and predicted trends of approaches/technologies focused on reducing aircraft-related airport emissions. These approaches have been discussed, alongside their merits and the main pollutant tackled. They have been classified as operational, technological or combination of both.

The promise of engine water injection in the compressor when applied to attain the same required net thrust is very clear. This approach addresses mainly NO_x emissions reduction and to a smaller extent CO₂ emissions. Of the approaches investigated, it is the most promising in terms of NO_x reduction and more ready to be implemented to current infrastructure when compared to the other alternatives evaluated.

The significant reductions in NO_x emissions that can be offered by EWI are particularly timely, given that incoming designs of aero-engines have transonic compressors, which achieve greater pressure ratios per stage and hence higher overall pressure ratios. Higher design overall pressure ratios are accompanied by higher flame temperatures and NO_x emissions, despite the thermal efficiency or SFC improvement.

The gains from the potential life extension of the hot component and reduced SFC are likely to outweigh the cost of demineralised water plus the reduced earnings from fewer passengers. In addition, the airline can take advantage of the increased earnings/competitiveness from the additional cabin space. The technical confrontations faced by the early onboard water injection systems can be more conveniently addressed when compared to the constraints of other approaches. This study, more importantly, provides the justification of why compressor water injection needs to be reconsidered: in

view of the growth in civil aviation and environmental implications and the promise in relation to other approaches.

Nomenclature

ACARE	Advisory Council for Aviation Research and Innovation in Europe	NASA	National Aeronautics and Space Administration
APU	Auxiliary Power Unit	NO _x	Nitrogen Oxides
ATM	Airport Traffic Management	O	Oxygen
ATo	Assisted Take-off	P	Pressure
C	Carbon	SET	Single Engine Taxiing
CAEP	Committee on Aviation Environmental Protection	SFC	Specific Fuel Consumption
CC	Combustion Chamber	SO _x	Oxides of Sulphur
CIT	Compressor Inlet Temperature	T	Temperature
CO	Carbon Monoxide	TAR	Towing Aircraft to Runway
CO ₂	Carbon Dioxide	TeDP	Turboelectric Distributed Propulsion
EEA	European Environmental Agency	TIT	Turbine Inlet Temperature
ETS	Electric Taxiing System	UHC	Unburned Hydrocarbons
EU	European Union	UK	United Kingdom
EWI	Engine Water Injection	USD	United States Dollars
FAA	Federal Aviation Authority	Subscripts	
FEP	Full Electric Propulsion	1	Inlet
GHG	Green House Gases	2	Outlet
GSE	Ground Support Equipment	i	Isothermal/gas species dimension index
HC	Hydrocarbons	j	LTO Flight phase dimension index
HPC	High-Pressure Compressor	k	Mitigating measure dimension index
IATA	International Air Transport Association	wi	Water Injection
ICAO	International Civil Aviation Authority	s	Isentropic
LPC	Low-Pressure Compressor	n	Polytropic
LTO	Landing and Take-Off Cycle		

Appendix

For the elaboration of Figure 5, the ICAO emissions certificate for each engine was obtained and the inventory of emissions per LTO stage and pollutant was computed by multiplying Time in Mode (TIM) of the engine by the Fuel Flow (FF) and the corresponding EI (Emission Index) as shown in equation [1]. Here “i” is a dimension corresponding to the gas species (NO_x, CO, HC) and “j” to the LTO flight cycle phase (Take-off, taxi, approach, and climb-out).

$$Emission_{ij}(kg) = TIM_j * FF_j * EI_i \quad (A.1)$$

To account for the corresponding theoretical emission reduction for a given technology analyzed, the following equation was applied to obtain a reduced emission inventory.

$$Emission\ Red_{ijk}(kg) = TIM_j * FF_j * EI_{REDijk} \quad (A.2)$$

Where the Reduced Emission Index (EI_{REDijk}) corresponds to the Emission Index of a particular gas species at a particular LTO flight phase. This value is then multiplied by the estimated percentage reduction depending on the approach/technology applied (k), this is mathematically expressed as

$$EI_{RED,ijk} = EI_{ij} * (1 - \%RED_k) \quad (A.3)$$

For example, it is estimated that Engine Water Injection can reduce NO_x emissions by 47% at take-off and climb-out, so the reduced Emission Index for NO_x only would be,

$$EI_{NO_x, Take-off, red} = EI_{NO_x take-off} * (1 - 0.47)$$

$$EI_{NO_x, climb-out, red} = EI_{NO_x, climb-out} * (1 - 0.47)$$

$$EI_{NO_x, taxi} = \text{Unchanged}$$

$$EI_{NO_x, approach} = \text{Unchanged}$$

Subsequently, the individual levels of emissions for the whole LTO cycle per pollutant were added to obtain an LTO inventory as a function of pollutant and engine type. The comparison of all the different technologies, applied to the 11 engine types gave the overall potential impact that each technology could have in reducing the LTO contributions to airport gaseous emissions for each gas species.

The details of the engines used for Figure 5 can be found in the table below. These are representative of old and new engines, with different architecture and specifications.

Table A 1 Engines Selected for the emissions reductions of Fig.5

Engine	Take-off Thrust (kN)	Pressure Ratio	Spools
GE-CF6-50E	230.00	28.44	2
CFM-56-5B1	133.45	30.20	2
GE90-90B-	419.00	39.85	2
GEnx-1B67/P2	308.70	42.20	2
RR Trent772	315.90	35.79	3
RR RB211-524H-T	264.40	34.00	3
Trent XWB-79	355.20	38.80	3
Trent1000-A	310.80	41.00	3
Trent 970	334.70	38.97	3
PW JT9D-7F	213.50	22.80	2
PW 6124A	105.87	28.00	2

References

- [1] Torres, R., Chaptal, J., Bès, C., and Hiriart-Urruty, J.-B., 2011, "Optimal , Environmentally Friendly Departure Procedures for Civil Aircraft," J. Aircr., **48**(1), pp. 11–23.
- [2] EEA (European Environment Agency), 2015, Evaluating 15 years of transport and environmental policy integration.
- [3] ICAO- International Civil Aviation Organization, 2013, 2013 Environmental Report, Aviation and Climate Change.
- [4] Heathrow Airport Limited, 2011, Heathrow Air Quality Strategy 2011-2020.
- [5] Zurich-Airport, 2010, Aircraft Emission Charges Zurich Airport, Zurich.
- [6] Stettler, M. E. J., Eastham, S., and Barrett, S. R. H., 2011, "Air quality and public health impacts of UK airports. Part I: Emissions," Atmos. Environ., **45**(31), pp. 5415–5424.
- [7] Lefebvre, A. H., and Dilip, R. B., 2010, Gas Turbine Combustion Alternative Fuels and Emissions, CRC Press, New York.
- [8] Macintosh, A., and Wallace, L., 2009, "International aviation emissions to 2025 : Can emissions be stabilised without restricting demand?," Energy Policy, **37**, pp. 264–273.
- [9] Sgouridis, S., Bonnefoy, P. A., and Hansman, R. J., 2011, "Air transportation in a carbon constrained world : Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation," Transp. Res., **45**, pp. 1077–1091.
- [10] Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C. N., Lim, L. L., Owen, B., and Sausen, R., 2009, "Aviation and global climate change in the 21st century," **43**, pp. 3520–3537.

- [11] IATA, 2015, "IATA Air Passenger Forecast Shows Dip in Long-Term Demand," Press Release no55 [Online]. Available: <http://www.iata.org/pressroom/pr/Pages/2015-11-26-01.aspx>. [Accessed: 21-Sep-2016].
- [12] ASPIRE, 2016, "Asia and Pacific Initiative to Reduce Emissions" [Online]. Available: <http://www.aspire-green.com/about/whyAspire.asp>. [Accessed: 06-Jul-2016].
- [13] Sorato, S., Pascovici, D. S., Ogaji, S. O. T., and Pilidis, P., 2008, "Investigating the Emissions and Performance of High Bypass Ratio Aero-Engines," *J. Aerosp. Eng. IMechE*, **222**, pp. 463–471.
- [14] Kyprianidis, K. G., and Dahlquist, E., 2017, "On The Trade-off Between Aviation NO_x and Energy Efficiency," *Appl. Energy*, **185**(x), pp. 1506–1516.
- [15] Lee, D. S., Pitari, G., Grewe, V., Gierens, K., Penner, J. E., Petzold, A., Prather, M. J., Schumann, U., Bais, A., Bernsten, T., Iachetti, D., Lim, L. L., and Sausen, R., 2010, "Transport impacts on atmosphere and climate : Aviation," **44**, pp. 4678–4734.
- [16] Jardine, C. N., 2005, *Calculating the Environmental Impact of Aviation Emissions*, Oxford.
- [17] H, B. S. R., E, B. R., and Waitz, I. A., 2010, "Global Mortality Attributable to Aircraft Cruise Emissions.," *Environ. Sci. Technol.*, **44**(19), pp. 7736–7742.
- [18] Schäfer, A. W., and Waitz, I. A., 2014, "Air transportation and the environment," *Transp. Policy*, **34**, pp. 1–4.
- [19] Atlanta-International-Airport, 2011, *Hartsfield-Jackson Atlanta International Airport Sustainable Management Plan*, Atlanta.
- [20] Carslaw, D. C., Beevers, S. D., Ropkins, K., and Bell, M. C., 2006, "Detecting and quantifying aircraft and other on-airport contributions to ambient nitrogen oxides in the vicinity of a large international airport," *Atmos. Environ.*, **40**(28), pp. 5424–5434.
- [21] Daggett, D. L., Ortanderl, S., Eames, D., Snyder, C., and Berton, J., 2004, "Water Injection : Disruptive Technology to Reduce Airplane Emissions and Maintenance Costs," *SAE Tech. Pap. Ser.*, **1**(3108).
- [22] Masiol, M., and Harrison, R. M., 2014, "Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution : A review Aircraft Particle Emissions eXperiment," **95**.
- [23] Vishal, S., 2015, "Gas Turbine Combustors - Lecture notes."
- [24] Lieuwen, T. C., and Yang, V., 2013, *Gas Turbine Emissions*, Cambridge University Press, Cambridge.
- [25] Lipfert, F. W., 1973, "Correlation of Gas Turbine Emissions Data," *Am. Soc. Mech. Eng.*, **72 GT 60**.
- [26] Maughan, J. R., Luts, A., and Bautista, P. J., 1994, "A Dry Low NO_x Combustor for the MS3002 Regenerative Gas Turbine," *ASME*, **3(94-NaN-2)**, pp. 1–8.

- [27] ICAO-International Civil Aviation Organisation, 2008, Environmental Protection, Annex 16, Volume II Aircraft Engine Emissions, Chicago.
- [28] ICAO, 2013, "ICAO Engine Exhaust Emissions Data Bank," **0**, p. 2013.
- [29] Balakrishnan, H., and Hansman, R. J., 2010, "Reducing Airport Surface Operations Environmental Impacts," Lab. Aviat. Environment, MIT [Online]. Available: <http://lae.mit.edu/reducing-airport-surface-operations-environmental-impacts/>. [Accessed: 11-Aug-2016].
- [30] ICAO, 2011, Airport air quality manual.
- [31] Norman, P., Lister, D., Lecht, M., Parlk, K., Penanhoat, O., Plaisance, C., and Renger, K., 2003, Development of the technical basis for a New Emissions Parameter covering the whole Aircraft operation: NEPAIR.
- [32] Daggett, D. L., 2004, Water Misting and Injection of Commercial Aircraft Engines to Reduce Airport NO_x, NASA Technical Report NASA/CR-2004-212957.
- [33] Brown, G. V., 2011, "Weights and Efficiencies of Electric Components of a Turboelectric Aircraft Propulsion System," AIAA Aerosp. Sci. Meet. Incl. New Horizons Forum Aerosp. Expo., (January), pp. 1–18.
- [34] Deonandan, I., and Balakrishnan, H., 2010, "Evaluation of Strategies for Reducing Taxi-out Emissions at Airports," 9th AIAA Aviation Technology, Integration and Operations (ATIO) conference, pp. 1–14.
- [35] IATA, 2015, "Demand for Air Travel in 2015 Surges to Strongest REsult in Five Years" [Online]. Available: <http://www.iata.org/pressroom/pr/Pages/2016-02-04-01.aspx>. [Accessed: 09-Sep-2016].
- [36] Mishra, A., 2010, Aviation Environment Circular 1 of 2013, New Delhi.
- [37] Heathrow-Airport-Limited, 2015, Heathrow 's Blueprint for Reducing Emissions, London.
- [38] Airways, 2016, "Performance Based Navigation" [Online]. Available: <http://www.airways.co.nz/products-and-services/aeronautical-support-services/performance-based-navigation/>. [Accessed: 11-Aug-2016].
- [39] EEA (European Environment Agency), 2016, European Aviation Environmental Report 2016.
- [40] Taxibot, 2016, "Taxibot main page" [Online]. Available: <http://www.taxibot-international.com/>. [Accessed: 19-Jul-2016].
- [41] Fontela, P., Soria, A., Mielgo, J., Blas, J. De, Gauchia, L., and Mart, J. M., 2007, "Airport electric vehicle powered by fuel cell," J. Power Sources, **169**, pp. 184–193.
- [42] Airbus, 2012, "Airbus Unveils its 2050 Vision for 'Smarter Skies'" [Online]. Available: <http://www.airbus.com/presscentre/pressreleases/press-release-detail/detail/airbus-unveils-its-2050-vision-for-smarter-skies/>. [Accessed: 19-Jul-2016].

- [43] Gohardani, A. S., Doulgeris, G., and Singh, R., 2011, "Challenges of future aircraft propulsion: A review of distributed propulsion technology and its potential application for the all electric commercial aircraft," *Prog. Aerosp. Sci.*, **47**(5), pp. 369–391.
- [44] Felder, J. L., Kim, H. D., and Brown, G. V., 2009, "Turboelectric Distributed Propulsion Engine Cycle Analysis for Hybrid-Wing-Body Aircraft," 47th AIAA Aerosp. Sci. Meet. Incl. New Horizons Forum Aerosp. Expo., (January), p. AIAA 2009-1132.
- [45] Gibson, A. R., Hall, D., Waters, M., Schiltgen, B., Foster, T., Keith, J., and Masson, P., 2010, "The Potential and Challenge of TurboElectric Propulsion for Subsonic Transport Aircraft," 48th AIAA Aerosp. Sci. Meet. Incl. New Horizons Forum Aerosp. Expo., (January), pp. 1–22.
- [46] NASA, 2015, "LEAPTech to Demonstrate Electric Propulsion Technologies," Armstrong Flight Res. Cent. [Online]. Available: <http://www.nasa.gov/centers/armstrong/Features/leaptech.html>. [Accessed: 08-Sep-2016].
- [47] NASA, 2013, "Hybrid Wing Body Goes Hybrid" [Online]. Available: <https://www.nasa.gov/content/hybrid-wing-body-goes-hybrid>. [Accessed: 07-Nov-2016].
- [48] Solar Impulse, 2016, "Solar Impulse, Exploration To Change The World" [Online]. Available: <https://www.solarimpulse.com/>. [Accessed: 06-Sep-2016].
- [49] Solar Impulse, 2016, "The Magic of Clean Techs," *Sol. Impuls. Blog* [Online]. Available: <http://blog.solarimpulse.com/post/143221367260/magic-of-clean-techs-solar-impulse>. [Accessed: 07-Nov-2016].
- [50] Moore, M. D., Distributed Electric Propulsion (DEP) Aircraft Near-Term Electric Propulsion Evolution Strategy.
- [51] Allen, J. E., 1999, "Global energy issues affecting aeronautics: a reasoned conjecture," *Prog. Aerosp. Sci.*, **35**(5), pp. 413–453.
- [52] Blakey, S., Rye, L., and Wilson, C. W., 2011, "Aviation gas turbine alternative fuels : A review," *Proc. Combust. Inst.*, (33), pp. 2863–2885.
- [53] Kivits, R., Charles, M. B., and Ryan, N., 2010, "A post-carbon aviation future : Airports and the transition to a cleaner aviation sector," *Futures*, **42**, pp. 199–211.
- [54] Re, F., 2012, Viability and State of the Art of Environmentally Friendly Aircraft Taxiing Systems, Germany.
- [55] WheelTug, 2016, "Wheel Tug Driving Aerospace" [Online]. Available: <http://www.wheeltug.com/>. [Accessed: 08-Jul-2016].
- [56] MagnetMotor, 2016, "Green Taxi" [Online]. Available: <https://www.magnet-motor.de/index.php?id=34&L=1>. [Accessed: 05-Jul-2016].

- [57] Safran, 2016, “Electric Taxiing” [Online]. Available: <http://www.safran-landing-systems.com/electric-taxiing>. [Accessed: 19-Jul-2016].
- [58] Easyjet, 2012, Press Information Kit, Luton.
- [59] Galea, M., Xu, Z., Tighe, C., Hamiti, T., Gerada, C., and Pickering, S., 2014, “Development of an aircraft wheel actuator for green taxiing,” Proceedings - 2014 International Conference on Electrical Machines, ICEM 2014, pp. 2492–2498.
- [60] Daggett, D. L., Fucke, L., Hendricks, R. C., and Eames, D. J. H., 2010, “Water Injection on Commercial Aircraft to Reduce Airport Nitrogen Oxides,” Nasa/Tm—2010-213179, (March).
- [61] Wilcox, E. C., and Trout, A. M., 1951, Analysis of Thrust Augmentation of Turbojet Engines by Water Injection at Compressor Inlet Including Charts for calculation Compression Process with Water Injection.
- [62] Bhargava, R. K., Meher-Homji, C. B., Chaker, M. a, Bianchi, M., Melino, F., Peretto, A., and Ingistov, S., 2007, “Gas Turbine Fogging Technology: A State-of-the-Art Review-Part I: Inlet Evaporative Fogging -- Analytic and Experimental Aspects,” J. Eng. Gas Turbines Power, **129/2**(April 2007), pp. 443–453.
- [63] Bhargava, R. K., Meher-Homji, C. B., Chaker, M. a, Bianchi, M., Melino, F., Peretto, A., and Ingistov, S., 2007, “Gas Turbine Fogging Technology : A State-of-the-Art Review — Part II: Overspray Fogging — Analytical,” J. Eng. Gas Turbines Power, **129**(April 2007).
- [64] Bhargava, R. K., Meher-Homji, C. B., Chaker, M. A., Bianchi, M., Melino, F., Peretto, A., and Ingistov, S., 2007, “Gas Turbine Fogging Technology: A State-of-the-Art Review—Part III: Practical Considerations and Operational Experience,” J. Eng. Gas Turbines Power, **129**(2), pp. 461–472.
- [65] Walsh, P. P., and Fletcher, P., 2004, Gas Turbine Performance, Blackwell Science, Oxford.
- [66] Bahr, D. W., and Lyon, T. F., 1984, “NO_x Abatement In Aircraft-Derivative Turbine Engines,” Am. Soc. Mech. Eng., **84-NaN-103**.
- [67] Roumeliotis, I., and Mathioudakis, K., 2010, “Evaluation of water injection effect on compressor and engine performance and operability,” **87**, pp. 1207–1216.
- [68] Daggett, D., 2005, “Water Injection Feasibility for Boeing 747 Aircraft,” Nasa Cr-2005-213656.
- [69] Becker, A., and Hartford, E., 2006, “Engine Company Evaluation of Feasibility of Aircraft Retrofit Water-Injected Turbomachines,” (April).
- [70] Bhargava, R., and Meher-Homji, C. B., 2002, “Parametric Analysis of Existing Gas Turbines With Inlet Evaporative and Overspray Fogging,” Vol. 4 Turbo Expo 2002, Parts A B, **4 A**(January 2005), pp. 387–401.

- [71] Utamura, M., Takehara, I., Horii, N., and Kuwahara, T., 1997, "A New Gas Turbine Cycle for Economical Power Boosting," *Am. Soc. Mech. Eng.*, **97-NaN-142**, pp. 1–10.
- [72] Cumpsty, N., 1997, *Jet Propulsion a Simple Guide to the Aerodynamic and Thermodynamic Design and Performance of Jet Engines*, Cambridge University Press, Cambridge.
- [73] Tomita, J. T., Bontempo, L. P., and Barbosa, J. R., 2011, "An Axial Flow Compressor for Operation With Humid Air and Water Injection," *J. Eng. Gas Turbines Power*, **133**(7), p. 71703.
- [74] Sun, L., Zheng, Q., Li, Y., Luo, M., Wang, J., and Bhargava, R. K., 2012, "Numerical Through Flow Simulation of a Gas Turbine Engine With Wet Compression," *ASME Turbo Expo*, pp. 1–13.
- [75] Wang, T., and Khan, J. R., 2010, "Overspray and Interstage Fog Cooling in Gas Turbine Compressor Using Stage-Stacking Scheme—Part I: Development of Theory and Algorithm," *J. Therm. Sci. Eng. Appl.*, **2**(3), p. 31001.
- [76] Roumeliotis, I., and Mathioudakis, K., 2006, "Evaluation of Interstage water injection effect on compressor and engine performance and operability," *Trans. ASME J. Eng. Gas Turbines Power*, **128**(4), pp. 849–856.
- [77] Wang, J., Zheng, Q., Sun, L., and Luo, M., 2012, "The Effective Positions to Inject Water Into the Cascade of Compressor," *proceedings of ASME Turbo Expo*, Denmark, pp. 1–14.
- [78] Bagnoli, M., Bianchi, M., Melino, F., and Spina, P. R., 2008, "Development and Validation of a Computational Code for Wet Compression Simulation of Gas Turbines," *J. Eng. Gas Turbines Power*, **130**(1), p. 12004.
- [79] Kim, K. H., Ko, H. J., and Perez-Blanco, H., 2011, "Analytical modeling of wet compression of gas turbine systems," *Appl. Therm. Eng.*, **31**(5), pp. 834–840.
- [80] White, A. J., and Meacock, A. J., 2004, "An Evaluation of the Effects of Water Injection on Compressor Performance," *ASME*, **126**(October 2004).
- [81] Balepin, V., Ossello, C., and Snyder, C., 2002, *NOx Emission Reduction in Commercial Jets Through Water Injection*, Ohio.
- [82] Hill, P. G., 1963, "Aerodynamic and Thermodynamic Effects of Coolant Injection on Axial Compressors," *Aeronaut. Q.*, **November**, pp. 331–348.
- [83] Askeland R., D., Fulay, P. P., and Wright, W. J., 2011, *The Science and Engineering of Materials*, Global Engineering.
- [84] FAA, 2005, *Advisory Circular- Aircraft Weight and Balance Control*.
- [85] British Airways, 2016, "Boeing 747-400," *Fleet Facts* [Online]. Available: <http://www.britishairways.com/en-gb/information/about-ba/fleet-facts/boeing747-400>. [Accessed: 27-Oct-2016].

III. Paper 2

Compressor Water Injection Effects: Reduced Temperature and Increased Humidity

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Reducing Airport Emissions through Aircraft Gas Turbine Water Injection at Take-Off.

David Alejandro Block Novelo and Uyioghosa Igie

School of Aerospace Transport and Manufacturing, Cranfield University, Cranfield,
UK

Abstract

Airport-related air pollution has become a global concern. Around Mexico City's Benito Juarez International Airport, the Nitrogen Oxide (NO_x) levels double the concentration suggested by international authorities. At Heathrow Airport in London, airlines are charged more than £15.00 per kilogram of NO_x emitted every time one of their aircraft takes-off. This contaminant is associated with respiratory diseases, and it has been recognized to damage the local vegetation and wildlife. Cooling the aircraft engine by compressor water injection is a way to reduce this pollutant by almost 50%. This study explains by means of an analytical method applied to the compressor, the physical mechanism behind the cooling of the thermodynamic cycle. The method is validated against other publications and used to evaluate the potential NO_x decrease on a common aircraft power plant. It is shown how a 2-spool engine can benefit from a decrease in operating temperature by the order of 10%, which can lead to a NO_x reduction of 45%. For an Airport like Heathrow, this can represent a reduction in total NO_x emissions of 12%. The effects that water injection has on a gas turbine in terms of reduced temperature and increased ambient air humidity are isolated and quantified.

Key Words: Water Injection, Gas Turbine, NO_x Emissions, Airport Pollution.

1- Introduction

According to the world bank, air pollution is the 4th leading cause of premature death in the world, causing 1 in 10 deaths in 2013 [1]. Mexico City has had a historical problem with air pollution, which has led to traffic restricting regulations and the plan to ban Diesel cars by 2025. Nitrogen Oxides (NO_x) are a contaminant produced as a by-product of combusting fuel at high temperatures and are inclusive of NO and NO_2 . In Mexico, the biggest contributor to NO_x is private vehicle use, accounting for 78 % of its generation [2]. It has been identified that NO_2 is harmful to human health as it can cause inflammation of the airways, reducing lung function and thus increasing the susceptibility to respiratory diseases [2,3]. Although aircraft-born NO_x emissions represent only 5% of anthropogenic NO_x generation in Mexico City, it is the concentration of this contaminant around airports that is a concern. According to the Mexico City Emissions Inventory, the

highest NO_x concentrations in the Mexican capital are found around the airport [2], and the levels are high enough to double the allowable threshold imposed by national and international regulations.

With an annual forecast in aviation demand increase of 5.1 % [4] this problem is bound to get worse. In Mexico, civil aviation increased by 50 % in the past four years, suggesting that by 2021 there could be twice as many aircraft landing at Mexico City's airport than there were in 2013 [5].

Efforts are being made around the world to mitigate the environmental impact of aviation, both, at high altitude, and around the airports. A comprehensive review of airport-related pollutants can be found in [6]. Balakrishnan and Deonodan [7], evaluate different mitigation measures focused on reducing Taxiing emissions. There are also initiatives focused on reducing emissions and fuel burn through alternative fuels [8,9], or new aircraft configurations like the NASA NX-3 Blended Wing Body[10]. Although many of these initiatives are useful and necessary to reduce emissions, few of them are focused on reducing emissions during take-off and climb.

The importance of reducing emissions at these flight stages is that it is here where NO_x productions rates are the highest. According to the International Civil Aviation Organization (ICAO), near ground aircraft operations can be described by the Landing and Take-Off (LTO) cycle. This cycle is composed of approach (4 minutes, 30 % power), Taxi (26 minutes, 7 % power), Take-Off (0.7 minutes, 100 % power) and Climb out (2.2 minutes, 85 % power). Since NO_x is proportional to engine power setting, and thus operating temperature, its production is highest at high power settings. Despite the short time this flight stage lasts, the take-off and climb out phases account for around 70 % of the LTO cycle NO_x production depending on engine type [11].

Water injection into an aircraft gas turbine during these critical flight phases can considerably reduce the compressor operating temperature, achieving compressor delivery temperatures that can be even lower than the ideal isentropic case [12]. This decrease in temperature brings about a reduction in the production of NO_x, which Daggett [13] evaluates in 47 % when 2 % water-to-air ratio is injected into the engine. The purpose of this article, thus, is to explore the potential of including this as a new technology on board an aircraft.

When water is injected into an aero-engine the gas properties will change due to the reduced operating temperature coming from the heat transfer between the gas and the water droplets. This intercooling effect reduces the compressor specific work, thereby increasing the thermal efficiency of the engine. The injected water, however, evaporates and increases the humidity of the air, also affecting the gas properties. These effects will

be isolated and commented for a constant thrust take-off case. In addition to this, the model used to evaluate the compressor temperature drop and water evaporation model will be commented and compared to other models available in the literature.

2- Evaporative Cooling inside a Compressor

Dalton's law of additive pressures states that the pressure of a gas is equal to the sum of the pressures each gas would exert if it existed alone at the mixture temperature and volume. The pressure of atmospheric air is then the sum of the partial pressures of water vapour and dry air (which is the sum of the partial pressures of N₂, O₂, Ar, and other constituents). The mass fraction of water vapour (v) to dry air (a) is known as the absolute or specific humidity of the air.

$$w = \frac{M_v}{M_a} = \frac{P_v/R_v}{P_a/R_a} \quad (1)$$

Where R_v and R_a are the specific gas constants of water vapour and dry air and are equal to the universal gas constant, R_u divided by the molecular weight (μ) of the components. Taking $\mu_v = 18.015$ kg/kmol and $\mu_a = 28.97$ kg/kmol, eq. (1), becomes.

$$w = 0.622 \frac{P_v}{P - P_v} \quad (2)$$

It can be seen that the amount of water vapour in dry air depends on its partial pressure, P_v . If water is added to dry air, w will increase up to a maximum value after which any addition of water will condense rather than add to the humidity content in the air. The relative humidity of a mixture is the ratio of the water vapour partial pressure, to the saturation pressure of the mixture at that temperature. It can be understood as a relation of the number of molecules of vapour (number of moles) in dry air, compared to the maximum amount of water particles that air can hold at a certain temperature and pressure.

$$\phi = \frac{P_v}{P_{sat@T}} \quad (3)$$

Combining Eqs. 2 and 3, an expression that relates absolute humidity to relative humidity and saturation pressure can be obtained (Eq.4). This analysis is only valid as long as the gasses don't react between them to create new constituents.

$$w = 0.622 \frac{\phi P_{sat@T}}{P - \phi P_{sat@T}} \quad (4)$$

Water cannot vaporize unless it absorbs energy from the surrounding air in the form of latent heat of vaporization, h_{fg} , which for water is 2501 kJ/ kg [14] at triple point.

Also, the mass, internal energy and enthalpy of a mixture are the sum of the individual gas component contributions.

$$H_m = \sum_{i=k}^N m_i h_i \quad (5)$$

Where m_i is the mass of the component. For a dry air-water vapour mixture (m) the enthalpy would be,

$$H_m = h_m m_m = h_a m_a + h_v m_v \quad (6)$$

Where the subscript m , stands for water vapour-dry air mixture and a , for dry air, and assuming that h_f is 0 at the triple point. The enthalpy of water vapour (v) is the sum of the required enthalpy to vaporize that quantity of water if it was in its liquid form to start with, plus the enthalpy due to the actual temperature compared to a 0 degrees datum.

$$h_v = h_{fg} + C_p v T \quad (7)$$

When air is sprayed with water, some of this water will evaporate (enough to saturate the air), and increase the moisture content of the mixture. The energy required for this process to occur will come from the air-water vapour mixture and so its temperature will decrease. The sensible heat lost by the air will equal the latent heat gained by the water, used to increase the moisture of the air. The steady-state energy equation for an adiabatic process with no work done then becomes.

$$(\dot{m}_a h_a + \dot{m}_v h_v)_1 + \dot{m}_{w1} h_{f1} = (\dot{m}_a h_a + \dot{m}_v h_v)_2 + \dot{m}_{w2} h_{f2} \quad (8)$$

Where h_f is the enthalpy of the liquid water at the injection temperature. The quantity of water injected, $\dot{m}_w$ is going to be the difference between the initial and final absolute humidities, $\dot{m}_a (w_2 - w_1)$. If all the water is evaporated, the second term, $\dot{m}_{w2} h_{f2}$.

By combining equations 4, 7, and 8, an expression for the energy balance that depends on inlet known conditions of the gas (state 1) and exit conditions (exit temperature, and exit absolute humidity) can be derived. However, the exit absolute humidity depends on the saturation and ambient pressures. The values for P_{sat} depend on the mixture temperature and can be computed using the correlations found in Saul and Wagner [14]. In this way, an equation that depends only on T_2 can be solved iteratively to obtain the saturation temperature and absolute humidity of a water-vapour mixture, given the initial ambient temperature, pressure and relative humidity. The main purpose of this iteration

is to calculate $w_{2,sat}$, which is the amount of water required to saturate the mixture, assuming that 100 % relative humidity has been reached. This value, will be used later on to calculate the amount of water that actually evaporates, by comparing the ambient absolute humidity with the absolute humidity corresponding to the saturation state.

The water injection limit, assuming that all the water evaporates and that the evaporation rate is constant, would be that of saturating the exit air of the compressor [15]. In that case, the relative humidity along the compressor will be constant and equal to 100 %. The absolute humidity, or water vapour content will increase as the air gets hotter and can absorb more water. The rest of the water will remain in liquid form until the end of the last stage where the outlet is saturated.

This case would achieve the highest temperature reduction; however, it will be seen that to achieve this a considerable amount of water would be needed. In reality, for wet compression, quantities around 1 to 2 % water to air mass flow are used. This water is quickly evaporated inside the first stages of the compressor. The efficiency of this process depends heavily on water droplet diameter, ambient conditions, and water quantity.

Different evaporative models have been suggested, and they summarize into three main models that Kim et al. [16] compare and classify as: Diffusion model, Natural convection model, and Stokes model.

The natural convection model is based on detailed droplet thermodynamics, it accounts for sensible and latent heat transfers due to natural convection. The assumption of natural convection as opposed to forced convection arises from the fact that the droplet quickly accelerates to the flow speed (<10 milliseconds) [17]. A detailed analysis using this method is offered by Chaker et al.[17], and was later on used by Sanaye and Tahani [18], Zheng et al. [12] and Kim et al. [16,19]. The correlation for the evaporative rate based on the natural convection model can be represented by Eq. (9).

$$\frac{dw}{dt} = \frac{D_v Sh}{D_a R_v} \left(\frac{P_s}{T_s} - \frac{P_a}{T_a} \right) \quad (9)$$

Where Sh is the Sherwood number and is a function of the Grashof number and Schmidt numbers which can be assumed to be constant and equal to 2 (Stokes model). D_v is the diffusion coefficient of water vapour in dry air, P_s and T_s the saturation pressure and temperature of air, and P_a , T_a is the ambient pressure and temperature.

The development of this method requires the calculation of many dimensionless quantities that add computational cost with little gains in precision. Since the aim of incorporating an evaporation model is to precisely predict the reduction in compression temperature and not the detailed drop behaviour, a more straightforward method was

used, which is based in mass convection theory [20] and ignores heat transfer by radiation or forced convection.

Defining the injection ratio as f , and the absolute humidity as w , we can state that, the injected water will be equal to the mass of each droplet (volume times density) multiplied by the number of droplets per kilogram of dry air, n .

$$f = \frac{4}{3} \pi r^3 \rho_l n \quad (10)$$

The rate of change of liquid water, by conservation of mass, has to be the rate of change of water vapour in the air.

$$\frac{df}{dt} = -\frac{dw}{dt} = -4\pi r^2 \rho_l n \frac{dr}{dt} \quad (11)$$

Based on mass transfer, Spalding [20] gives the following expression for the rate of change of droplet size with time and was later written by White [21] and Bagnoli [22] in terms of the fraction of mass of water vapour to the mass of dry air (w). The expression, known as diffusion model [10] can be found below.

$$\frac{dr}{dt} = \frac{D_v \rho}{r_d \rho_l} \ln \left(\frac{1+w}{1+w_l} \right) \quad (12)$$

The mass diffusion coefficient, D_v is a function of pressure and temperature, and expressions for this are shown in Chaker et al. [17], Roumeliotis et al. [23], Bagnoli [22] and Eckert [24]. The correlation proposed by Eckert (Equ.13) was chosen for this analysis, although they all seem to deliver similar results.

$$D_v = 10^8 \frac{0.00143 T^{1.75}}{120.5 P} \quad (\mu\text{m}^2/\text{s}) \quad (13)$$

Where P is the pressure of the mixture and T is the reference temperature. Since all these properties are calculated at each time step, if the time-step is small enough, the reference temperature, T , can be taken to be that at the previous time-step ($T_{t=t} \sim T_{t=t-1}$).

Integrating Eq.(12) an expression for the radius change for a given time-step can be found and is shown in Eq.(14). Equation (14) depends on the saturation conditions of the gas (w_l) which at the same time depend on the dew-point temperature of the mixture at any particular point. It is assumed that the water is always injected at 15°C. Equation (8) considers the change in enthalpy from liquid water at 15 °C to water vapour at the mixture temperature.

$$r_2^2 = r_1^2 + \frac{2D_v\rho}{\rho_l} \ln\left(\frac{1+w}{1+w_l}\right) \Delta t \quad (14)$$

The compression equation can then be computed from a compression rate as shown below,

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{n_{wet}} \quad (15)$$

Where n_{wet} is the coefficient of wet compression which is the ratio of Cp^* and R^* . The wet coefficient of compression will be lower for wet compression than it is for dry air. This variation also brings about a reduction in compression work. Expressions for Cp^* and R^* can be found in White and Meacock [21] and are shown in eq. (15)². This expression is valid for equilibrium evaporation only. According to White and Meacock such conditions will only be approximated with very small droplets (<5 μm), which might be hard to obtain in practice. [Chapter IV](#) extends the model to be applied to non-equilibrium evaporation, for variable evaporative rate, and considering entropy generation of a polytropic process.

$$\begin{aligned} Cp^* &= Cp_a + wCp_v + fCp_l + \left(1 + \frac{\mu_a}{\mu_v} w\right) \frac{wh_{fg}^2}{R_v T^2} \\ R^* &= R_a + wR_v + \left(1 + \frac{\mu_a}{\mu_v}\right) \frac{wh_{fg}}{T} \end{aligned} \quad (16)$$

The compressor is described here based on a compression rate, as suggested by White and Meacock [21] and Kim et al. [16], taking the compression rate³ to be 200s^{-1} . This parameter is used to represent the loading on the compressor stages. Transonic compressors with high pressure ratio per stage can be represented with higher values of the compression rate. With the average axial velocity of 75 m/s, the pressure, temperature, droplet diameter and moisture content, w is computed at each time step. The final moisture content or absolute humidity is obtained from Eq. (11) and (17) and increases at each time step as water evaporates.

$$w_2 = w_1 + \frac{dw}{dt} \Delta t \quad (17)$$

² Further analysis presented on [chapters IV](#) and onwards use another correlation for non-equilibrium evaporation. Both correlations gave similar results, but the correlation used for further analysis was more adequate for this specific analysis.

³ Further analysis from chapter IV onwards, consider the calculation of the compression rate, based on an assumed axial flow velocity and an estimated compressor length.

3- Results and Discussion

The temperature along the compressor is shown in Figure 1 for the case of a day at 298 K and 25 % relative humidity, under take-off conditions. The compressor is modelled based on a common 2-spool turbofan engine similar to the CFM-56. The cases analysed are with (wet) and without (dry) water injection, at a rate of 2 % water-to-air ratio by mass. It is assumed that the water is injected between the Fan and the booster or Low-Pressure Compressor (LPC). The pressure ratios of the Fan and the booster are 1.65 and 2.36 respectively.

The Dry Compression line depicts a normal process of compression, the temperature and pressure will have an initial rise after passing through the Fan, then the temperature will be unchanged between the Fan and the LPC. As the air enters the LPC and gets compressed the temperature will increase. The slope of the curve depends on the isentropic coefficient of compression, which in this case is 0.2857, corresponding to dry air. The booster exit temperature for this case is 461 K.

When water is injected into the duct between the Fan and the LPC, the air sees an immediate cooling, and hence there is an initial temperature drop from 349 K to 329 K corresponding to constant pressure evaporative cooling, also known as inlet fogging. Since the water is not fully evaporated, it will flow into the compressor, and a phenomenon known as wet compression, and described by equations (14) and (15) will start. The slope of the temperature curve for this case is initially smaller, while the polytropic coefficient of compression is still affected by a heat transfer from the gas to the water droplets. This coefficient is around 0.12, in agreement with what was suggested by White and Meacock [21]. At “x” coordinate 0.6 the water is fully evaporated, and the slope of the curve changes and is very similar to that of dry air. The slight difference in the polytropic coefficient of compression is due to the presence of humidity in the air (Humid air $n=0.2842$, for this case).

In this case, a 13 % reduction in compressor exit temperature (56K) is achieved under the injection conditions and with droplets of an initial diameter of $5\mu\text{m}$. According to Ref. [21] droplets this size will follow the flow path, meaning they will not impact on the blades nor will they be centrifuged outwards, opposite to what would be expected of rain droplets which can be 10 or 100 times larger.

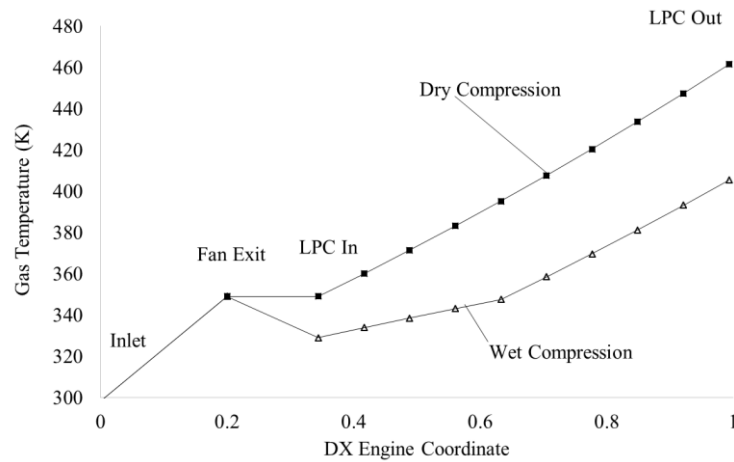


Figure 1 Gas Temperature vs x Coordinate. Comparison between dry and wet compression cases.

The effectiveness of this process is heavily influenced by the droplet diameter. The droplet diameter reduction model adopted here (Diffusion model) (Eq.13) was compared to Kim et al. [19], with acceptable results (Figure 2). Kim et al. [16] is a comparison of three of these models. In the study, the longer evaporative time associated with the diffusion model is acknowledged. The differences between the models and a more thorough comparison can be found in ref. [16].

From Figure 2 it can be seen the strong effect that initial droplet diameter has on evaporative time and rate. As expected droplets with a larger diameter take longer to evaporate, but most interestingly are the change in slope of the curves as the diameter decreases. This change comes about as the surface area to volume ratio changes. Smaller droplets have a higher surface area to volume ratio, and thus are more effective at absorbing heat from the surrounding air than bigger droplets. This leads to the conclusion that the evaporative rate is not constant but is a function of droplet diameter and thus, time. For the same injection rate, smaller droplets will have a cooling effect mainly at the front stages of the compressor, while bigger droplets will have it at the rear. The referenced model (Kim et al. in the figure) evaporates faster as it accounts for sensible heat transfer between the droplets and the air, while the Diffusion model ignores this effect and considers diffusion-driven mass transfer only.

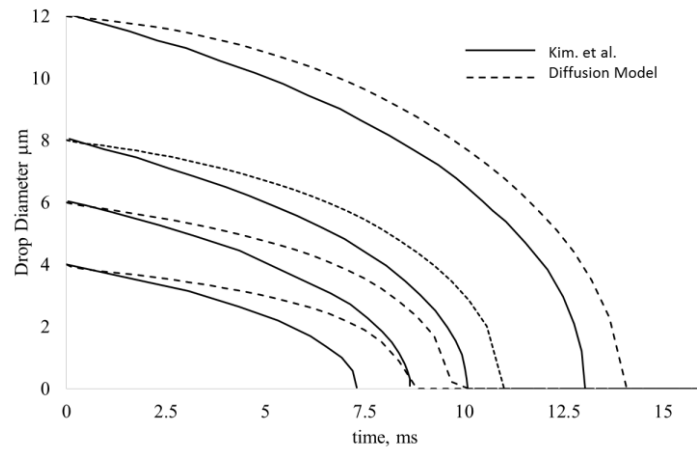


Figure 2. Influence of Droplet diameter with Evaporative time for initial droplet diameters of 12, 8, 6, and 4 micrometres, and comparison with Kim et al. [16]

For a given nozzle size, the droplet diameter is a function of water pressure [17]. This means that for a fixed water quantity, a user can decide where the cooling effect is desired, at the back or front stages of the compressor, just by controlling system pressure. Figure 3 shows how droplet diameter might impact compressor exit temperature for a fixed injection ratio of 2 %. Notice that this figure also includes the duct between the booster and the HPC.

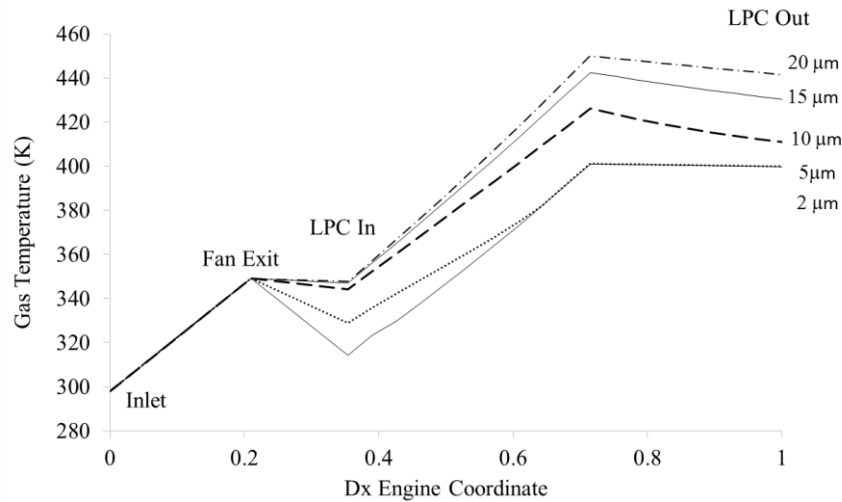


Figure 3 LPC Temperature change for the cases of wet compression at different initial droplet diameters.

It can be seen that the curves corresponding to droplet diameters of 2 μm and 10 μm do not change their slope as seen for the 5 μm case. For the 2 μm case, the reason is that since the droplets are so small and the evaporative process is so efficient, all the water evaporates in the duct between the Fan and the LPC, and hence the slope of the temperature curve is almost the same as that seen for the dry case. For the 10 μm droplets, the mechanism is quite different. The smaller surface area to volume ratio of these

droplets allows for a slower evaporation, which means the droplets will evaporate throughout the whole compression process. The intercooling effect last for longer and the slope of the curve will be less than for dry compression.

The final effect will heavily depend on compression rate, axial flow velocity and compressor length. Smaller droplets have a higher intercooling effect as the mass of water (2% of the core airflow) is distributed into more droplets of smaller diameter, compared to the case of larger droplets.

It has been mentioned that injecting water into a gas turbine will have two main effects: Reduce compressor operating temperature and increase the humidity of the working fluid. The effects of humidity have been studied since the 1950s and widely accepted methods to correct gas properties for humidity can be found in [25,26]. For this analysis, a method similar to Fishbeyn [27] was adopted. According to Fishbeyn, the presence of humidity in the air will decrease the air flow rate, Turbine Inlet Temperature (TIT) and Overall Pressure Ratio (OPR), while it will increase Specific Fuel Consumption (SFC). This method was compared to Samuels and Gale [25] with good agreement. The effects of humidity were isolated to those from temperature by doing Gas Turbine performance simulations at a fixed ambient temperature but varying absolute humidity or water to air ratio (WAR) for a constant thrust case. The former was achieved using the in-house 0-D software for gas turbine performance, *Turbomatch*. This tool uses standard compressor and turbine maps to model the aero-components and takes as inputs the engine characteristics such as turbine inlet temperature, pressure ratios, efficiencies and by-pass ratios. More details on this tool can be obtained in [29,30].

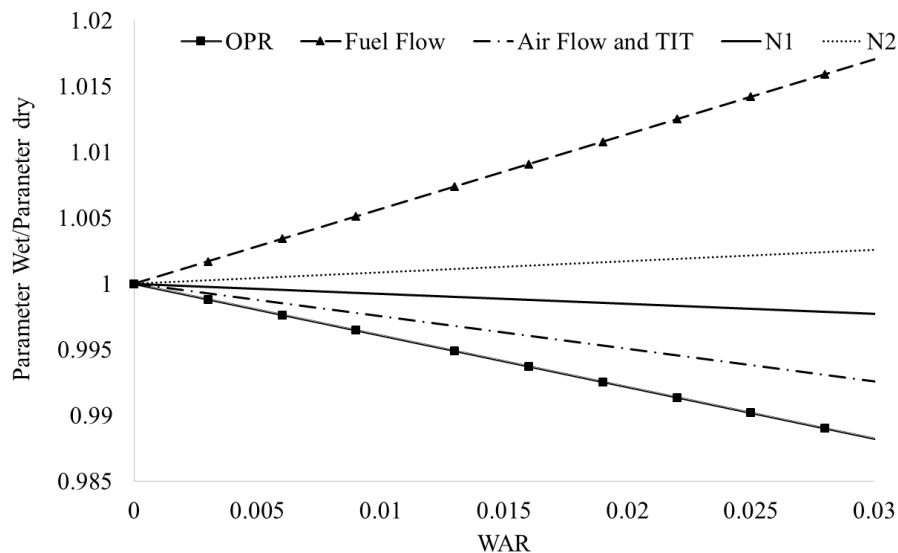


Figure 4 Effects of Humidity on Performance parameters as a consequence of Water Injection.

The results can be found in Figure 4. It can be seen that although humidity affects the engine performance parameters (this engine is a two-spool turbofan, with a by-pass ratio of 5), the impact is in the order of 1-2 % depending on the parameter and the Water to Air Ratio.

The effects of decrease LPC exit temperature can also be plotted against injection ratio. Notice that in this case, water injection ratio is not the same as WAR or absolute humidity. The cases analysed for a 25 % relative humidity assume that when the injection rate is 0, the air still has water vapour since the ambient relative humidity is higher than 0 %.

Figure 5 represents the change of performance parameters with decreased temperature as an effect of different water injection ratios. It can be seen that the effect of temperature is a lot more pronounced than the effect of humidity. Properties vary in the range of 10- 15 % depending on the performance parameter and injection ratio. Daggett et al. [28], found similar changes in SFC and temperature reduction as those presented in this study. The performance parameters, again, were obtained by means of *Turbomatch*.

For example, injecting close to 2 % water to air ratio by mass will reduce the engine fuel flow in about 5 % as a consequence of reduced operating temperatures (and reduced compressor work), but the increase in humidity will affect this parameter by increasing its value by about 1 %. It can be concluded thus, that the effects of temperature reduction due to water spraying are a lot higher than those seen by the gas property changes due to the increase in water vapour.

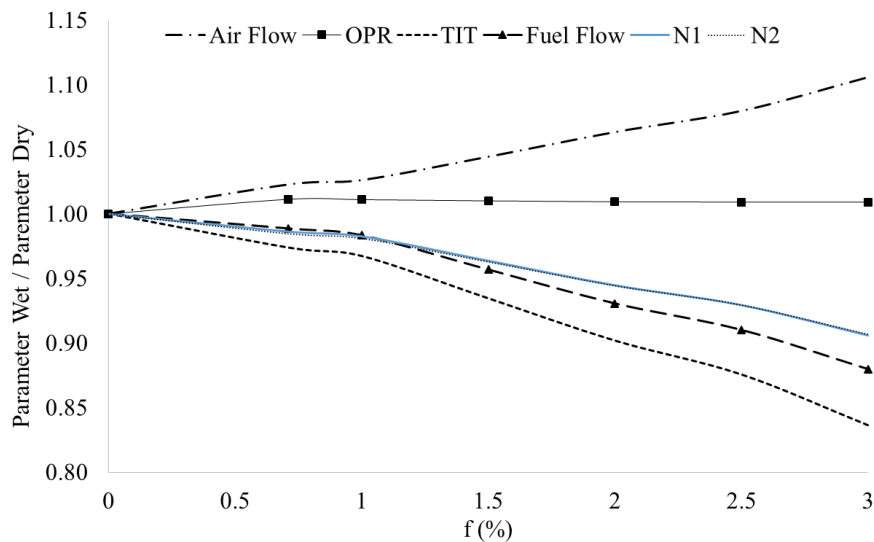


Figure 5. Effects of LPC exit temperature reduction as an effect of water injection for various levels of injection, f .

4- Estimation of NO_x reduction due to Engine Water Injection

Preliminary design point performance calculations show that for the case studied here (298 K, 25 % RH atmospheric pressure and take-off), with an injection ratio of 2 % a reduction in NO_x of around 45 % is achievable. This is done by analysing injection into a two spool turbofan engine with take-off rated thrust of 133.4 kN, and a By-Pass Ratio of 5, similar to what is found on the CFM56-5B engine. The results so far agree with previous studies where reductions in the order of 40 – 50 % were achieved for higher injection rates [31]. These higher reductions would come especially in situations where the ambient temperature is high and the relative humidity low.

The former is calculated by using the ICAO engine exhaust emissions data bank for the before mentioned engine [11] and correcting the published values for temperature and humidity. The correlation used to correct these values can be found in the NEPAIR report [32] and is regarded as an ICAO certified method for emissions corrections at different altitudes and ambient conditions ([Appendix A](#)).

According to Heathrow airport (London), the main sources of NO_x emissions around this travel hub are: aircraft on the ground, airport-related road traffic, ground support equipment, and boilers. Out of these sources, aircraft on the ground have the biggest contribution, accounting for 54 % of this emission. Moreover, aircraft ground movements can be classified into, taxiing, holding, APU use, landing roll, and take-off roll. Take-off roll accounts for the highest NO_x production, with a value of 46 % [33]. Considering these values, then if every aircraft departing from Heathrow was to be equipped with Water Injection, the overall London airport NO_x emissions could be reduced by up to 12 %. This value might depend on environmental conditions (ambient temperature, and relative humidity) and is calculated assuming that water injection can reduce NO_x emissions by up to 47 % as noticed by Daggett [13].

5- Concluding Remarks

The mechanism behind compressor air cooling through water injection has been explained. The influence of droplet diameter and quantity have been mentioned. It is shown that injecting atomized water into a gas turbine has the effect of reducing compressor delivery temperature (~10%), therefore reducing the overall cycle's operating temperature. This reduction in temperature is proven to lead to a decrement in the production of NO_x emissions. For the case of Heathrow Airport, these reductions could be as high as 12 % of the overall NO_x production.

Future studies of this research involve a more comprehensive model that can calculate NO_x emission reductions for different engine operating conditions (off-design cases),

ambient temperatures, injection ratios, and droplet diameters. In addition to this, efforts are being made to evaluate the impact that water injection can have on hot component life due to lower TIT. This translates into maintenance costs savings for airline operators.

Despite the negative effects that humidity can have on the gas properties, such as a small increase in SFC, it has been proven that the benefits of decreased temperature outweigh humidity effects, having as an overall outcome a fuel saving which can contribute to the reduction of other emissions such as CO₂.

The model presents limitations such as the lack of ability to model the aerodynamic changes inside the compressor when water is injected. Also, droplet break-up and blade impingement are not considered. The droplets are assumed to follow the flow path with no-slip velocity.

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Nomenclature

CAEP	Committee on Aviation Environmental Protection	h_{fg}	Enthalpy of vaporization (J/kgK)
CO ₂	Carbon Dioxide	kN	Kilo Newtons
HPC	High-Pressure Compressor	m	Mass flow rate (kg/s)
HPR	High-Pressure Ratio	n	Number of droplets
ICAO	International Civil Aviation Authority	Nu	Nusselt number
LPC	Low-Pressure Compressor	P	Total Pressure (Pa)
LTO	Landing and Take-Off Cycle	r	Radius (m)
NO _x	Nitrogen Oxides	R	Gas Constant (J/kgK)
PR	Pressure Ratio	Sh	Sherwood number
TIT	Turbine Inlet Temperature	t	Time (s)
ρ	Density (kg/m ³)	T	Total temperature (K)
η	Efficiency	w	Specific humidity
γ	Specific heat ratio	Subscripts	
ϕ	Relative humidity	1	inlet
A	Cross-sectional area (m ²)	2	outlet
C _p	Specific Heat (J/kgK)	a	Dry air
D _v	Mass diffusion coefficient (m ² /s)	m	mixture
f	water injection rate (kgw/Kga)	s	saturation
h	Specific enthalpy (J/Kg)	v	vapour
H	Enthalpy (J)	w/f	water

Appendix

In order to calculate the NO_x reductions, the Emission Index (EI) of the mentioned engine was correlated to the combustor inlet temperature by means of the Cranfield In-house gas turbine performance tool, Turbomatch. This was done by simulating the engine at the different power settings corresponding to the ICAO LTO cycle (7 %, 30 % 85 % and 100 % of the TO thrust). Then the combustion inlet temperature was calculated, and a correlation for EINO_x that depends on temperature only was derived. This value can be used to calculate the emission index at any power setting of the engine. Then this value is corrected to account for humidity or pressure changes as shown below. More details about this methodology are provided in chapters [5](#) and [6](#).

$$EINO_{x \text{ corrected}} = \frac{EINO_x}{\left(\frac{P_{ref}}{P}\right)^{0.5} * e^{(19*(w-w_{ref}))}} \quad (A.1)$$

References

- [1] World Bank, 2016, The Cost of Air Pollution, Official Report.
- [2] Secretaria del Medio Ambiente del Gobierno de la Ciudad de Mexico, 2016, Inventario de Emisiones de la CDMX 2014, Mexico City.
- [3] EEA (European Environment Agency), 2016, “Nitrogen Oxides (NO_x) Emissions”.
- [4] ICAO- International Civil Aviation Organization, 2013, 2013 Environmental Report, Aviation and Climate Change.
- [5] La Jornada, 2017, “Vuelos han Incrementado 50 % en Cuatro Años: SCT”
- [6] Masiol, M., and Harrison, R. M., 2014, “Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution : A review Aircraft Particle Emissions eXperiment,” **95**.
- [7] Deonandan, I., and Balakrishnan, H., 2010, “Evaluation of Strategies for Reducing Taxi-out Emissions at Airports,” 9th AIAA Aviation Technology, Intergration and Operations (ATIO) conference, pp. 1–14.
- [8] Allen, J. E., 1999, “Global energy issues affecting aeronautics: a reasoned conjecture,” *Prog. Aerosp. Sci.*, **35**(5), pp. 413–453.
- [9] Kivits, R., Charles, M. B., and Ryan, N., 2010, “A post-carbon aviation future : Airports and the transition to a cleaner aviation sector,” *Futures*, **42**, pp. 199–211.
- [10] Felder, J. L., Kim, H. D., and Brown, G. V., 2009, “Turboelectric Distributed Propulsion Engine Cycle Analysis for Hybrid-Wing-Body Aircraft,” 47th AIAA Aerosp. Sci. Meet. Incl. New Horizons Forum Aerosp. Expo., (January), p. AIAA 2009-1132.
- [11] ICAO, 2013, “ICAO Engine Exhaust Emissions Data Bank,” **0**, p. 2013.
- [12] Zheng, Q., Sun, Y., Li, S., and Wang, Y., 2003, “Thermodynamic Analyses of Wet Compression Process in the Compressor of Gas Turbine,” *J. Turbomach.*, **125**(3), p. 489.
- [13] Daggett, D. L., 2004, Water Misting and Injection of Commercial Aircraft Engines to Reduce Airport NO_x.
- [14] Saul, A., and Wagner, W., 1987, “International Equations for the Saturation Properties of Ordinary Water Substance,” *J. Phys. Chem.*, **16**(4), pp. 893–901.
- [15] Wilcox, E. C., and Trout, A. M., 1951, Analysis of Thrust Augmentation of Turbojet Engines by Water Injection at Compressor Inlet Including Charts for calculation Compression Process with Water Injection.
- [16] Kim, K. H., Ko, H. J., Kim, K., and Perez-Blanco, H., 2012, “Analysis of water droplet evaporation in a gas turbine inlet fogging process,” *Appl. Therm. Eng.*, **33–34**(1), pp. 62–69.

- [17] Chaker, M., Meher-Homji, C. B., and Mee, T., 2002, "Inlet Fogging of Gas Turbine Engines- Part A: Fog Droplet Thermodynamics, Heat Transfer And Practical Considerations," ASME Turbo Expo, Amsterdam, pp. 1–16.
- [18] Sanaye, S., and Tahani, M., 2010, "Analysis of gas turbine operating parameters with inlet fogging and wet compression processes," *Appl. Therm. Eng.*, **30**(2–3), pp. 234–244.
- [19] Kim, K. H., Ko, H. J., and Perez-Blanco, H., 2011, "Analytical modeling of wet compression of gas turbine systems," *Appl. Therm. Eng.*, **31**(5), pp. 834–840.
- [20] Spalding, D. B., 1979, *Combustion and Mass Transfer*, Pergamon Press, London.
- [21] Meacock, A. J., 2016, "An Evaluation of the Effects of Water Injection on Compressor," **126**(October 2004).
- [22] Bagnoli, M., Bianchi, M., Melino, F., and Spina, P. R., 2008, "Development and Validation of a Computational Code for Wet Compression Simulation of Gas Turbines," *J. Eng. Gas Turbines Power*, **130**(1), p. 12004.
- [23] Roumeliotis, I., and Mathioudakis, K., 2006, "Evaluation of Interstage water injection effect on compressor and engine performance and operability," *Trans. ASME J. Eng. Gas Turbines Power*, **128**(4), pp. 849–856.
- [24] Eckert, E., and Drake, R. M., 1959, *Heat and Mass Transfer*, Mc Graw-Hill, New York.
- [25] Samuels, J. C., and Gale, B. M., 1950, *Effect of Humidity on Performance of Turbojet Engines TN 2119*, Lewis Flight Propulsion Laboratory, Cleveland Ohio.
- [26] AGARD, 1995, *Recommended Practices for the Assessment of the Effects of Atmospheric Water Ingestion on the Performance and Operability of Gas Turbine Engines*, Neuilly-Sur-Seine.
- [27] Fishbeyn, B. D., and Pervystin, N. V, 1970, *Determination of the Effect of Atmospheric Humidity on the Characteristics of a Turbofan Engine*.
- [28] Daggett, D. L., Ortanderl, S., Eames, D., Berton, J. J., and Snyder, C. A., 2004, "Revisiting Water Injection for Commercial Aircraft," *World Aviation and Exposition*, Reno, USA.
- [29] Macmillan, W. L., 1974, "Development of a Modular Type Computer Program for the Calculation of Gas Turbine Off Design Performance- Phd. Thesis," Cranfield Institute of Technology.
- [30] Igie, U., and Minervino, O., 2014, "Impact of Inlet Filter Pressure Loss on Single and Two-Spool Gas Turbine Engines for Different Control Modes," *J. Eng. Gas Turbines Power*, **136**(September), pp. 1–9.
- [31] Daggett, D. L., Ortanderl, S., Eames, D., Snyder, C., and Berton, J., 2004, "Water Injection : Disruptive Technology to Reduce Airplane Emissions and Maintenance Costs," *SAE Tech. Pap. Ser.*, **1**(3108).

- [32] Norman, P., Lister, D., Lecht, M., Parlk, K., Penanhoat, O., Plaisance, C., and Renger, K., 2003, Development of the technical basis for a New Emissions Parameter covering the whole Aircraft operation: NEPAIR.
- [33] Heathrow Airport Limited, 2011, Heathrow Air Quality Strategy 2011-2020.

IV. Paper 3

Compressor Models: 2 and 3 spool.

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Aero Engine Compressor Cooling by Water Injection - Part 1: Evaporative Compressor Model

David Alejandro Block Novelo and Uyioghosa Igie

School of Aerospace Transport and Manufacturing, Cranfield University, Cranfield,
UK

Abstract

The need for more fuel-efficient turbofan engines has led to a rise in compressor pressure ratio and turbine inlet temperature respectively. The latter has been possible with advancements in turbine blade technology. Nevertheless, this higher temperature during combustion increases the production of thermal Nitrogen Oxides. Contrary to this high-pressure, high-temperature aero-engine design trend, regulations are pushing towards capping or reducing emissions. Injecting atomised water into a jet engine is an alternative to mitigate Nitrogen Oxides that is applied extensively to stationary gas turbines. The application for jet engines is very limited and dates back to the early Boeing 707 and 747 for thrust augmentation. The focus of this study is to investigate the performance benefits of water injection when applied to 2 and 3-spool compressors, under a wide range of different environmental conditions, and for different injection properties. In this first paper, a thermo-analytical compressor model with water droplet investigations in the Lagrangian frame of reference is explored. The methodology is applied to two different engine architectures, representative of modern turbofan engines. This water injection study focuses on cooling the core and shows that the percent reduction in compressor discharge temperature is promising over a wider range of ambient conditions than expected. The effect of droplet sizes or quantity utilised were seen to be more influential. The 3-spool compressor also appears to benefit more from water injection, mainly due to the higher operating pressures and temperatures found on the Intermediate Pressure Compressor which enables more efficient evaporation, as compared to a booster compressor. Given the design of this compressor, two locations of injection were considered. Reductions in Compressor Discharge Temperature of 60 and 80K were seen for the 2 and 3-spool engines, for a 2% injection ratio, accompanied by reductions in specific compressor work of 16 and 17%. Part 2 of this study has considered boundary conditions obtained here, to investigate the performance and emissions of complete jet engines.

Keywords: compressor, water injection, evaporation, cooling, droplets, turbofan

1- Introduction

The rise in air travel demand estimated at 5% per year [1] has brought optimism about the future of the civil aviation industry. This, of course, has been met with more public discourse and regulations related to increasing environmental impact. Block and Igie [2] shows different measures focused on mitigating the environmental impact of aviation at and around airports. The study points out that most of the proposed solutions are focused on reducing CO, HC, and CO₂. Only a few measures address Nitrogen Oxides (NO_x) emissions. Daggett et al. [3] estimate a 47% reduction in NO_x when 2% water to air ratio is injected into the core flow of the engine. The mechanism for this reduction is the cooling of the thermodynamic cycle, which also reduces the specific compressor work, enabling higher useful work outputs. With this improvement in pressure ratio, less fuel can be utilised for the same thrust requirement, which brings about an improvement in the Specific Fuel Consumption (SFC). The use of such a system on an aircraft, at take-off and climb when the engine is operated at peak Turbine Inlet Temperatures (TIT) also offers benefits in turbine blade creep life. This comes in an era where governments and companies have set emissions and noise limits as a key priority in aerospace research [4].

Water ingestion related to rain suction into a jet engine has been studied [5,6] and since 1998 there have been regulations in place to ensure that engines don't flame out under heavy rain conditions. Rain or runway splash ingestion has a negative effect on engine performance due to possible erosion, and a loss of momentum of the rotating parts, due to droplet impingement, apart from the resulting aerodynamic effects. Film forming on the blades decreases the aerodynamic efficiency of the compressor blade due to the alteration of the geometry and change in blade surface roughness [5]. Roumeliotis et al. [7] indicate that for some cases of rain ingestion, about 60% of the water ingested can remain unevaporated and reach the combustion chamber, causing a decrease in combustor efficiency or even flame-out.

Deliberate compressor water injection, however, is substantially different. The most important difference is that for this approach, atomised droplets of typically small diameters (5-10 μ m) are injected into the engine and have been observed to follow the flow path [8–11]. These droplets usually begin to evaporate in the initial/front stages of the compressor that brings about the cooling of the air flow (drop in temperature), increased density and moisture content. This procedure has been studied extensively through compressor analytical methods [11–14], through-flow approach, CFD approach [8,15–18], and experimental investigations [9,19–21] that have mostly focused on stationary gas turbines. For the analytical methods, Kim et al. [22] categorise the models into: natural convection model, diffusion model, and Stokes model. The authors conclude that the three models agree with minor differences. The natural convection model is based

on detailed droplet thermodynamics and accounts for sensible and latent heat transfers due to natural convection. A detailed analysis using this method is offered by Chaker et al. [23] and subsequently applied by Sanaye and Tahani [24], Zheng et al. [25] and Kim et al. [22].

The diffusion model assumes that the evaporation of the droplets occurs mainly due to mass concentration differences and ignores radiative and convective heat transfers. This approach was chosen as the main mechanism applied in this study, following Chaker et al. [26] conclusions that the droplet temperature will very quickly converge to the saturation temperature, hence the heat transfer term can be neglected. The diffusion model is described further, in a subsequent section. Hill [27] proposes the use of this model to offer a thermodynamic analysis implemented in White and Meacock [11]. Ref. [11] uses the diffusion model to evaluate the compressor operating point changes with water injection using through-flow methods and proposes an expression for the evaporation rate for equilibrium evaporation. Zheng and Sun [12], subsequently applied these expressions and extend them to a non-ideal case for non-equilibrium evaporation. In the article, wet compression efficiency is defined and inlet fogging is compared to internal intercooling. The investigation gives a comprehensive insight into the thermodynamics of wet compression but does not provide an expression for the evaporation rate and a constant value is used. The study shows the influence of compressor water injection on the polytropic coefficient of compression, which is smaller than that seen for the “dry” case. The reductions in compression specific work are evaluated and accounted for due to the fact that ideal compression will no longer be adiabatic but will have a heat transfer term due to water evaporation.

In a later investigation, White and Meacock [28] study multi-spool compressors and conclude that multi-spool engines adapt better to water injection due to the extra degree of freedom of the intermediate shafts. The results were confirmed with Bagnoli et al. [7] analytically, whose work is also taken here as the basis for the development of the compressor model. The research is validated against the experimental results presented by Utamura et al. [9].

A similar outcome for a single shaft compressor was obtained by Roumeliotis and Mathioudakis [29], where experimental results on a single stage axial flow compressor are provided. Further experimental work was carried out by Favorskii et al. [19]. In the study, the authors note that the compressor specific work is reduced, but the mass flow is increased, giving as a result almost unchanged compressor power requirement for a 1.5% water to air ratio. The experiment is compared to an analytical method with good agreement.

The focus of most of the mentioned studies is the increment of thermal efficiency and power output of a gas turbine. The idea of using compressor water injection for NO_x emission reduction in aircraft was studied by Daggett et al. [3,30], however, the impact of different environmental conditions in combination with water injection ratios have not been evaluated. There are currently no studies in the open literature that investigate different jet engine configurations and their performance changes during compressor water injection. To achieve indicative operating conditions in the engine models, a stand-alone compressor tool has been developed and it is the focus of this first part of the study. The outcomes are set as boundary conditions for the engine models in part 2 of this study. This study thus is based on previous investigation of the science of water injection, and specifically achieves the following:

- Shows the drop in intermediate Compressor Discharge Temperature (CDT) as a function of water-to-air ratio, droplet size, and ambient conditions
- Highlights the changes in temperatures and hence evaporation rates for 2 and 3-spool compressors representative of modern aero-engines
- Evaluates the impact of injection location in the evaporation process and hence reduction in the intermediate CDT

The results presented in this section, use an evaporative model different to that presented in [chapter III](#). The thermodynamic model used in this section extends the application of water injection to non-equilibrium conditions, where saturation is not necessarily reached. The model also includes a term that accounts for the aerodynamic entropy generation of a polytropic process, and as such depends on the polytropic efficiency of the compressor. The latter is assumed to remain constant at its “dry” value. Previous studies have shown that for some applications of water injection, especially at constant rotational speed, the flow coefficient in the first stages increases considerably in comparison to the design “dry” flow coefficient. This behaviour is a consequence of the higher mass flow going through the compressor due to the increased density, which in turn increases the axial flow velocity. The rear stages are also seem to work off-design but at a reduced flow coefficient, once the initial cooling effects are overcome by an increase in pressure ratio. It is expected that in this particular application, where the rotational speed of the components is allowed to change, this off-design behaviour of the flow coefficient will be diminished, and so the polytropic efficiency is assumed to remain at its original “dry” value.

2- Evaporative Cooling Model

To model a compressor’s thermodynamic performance analytically, an estimated axial pressure distribution along the compressor length, an average axial velocity, and compressor length are required. The pressure distribution can be obtained by means of Eq.(1), as indicated in Refs [11,14].

$$P_2 = P_1 e^{ct} \quad (1)$$

Where P_1 and P_2 are the inlet and exit stage pressures respectively, c is the compression rate, which according to Refs.[11,14], amounts to 200 s^{-1} , and t is the compression time.

With known flow velocity and an axial length of the compressor, one droplet of water can be tracked through the compressor. The droplet absorbs sensible heat from the surrounding gas and uses it as latent heat of evaporation. As the droplets travel and follow the streamlines, they reduce in size and heat up. The surrounding air will be cooled while increasing its humidity or water vapour content.

The mass fraction of water vapour (v) to dry air (a) is known as the specific humidity of air (ω), which can be expressed in terms of the partial pressures of water vapour and dry air. The partial pressure of dry air will be the atmospheric pressure, P , minus the partial pressure of water vapour, P_v ,

$$\omega = \frac{M_v}{M_a} = \frac{P_v/R_v}{P_a/R_a} = 0.622 \frac{P_v}{P - P_v} \quad (2)$$

If water is added to the dry air, w will increase up to a maximum value after which further addition of water will condense in the air rather than humidify it. The relative humidity of a mixture relates the number of molecules of vapour in dry air, compared to the maximum number of water particles that air can hold at a certain temperature and pressure. It can be computed as the ratio of the water vapour partial pressure in air, to the saturated vapour pressure of air at that same temperature, as in Eq. (3).

$$RH = \frac{P_v}{P_{sat@T}} \quad (3)$$

Combining Eqs. 2 and 3, an expression that relates specific humidity to relative humidity and saturation pressure can be obtained as follows:

$$\omega = 0.622 \frac{RH * P_{sat@T}}{P - RH * P_{sat@T}} \quad (4)$$

Also, the mass, internal energy and enthalpy of a mixture are the sum of the individual gas component contributions

$$H_m = \sum_{i=k}^N m_i * h_i \quad (5)$$

For a dry air-water vapour mixture, the enthalpy would be

$$H_m = h_m m_m = h_a m_a + h_v m_v \quad (6)$$

Where the subscript m , stands for water-vapour dry-air mixture. The enthalpy of water vapour is the sum of the required enthalpy to vaporize that quantity of water if it was in its liquid form to start with, plus the enthalpy due to the actual temperature compared to a 0° C datum.

$$h_v = h_{fg} + c_{pv}T \quad (7)$$

The sensible heat lost by the air will be equal to the latent heat gained by the water, so the steady-state energy equation for an adiabatic process with no work then becomes,

$$(\dot{m}_a h_a + \dot{m}_v h_v)_1 + \dot{m}_{w1} h_{f1} = (\dot{m}_a h_a + \dot{m}_v h_v)_2 + \dot{m}_{w2} h_{f2} \quad (8)$$

Where h_f is the specific enthalpy of the liquid water at the injection temperature. The quantity of water injected, $\dot{m}_w$ is the difference between the initial and final absolute humidities, $w_2 - w_1$. If all the water is evaporated, the second term, $\dot{m}_{w2}$ is equal to zero. Chaker et al. [26] shows how the water temperature quickly reaches the saturation temperature and remains constant throughout the evaporation process. Roumeliotis and Mathioudakis [31] present results for compressor water injection, accounting for the change in water temperature. The results presented in this study assume constant water temperature and compare well with those presented by Ref. [31,32] as shown in [Appendix A](#). From combining Eqs. 4, 7, and 8, an expression for the energy balance that depends on known inlet conditions (temperature, and specific humidity) of the gas, the exit conditions can be derived. However, the exit specific humidity, w_2 depends on the saturation and ambient pressures. These values are dependent on the mixture temperature and can be computed using the correlations found in Saul and Wagner [33]. In this way, an equation that depends only on T_2 can be solved iteratively to obtain the saturation temperature and specific humidity of a water-vapour mixture (as shown in [Appendix B](#)).

The injected water, or injection ratio, f , will be equal to the mass of each droplet multiplied by the number of droplets per kilogram of dry air, n , assuming spherical droplets,

$$f = \frac{4}{3} \pi r^3 \rho_l n \quad (9)$$

The decrease in mass of the liquid water must be equal to the rate of change of water vapour, by conservation of mass, so that

$$-\frac{df}{dt} = \frac{dw}{dt} = 4\pi r^2 \rho_l n \frac{dr}{dt} \quad (10)$$

Based on mass transfer, an expression based on mass diffusion for the rate of change of droplet size with time can be obtained [34]. The original correlation was adapted here to be presented in terms of the fraction of water vapour to dry air (w) [11,13].

$$\frac{dr}{dt} = \frac{D_v \rho}{r_d \rho_l} \ln \left(\frac{1+w}{1+w_l} \right) \quad (11)$$

The mass diffusion coefficient, D_v is a function of pressure and temperature, and expressions for this are provided in Refs. [13,23,32,35]. The correlation proposed by Eckert [35] was chosen for this analysis.

From Eq. (10) an expression of the change in droplet diameter radius can be found

$$r_2^3 = r_1^3 - \frac{3\Delta f}{4\pi n \rho_l} \quad (12)$$

The compression equation can be computed from Eq. (13)

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1} \right)^{n_{wet}} \quad (13)$$

Where n_{wet} is the polytropic coefficient of compression⁴, the formulation given by Zheng et al. [12] is shown in Eq.(14) considering a polytropic process. Notice that for constant, ideal gas conditions, the first term on equation (14) would be 3.5, the second term of positive sign, relates to the heat transfer between the droplets and the air and has an approximate value of 1.5 which is not constant and varies depending on the evaporative rate dw/dT . The third term is negative and has a constant value of around 0.4, depending on the polytropic efficiency. The combination of these effects creates an n_{wet} value which is higher than the standard dry isentropic/polytropic coefficient. For a given temperature ratio, the pressure ratio of wet compression will be higher than that of “dry” compression, showing an increase in the turbomachinery overall efficiency. If the pressure ratio is fixed, then the compressor outlet temperature, T_2 , will be lower than the “dry” case, again as a consequence of a higher coefficient of compression. This variation also brings about a reduction in compression specific work.

$$n_{wet} = \frac{\gamma}{\gamma - 1} + \frac{h_{fg}}{R_a} \frac{dw}{dT} - \left(\frac{1}{\gamma - 1} \right) \left(\frac{n_{poly} - \gamma}{n_{poly} - 1} \right) \quad (14)$$

$$n_{poly} = \frac{\eta_{poly} \gamma}{\eta_{poly} \gamma - \gamma + 1} \quad (15)$$

⁴ Notice that the coefficient for wet compression used here is different from the one used in [Chapter III](#). The coefficient presented here was used for subsequent results throughout the thesis as it is a more general case for non-equilibrium evaporation.

Equations (13), (14), and (15) help to determine the compressor exit temperature, however, the polytropic coefficient of compression depends on the term dw/dT , so an initial guess must be made for this evaporative rate. The equations can be solved iteratively for T_2 and dw/dT . This term was considered constant by Zheng et al. [12], but was noticed to change as the droplet volume reduced, this methodology thus, is an extension of the model presented in Ref. [12], with a variable evaporative rate. The pressure, temperature, droplet diameter and moisture content, w are computed at each time step. The final moisture content or absolute humidity is obtained from Eq. (10) and (16) and increases at each time step as water evaporates. The final stage humidity will then be the inlet humidity plus the amount of water that evaporated in the fraction of time that the droplet travelled through the stage (Eq. (16)).

$$w_2 = w_1 + \frac{dw}{dt} \Delta t \quad (16)$$

3- Compressors under Investigation

Two and three-spool turbofan engine compressors, applicable to civil aviation, have been considered. As shown in Figure 1, the 2-spool design consists of a fan and booster compressor mounted on the same shaft and powered by a Low-Pressure Turbine (LPT). This configuration also consists of a high-pressure compressor (HPC), on a separate shaft, operating about 3 times the speed of the low-pressure spool [36]. The 3-spool turbofan configuration is also shown in Figure 1 and consists on a fan (low-pressure compressor – LPC) attached to a LPT followed by an intermediate pressure compressor (IPC) which spins 3.3 times faster than the LP spool. Finally, a HPC on a sperate shaft that spins 1.5 times faster than the IPC spool [37]. Table 1. Shows some of the design specifications for both compressors from fan to middle compressors sections (booster and IPC respectively) with the inclusion of the HPC PR. To minimize flow distortion in practice and the potential waste of water, the injection is considered behind the fan as shown in Figure 1. This location of injection takes advantage of the rise in temperature of the flow exiting the fan, providing water injection benefits even in instances when the ambient temperature is low. For the 2-spool compressor, the water is assumed to be injected 144 mm away from the booster while for the 3-spool compressor two positions are considered due to more space between the Fan and the IPC. These are P1- Short Distance (SD) injection - 144 mm away from the IPC and P2- Long Distance (LD) injection - 400mm away from the IPC. The influence of droplet diameters (2, 5, 10, 15 and 20 μm), injection ratios or water-to-air ratios (1 - 3%), ambient temperatures (278, 288, 298, 303 and 313K) and ambient relative humidity (30, 60 and 80%) were analysed for both compressors, all at same ambient pressure of 101 kPa. Each compressor, studied at a given water injection

ratio and droplet diameter is compared to the corresponding dry case at the same ambient temperature and relative humidity.

Table 1 Specification of 2 and 3-spool compressors at take-off

Engine Design	Fan PR	Booster/ IPC PR	HPC PR	Injection Distance (mm)
2-Spool	1.65	2.36	8.4	144
3-Spool	1.6	5.16	5.16	144 and 400

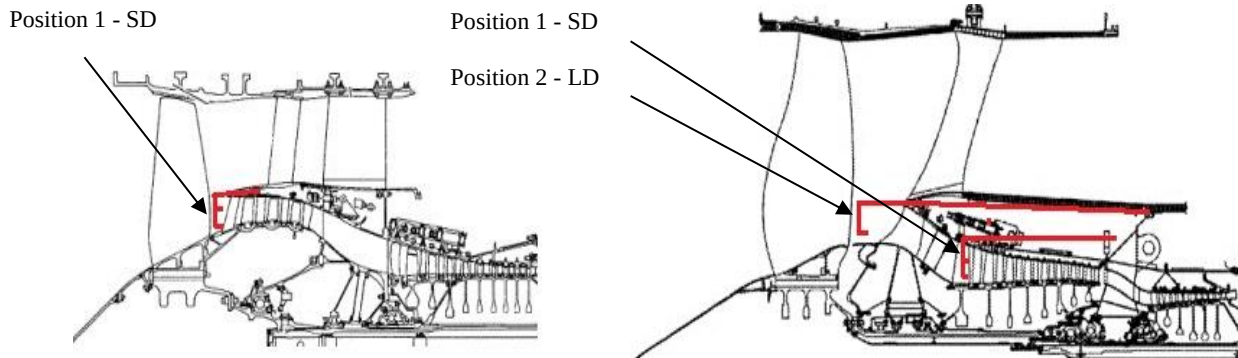


Figure 1 Cross-section of 2 (left) and 3-spool (right) compressor indicating injecting positions. Image adapted from [43]

3.1 Two-spool Compressor Analysis

Effect of Ambient Conditions

Aircraft engines experience very different weather conditions depending on the take-off and landing destination. Figure 2 shows the gas temperatures from the fan intake ($x=0$) to the inlet of the HPC ($x=1$) for the case of dry compression ($f = 0\%$) and different injection ratios (2-s compressor). For a dry compression case, the temperature rises from ambient temperature 298K (25°C) to 349K (66°C) due to the compression that occurs in the fan. This value stays almost unchanged as the air flows through the duct between the fan and the booster and then increases as the air gets compressed again. Although the points on the curves are joined, for visual representation, the temperature increase would happen monotonically and not in straight lines due to the nature of the compression process. When the gas is atomized with water, however, a first temperature reduction is seen between the fan exit and the inlet of the booster. The higher the injection ratio, the more dramatic this temperature decrease will be. For a lower injection ratio of 1%, the inlet fogging effect is small and the temperature only reduces in a few degrees. The water

will then be ingested into the booster and the slope of the temperature curve will be affected due to the heat transfer term in the coefficient of compression (Eq. 14, 15). After the mixture leaves the booster, it will flow into a duct where the remaining water (if any) will evaporate providing further cooling to the HPC inlet.

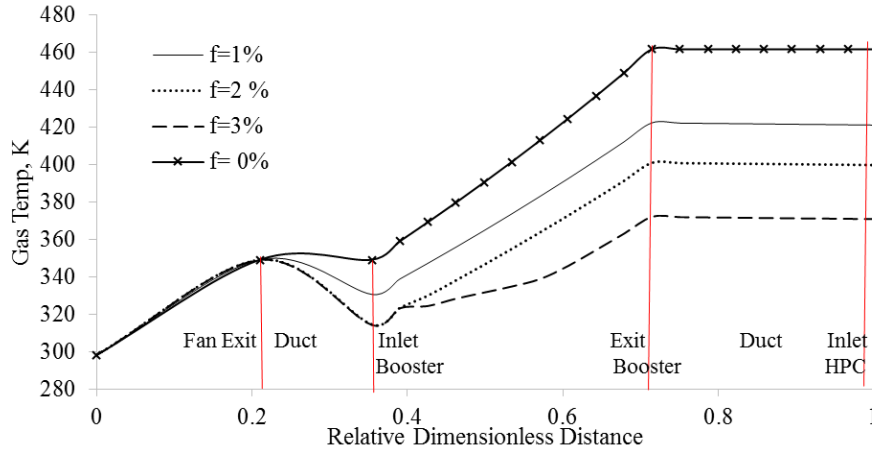


Figure 2 Gas temperature from the intake to booster exit (10µm and 60% RH)

Although as seen in Figure 2, the booster exit temperature depends on the amount of water, the pressure ratio and the initial ambient temperatures, it will be seen that the reductions in the booster exit temperature (as a percentage of the dry value) are independent of the inlet ambient temperature. Figure 3 demonstrates the effects of injecting water at different ambient temperatures for a fixed injection ratio of 2% and relative humidity of 60%. This figure shows the droplet evaporation based on droplet size reductions with respect to the actual compression time, from the inlet to the exit of the booster compressor. The droplet diameter reduction from an initial value of 5µm to a new value at $t = 0$ accounts for the evaporation that takes place in the duct before the droplet enters the booster since water is injected 144 mm before the 1st stage rotor of the booster. This initial reduction in droplet size is influenced by the ambient temperature as shown. The highest ambient temperature (313K or 40°C) considered leads to higher fan exit temperatures, causing the highest droplet size reduction compared to other ambient temperatures, with the least at 278K or 5°C. The figure shows that with time, the droplets become smaller, due to heat absorbed and used as latent heat of vaporization. At ambient temperatures below 278K, it is expected that the droplet will not fully evaporate in the booster but flow further into the HPC. As the droplets reduce in diameter from 5 to about 2.5 µm, the surface area-to-volume ratio increases linearly with radius, and after this, the increment happens exponentially, and so the heat transfer becomes more effective; this and the increasing compressor temperature explain the sudden change in slopes seen on Figure 3.

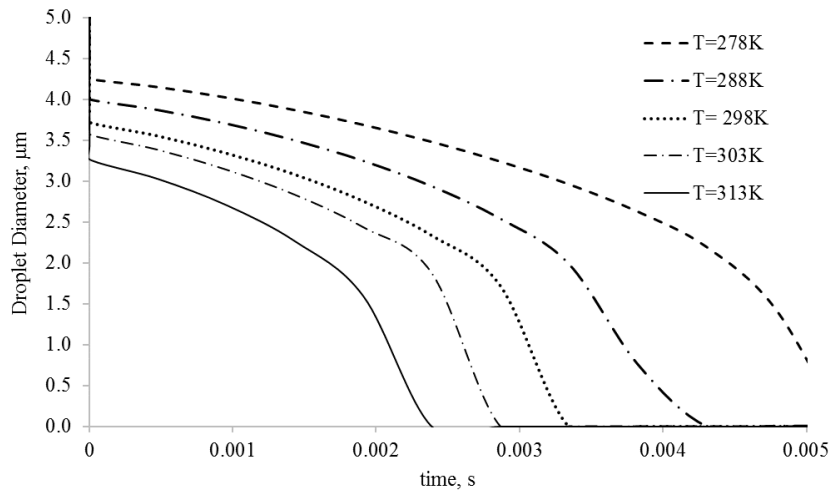


Figure 3 Effect of ambient temperature on droplet evaporation (2% injection ratio at 60% RH)

The effect of water injection at different ambient temperature on the booster exit temperature is shown on the left-hand side of Figure 4 for 5μm droplets, compared to the “dry” case. This exit temperature reduction is seen to increase with an increase in the injection ratio. At 2% injection ratio, which is 20 g of water per kg of air, the temperature drops by 12% irrespective of the ambient temperatures investigated. Sexton et al. [10] report the same reduction for the same water quantity using an analytical tool to simulate a 16 stage compressor, while Sun et al. [16] shows a 10% reduction using through-flow methods on a 3-stage compressor mounted on a single shaft engine. There is a slight divergence in the temperature reduction with respect to the various cases of ambient temperatures at higher injection ratios that are attributed to incomplete evaporation (Figure 4 Left- $f > 2\%$).

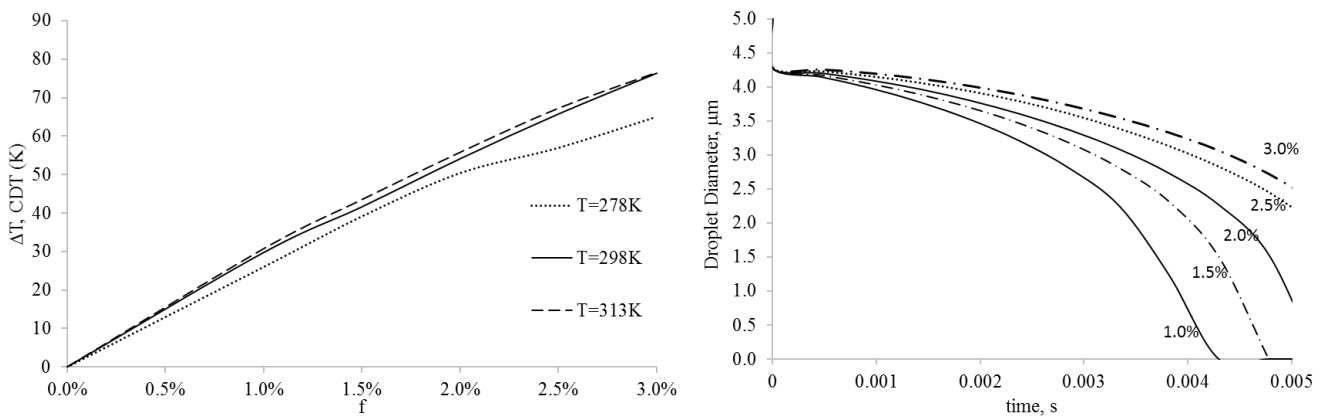


Figure 4 Influence of ambient temperatures on booster exit temperature drop for increasing injection ratio (left) and evaporation rate for injection ratios (right)

The right-hand side of Figure 4 shows one case of ambient temperature (278K or 5°C), and the evaporation of 5 μ m droplet injected at varied injection ratio. At 2%, the droplet does not evaporate completely at the booster exit as the droplet diameter is down to 1 μ m. High injection ratios (2.5 and 3%) create a larger heat sink; the sensible heat that is absorbed from the surrounding air is distributed into a larger mass. This is the reason why higher amounts of water have more cooling capacity (left) and last for longer in the booster (right). The results show that 2% injection ratio is a good compromise between maximizing the heat sink and ensuring complete/significant evaporation in the booster for ambient temperatures as low as 278K. It is important to indicate that for this 278K case, the amount of evaporated water in the duct before the booster compressor was exactly 37.2% of the original injected value irrespective of the amount of injected water (only 62.8% flows into the booster). The relative humidity in the duct increased with increasing injection ratio, and so did the absolute amount of evaporated water. For example, 37.2% of 20 g of water is greater than 37.2% of 10 g of water, nevertheless, the proportion of evaporated water was always the same. This explains the linear relationships between booster exit temperature reduction and injection ratio, since the evaporation rate for an isolated droplet depends on the fluid density, mixture saturation conditions, droplet diameter and amount of water. If the residence time is the same, the proportion of evaporated water will also be the same irrespective of the number of droplets present in the flow (Figure -Left.).

The RH in a gas turbine has been studied by Refs. [38–40]. RH impacts the evaporation time because evaporation is a mass-diffusion process driven by temperature and mass concentration differences as indicated in Eq.11. The left-hand side of Figure 5 shows that the booster exit temperature still decreases with injection ratio, with negligible influence at the different ambient RH (constant ambient temperature of 298K- 5 μ m). The right of the figure shows that an increasing RH delays the evaporation time. Further details of the change in RH before and after injection is shown in subsequent results.

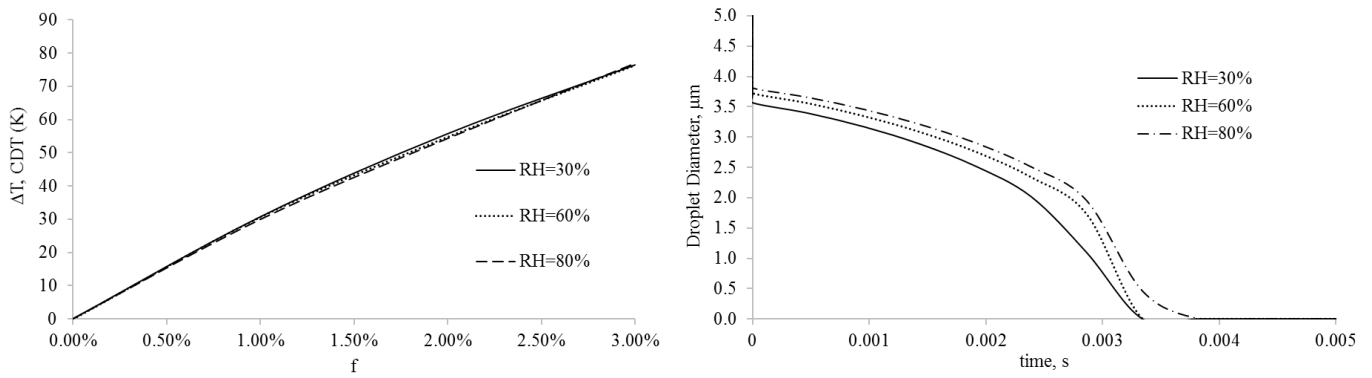


Figure 5 Booster exit temperature drop with injection ratio at different relative humidity (left) and the related evaporation rates (right)

Table 2 shows how the gas properties change when it goes from different ambient temperatures at 30% relative humidity to the fan exit/booster intake. The temperature drop achieved at the exit of the compressor for an injection ratio of 2% is also shown. The first thing to note is that the relative humidity drops considerably after the gas passes through the fan. The clear advantage of injecting after the fan is the enhancing of the evaporation effectiveness by injecting water at temperatures above 325K and relative humidity below 5% (as opposed to 30%). The next thing to note is that the saturation temperature at the booster inlet becomes almost constant. While the highest and lowest ambient temperatures differ by 11.2%, the saturation temperatures after the fan only differ by 5.4%. This property of the saturation temperature becoming almost independent of the ambient conditions increases with higher temperatures, and thus allows for a constant drop in booster exit temperature for a given water quantity. This drop in the 2-spool engine amounts to a reduction in about 10-12% of its “dry” operating temperature and is independent of the ambient conditions analysed here.

Table 2 Temperature reductions by evaporative cooling for RH=30%

Ambient Temperature (K), at 30% RH	Fan exit/ Booster Inlet temperature (K)	Relative Humidity at booster inlet (K)	Saturation Temperature at booster inlet (K)*	ΔT drop at booster exit in relation to dry (f=2%) (K)
278	325	3%	302	50
288	337	3%	307	53
298	344	4%	311	54
303	355	4%	314	55
313	367	5%	319	56

*Lowest temperature achievable by evaporative cooling

Effect of Water Injection Properties: Water Quantity and Droplet Size

The increment in size of the water droplet is not an increase in the amount of water, as the injection ratio of 2% is the same for all the cases. An increase in droplet diameter amounts to the utilisation of fewer droplets, so the mass is distributed differently. Figure 6 on the left shows the gas temperatures for these different droplet diameters ranging from $2\mu\text{m}$ to $20\mu\text{m}$. Droplets larger than $10\mu\text{m}$ have particularly negligible effect in booster exit temperature. This is attributed to the lower surface-area-to-volume ratio found on larger droplets. A droplet diameter of $10\mu\text{m}$ has 4 times less surface area of $20\mu\text{m}$, nevertheless twice the surface-area-to-volume ratio, which reflects a more efficient evaporation process. As such, the case of $2\mu\text{m}$ indicates the best case of temperature drop in the compressor, with complete evaporation immediately after entry to the booster section, before 0.4 dimensionless distance. For $5\mu\text{m}$ droplet, this evaporation is achieved after 0.6 dimensionless distance (Figure 6-Right), after which the slope of the temperature curve (Figure 6-Left) changes because the second term of Eq. (14) becomes 0, and the polytropic coefficient of compression, that defines the temperature curve slope, is almost the same as that of the dry case. The 2 and $5\mu\text{m}$ droplets absorb more energy as they pass through the compressor booster as compared to the 10 – $20\mu\text{m}$ cases, causing a higher reduction in temperature. The left of the figure also captures the cooling/evaporation in the duct between the booster and the HPC, in the form of constant pressure evaporation for the larger diameter droplets that do not entirely evaporate inside the booster.

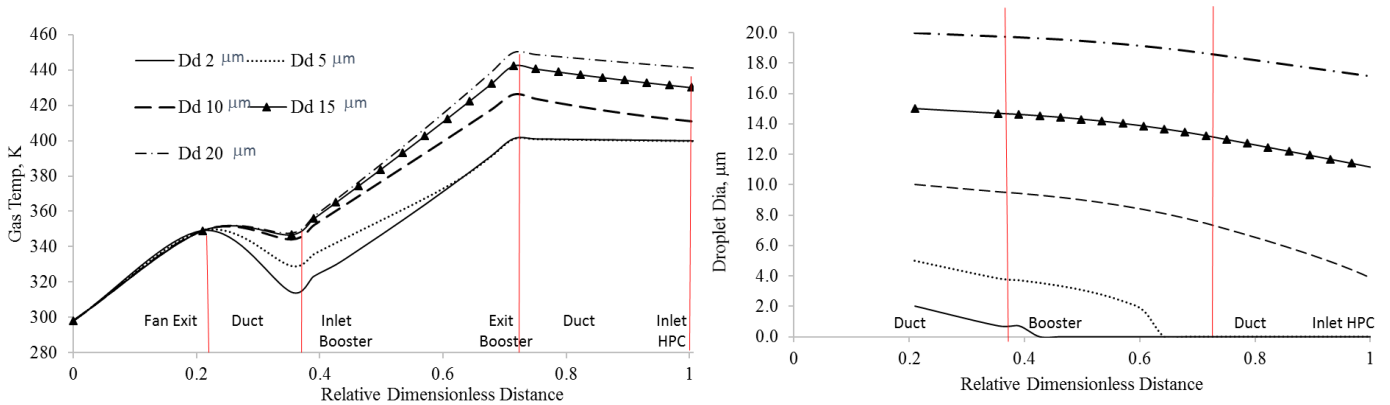


Figure 6 Gas temperature from the intake to booster exit ($f = 2\%$, at 298K and 60% RH)

Figure 7 shows the reductions in the booster exit temperature for the range of droplet sizes discussed but for varied injection ratios up to 3%. This figure shows an improvement in the booster temperature drop with increase in injection ratio. As indicated, the $2\mu\text{m}$ droplets are so efficient at evaporating that for injection ratios of 1, 1.5, and 2% the air gets saturated before it enters the compressor, and no further cooling is possible in the duct, that explains the small flattening of the curve between 1 and 2%.

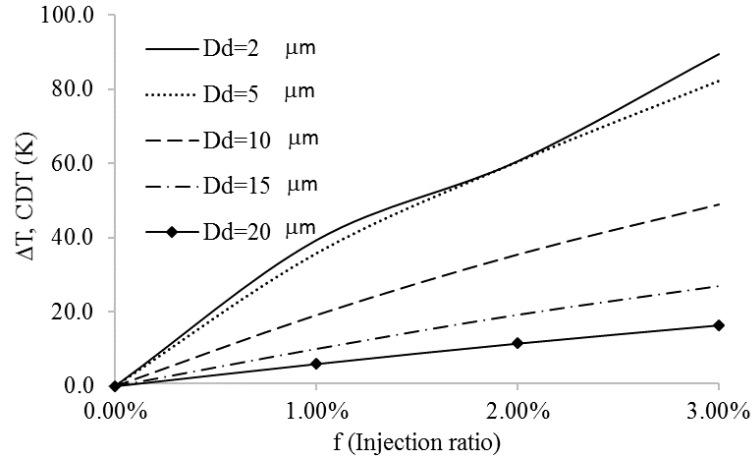


Figure 7 Booster exit temperature drop vs injection ratio for different droplet diameters

Previous studies, [41,42] show that when injecting 5μm droplets, 99.15% of the injected volume will follow the flow path without impacting the blades, braking or being centrifuged towards the casing. Since this model does not account for droplet brake-up or impact, and based on the promise found on 5μm droplets, this size will be used from now on. It is acknowledged, however, that it would be challenging to produce a monodispersed spray with 5 μm spherical droplets. Although state-of-the art nozzles operated under certain conditions might achieve a Sauter-Mean-Diameter (SMD) of 5 μm, this would only be representative from a thermodynamic perspective. The SMD represents the surface area-to-volume ratio of the spray, so the heat sink effect of the droplets could be modelled with some level of accuracy, but the droplet interactions such as merge, brake-up, bouncing or splashing are ignored for this analysis.

3.2 Three-spool Compressor Analysis and Comparison

As mentioned previously, two injecting positions are considered for the 3-spool compressor. These are SD and LD positions. The latter allows for more evaporation of droplets before entry into the IPC. SD in this configuration is for direct comparison with the 2-spool compressor. Injecting in this position, closer to the intake of the compressor will presumably cause farther intercooling comparatively, but less initial temperature drop in the duct than the LD position. Figure 8 and Figure 9 show the gas temperature (left) and relative humidity (right) from the intake of the fan to the HPC inlet, for SD and LD respectively. The temperatures and relative humidities still represent a tracked particle through the flow, for different injection ratios with a droplet size of 5μm. The gas temperature plots indicate the reduced gas temperature now expected with an increase in the injection ratio. As water is injected closer in the SD position case, the intercooling effect lasts for longer than in the LD case. In the SD cases (Figure 8), saturation is never reached in the duct before the IPC, and the initial temperature drop is smaller. However,

the slope of the temperature curve maintains a lower value for an extended period due to the intercooling effect.

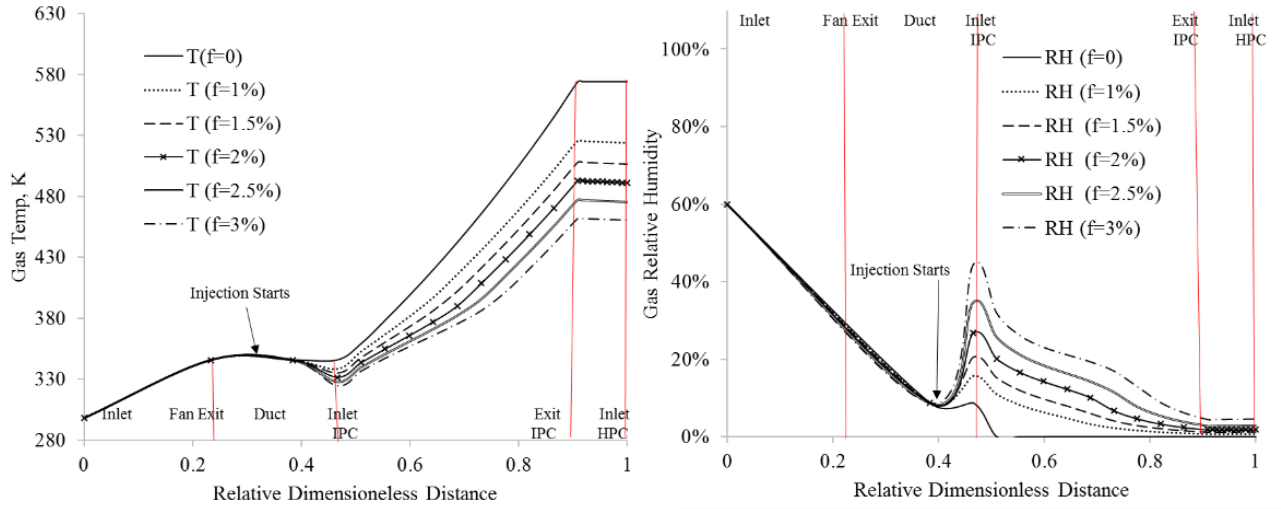


Figure 8 Gas temperature (left) and RH (right) across compressor at SD position for varied injection ratio

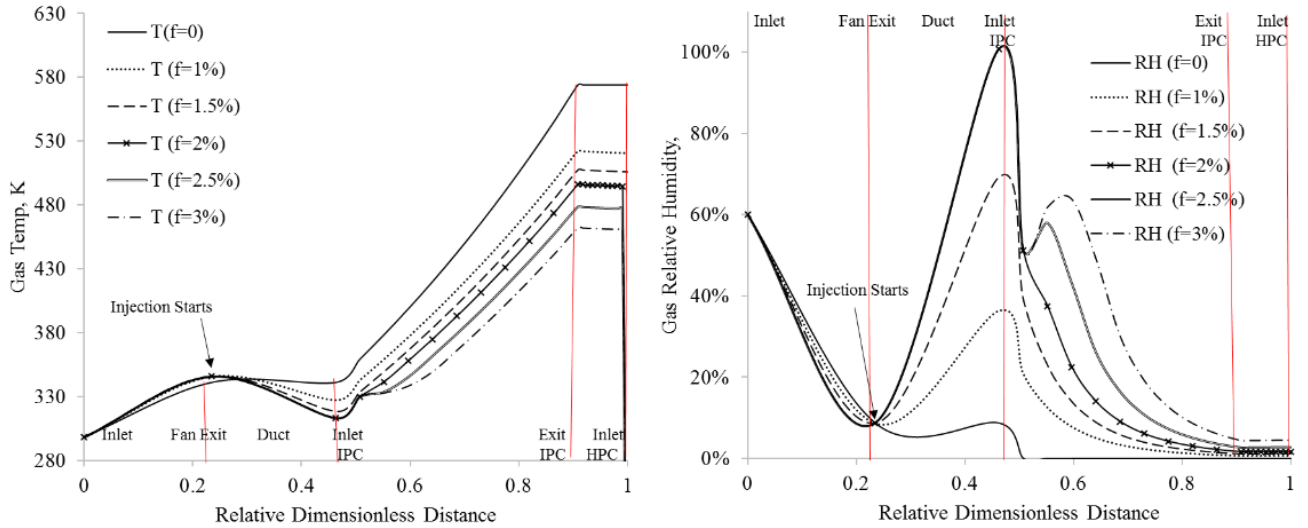


Figure 9 Gas temperature (left) and RH (right) across compressor at LD position for varied injection ratio

The trend of RH in Figure 8 shows a decrease in RH across the fan that approaches zero in the duct before the IPC, for the dry case. A rise in wP (Eq. 17, below), as a consequence of the FPR, occurs just after the Fan, but the denominator, in this case, becomes 10 times higher as a result of the increased temperature and its relationship to P_{sat} , which has as a consequence a dramatic reduction in RH in the duct between the fan and the IPC (hence the small effect of CDT change with Relative Humidity seen on Figure 5). With water injection, the RH increases in this duct (after the injecting point) until the IPC inlet where a second increase in temperature starts. The rise in RH in the duct occurs at constant pressure, as pressure losses are neglected. The drop in temperature of air, and increase in

water vapour content, w , inside the duct, ensures that the vapour pressure approaches the saturation vapour pressure, raising the RH (Eq.17). For the LD position in Figure 9, 100% RH is reached for injection ratios from 2% and above due to a further drop in temperature in the duct. Once the RH reaches 100% no further water evaporates, and the left-over water flows in liquid form into the IPC. The rise in temperature and pressure in the IPC generally causes reductions in the RH inside the compressor, as seen for the fan case. This sudden decrease in RH at the inlet of the IPC, creates favourable conditions for the water to evaporate again, and so fast evaporation is seen at this stage. Although the pressure in the first stage increases, the temperature is seen to stay almost constant (in the LD injection) due to the fast evaporation, and hence the RH rises again slightly at $x=0.6$. In subsequent stages, there is less available water, which means the cooling effects are diminished and so the denominator in Eq.(17) increases much more than the numerator, and the RH drops to almost 0. In the cases where there is less available water ($f<2\%$), the relative humidity is seen to decrease after the first IPC stage without the presence of the second peak. Khan and Wang [17] report a similar RH behaviour for the case of an 8-stage compressor, analysed with stage stacking techniques under equilibrium and non-equilibrium evaporation. On the temperature graph, (Figure 8&Figure 9 Left) the point at which the temperature-curve slope changes coincide with the point where the water is fully evaporated, this behaviour is more obvious in Figure 10.

$$RH = \frac{wP}{P_{sat}(w + 0.622)} = \frac{f(P, w)}{f(T, w)} \quad (17)$$

The calculated drop in gas temperature at the exit of the IPC in relation to the dry case for both SD and LD positions are highlighted in Table 3. That of the 2-spool booster compressor exit is also included, all at 298K ambient temperature. The results for the 3-spool show that the drop in the IPC exit temperature for both positions is very similar given the axial length injecting difference of 256 mm. The extra initial cooling on the LD position seems to be compensated by longer intercooling on the SD case. When comparing the two compressors at their exits (IPC and booster) for the same injection position, it can be observed that the drop in temperature of the 3-spool configuration is more significant. This is attributed to higher pressure and temperature ratio with respect to the work done up till this location. Figure 10 provides further evidence indicating that for the 2-spool, the water droplets do not evaporate at the booster compressor, unlike the 3-spool compressor in all the cases investigated.

Table 3 IPC and booster ΔT exit for different injection ratios

f (%)	3- Spool		2- Spool
	$\Delta T(K)$ - SD	$\Delta T(K)$ - LD	$\Delta T(K)$ - SD
1.0	50.09	53.60	35.78
1.5	67.43	68.14	48.27
2.0	82.75	79.36	60.44
2.5	98.56	96.88	71.02
3.0	113.62	113.61	82.23

Figure 11 complements Figure 8 and Figure 9, indicating the evaporation of the droplets at SD and LD positions of the 3- spool compressor using the same droplet size of $5\mu\text{m}$ for different injection ratios. In fact, for the case of 1% injection ratio, all the water is evaporated before the gas enters the IPC for the LD position, and the curves for diameter change diverge considerably during this initial inlet cooling. If the injecting position is moved closer to the IPC (at SD position), the water has less time to evaporate in the duct and this occurs inside the IPC compressor. This also infers the influence of injection position on the evaporation time.

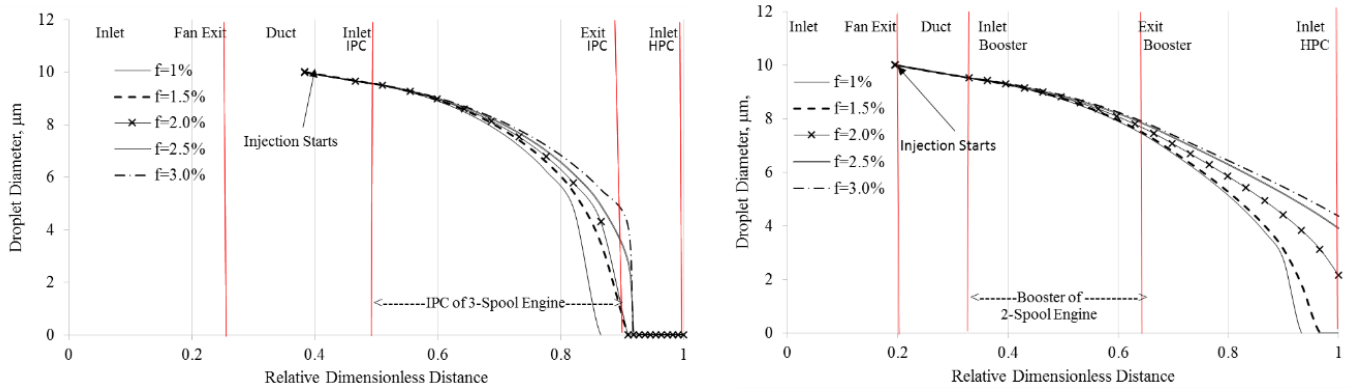


Figure 10 Comparison between droplet depletion on the 3 and 2-spool compressor for different injection ratios

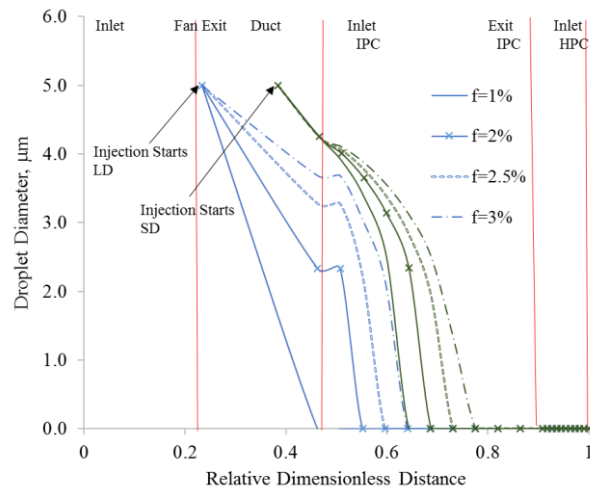


Figure 11 Droplet depletion for different injection ratios at SD and LD positions – 3-spool compressor

Figure 12 demonstrates the reductions in compressor specific work with water injection at SD position, calculated with the changes in enthalpy as shown in Eq. (8). The maximum reductions are about 22% for 2 μm droplets and 12% for 10 μm , that is similar to outcomes of White and Meacock [11] that showed 18 and 12% for a subsonic compressor with a PR of 15. The 2 μm droplets in both cases of compressors evaporate very fast and reach saturation conditions in the duct, this explains the plateau seen between 1 and 2%. Two processes are seen for small droplets; up to 1% injection ratio, the reduction in work is mainly due to the cooling of the gas before it enters the compressor. After 2% injection ratio, significant amounts of unevaporated water start flowing into the compressor, intercooling the gas as it gets compressed. For the 10 μm droplets, the reductions are linear as saturation is not reached before the compressor inlet. The 2-spool engine seems to have a comparatively higher reduction in specific work than the 3-spool, since the 2-spool engine has a short 3-stage booster, while the 3-spool engine has a longer 8-stage IPC. The implications of this are shown previously in Figure 10. In the IPC, the water will evaporate before the exit of this intermediate compressor, and thus comparatively, the specific work decrease is less. In the shorter booster, the water will travel the whole length of the compressor and thus all the stages will get intercooled. Although the specific work reduces, depending on the operation of the gas turbine, the mass flow might increase, and the specific enthalpy change, when combined with the increase in mass flow, could result in an increased, decreased or unchanged compressor power consumption.

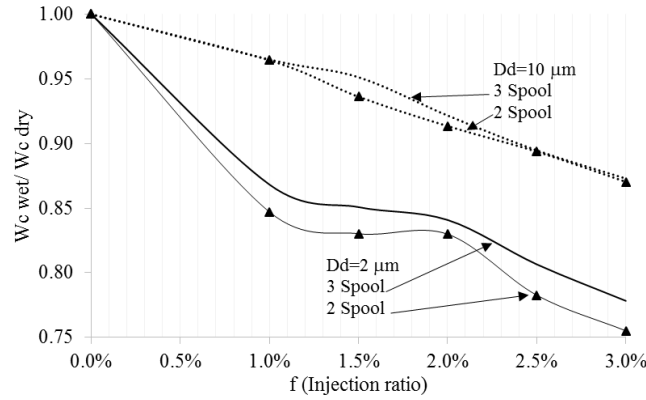


Figure 12 Reduction in compressor specific work due to injection ratio and droplet size for both compressors

4- Assumptions and Limitations

This model does not account for droplet breakup, interaction or for droplet-blade impaction. The simplification is a lot more applicable to droplets of up to 10μm diameters. For 15 and 20μm also investigated, there is a high degree of uncertainty due to other transport mechanisms that begin to be more influential. It is the assumption that the droplets are spherical and travel along the flow path.

All the simulations have been conducted at an ambient pressure of 101 kPa, and the pressure ratios of the fan and intermediate compressors are assumed constant. The off-design re-matching of the compressors caused by a change in the inlet conditions have not been accounted for. The off-design simulations for different ambient temperatures were later simulated for a gas turbine engine using the in-house software, TURBOMATCH, and the pressure ratios were compared for those of the stand-alone model as shown in [Appendix C](#). The highest relative error in terms of booster exit temperature difference and pressure ratio is 1.34% and 2.67% respectively. Hence, this limitation in the stand-alone model does not lead major inaccuracies in the predictions for droplet evaporation.

Generally, the interpretation of the results is in parts not straightforward and depends on the saturation conditions of the duct between the fan and the following turbomachinery component.

5- Conclusions

This first part of the study has focused on a stand-alone evaporative compressor model exploring the effect of water injection behind the fan, at different ambient conditions, droplet size and injection rate. This allows for the necessary specification of boundary condition in part 2 study. The new findings unique to this study are:

- Internal compressor water injection still offers benefit in reducing the specific compressor work at low ambient temperature, given the rise in ambient temperature by the exit of the fan. About 2% injection ratio is a good compromise between maximizing the heat sink and ensuring complete/significant evaporation in the compressor for ambient temperatures as low as 278K (5°C).
- The 3-spool compressor benefits more from this configuration of water injection than the 2-spool, due to higher operating intermediate compressor temperatures.
- The 2-spool engine seems to have a comparatively higher reduction in specific work than the 3-spool, since the 2-spool engine has a short 3-stage booster, while the 3-spool engine has a longer 8-stage IPC, and so all the stages are intercooled in the booster, while only about half of the stages are intercooled on the IPC.
- The SD and LD positions considered for the 3-spool compressor shows that the minimal influence of these relative positions in terms of reduction in IPC exit temperature. However, for the LD position, saturation is reached prior to entry into the IPC for injection ratios from 2% and above, and so longer intercooling is replaced by a larger drop at the entry of the compressor.
- The influence of ambient temperature and relative humidity for constant pressure shows that the same temperature drop can be achieved independently of the ambient temperature or humidity levels for the range considered here. This is due to the saturation temperature becoming almost independent of the air temperature at the positions where the water is injected, where the gas has reached 325K or more.

More generally, the study verifies that:

- Smaller droplets for the same injection rate are more effective in reducing compressor operating temperatures, due to their higher surface-area-to-volume ratio. By controlling the droplet diameter, it is also possible to control the place at which the stages benefit from the highest cooling (where the slope of the diameter change curve becomes steeper).
- The initial reduction in droplet size is influenced by the ambient temperature and the fan pressure ratio. The booster or IPC exit temperature reduces with increase in injection ratio.

Acknowledgments

This work was supported by the Mexican National Council for Science and Technology (Conacyt), and by the Centre for Propulsion of Cranfield University.

Nomenclature

CDT	Compressor Discharge Temperature	P_2	Position 2
CO	Carbon Monoxide	q	Specific heat transfer (J/Kg)
CO ₂	Carbon Dioxide	ρ	Density (kg/m ³)
C_p	Specific Heat (J/kgK)	R	Gas Constant (J/kgK)
D_v	Mass diffusion coefficient (m ² /s)	r	Radius (m)
D_d	Droplet Diameter (μ m)	RH	Relative humidity
f	water injection ratio (kgw/kg _a)	SD	Short Distance
Γ	Mass transport coefficient	t	Time (s)
γ	Specific heat ratio	T	Total temperature (K)
η	Efficiency	TIT	Turbine Inlet Temperature
H	Enthalpy (J)	u	Internal energy (J/Kg)
h	Specific enthalpy (J/Kg)	v	Flow velocity (m/s)
HC	Hydrocarbons	ω	Specific humidity (kgvap/kgair)
HPC	High-Pressure Compressor	C_w	Specific Compressor Work (J/Kg)
h_{fg}	Enthalpy of vaporization (J/kgK)		
IPC	Intermediate-Pressure-Compressor		
LD	Long Distance		
LPC	Low-Pressure Compressor		
LPT	Low Pressure Turbine		
m	Mass flow rate (kg/s)		
n	Number of droplets		
P	Total Pressure (Pa)		
PR	Pressure Ratio		
P_1	Position 1		

Subscripts	
1	inlet
2	outlet
a	air
c	Critical temperature/ pressure
m	mixture
s	saturation
v	vapour
w/f	water

Appendix A. Comparison against other analytical methods

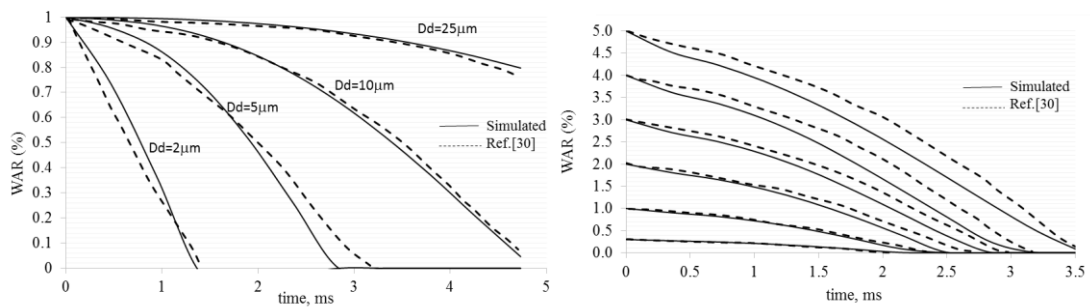


Figure A 1 Dependency of droplet diameter (Left) and water quantity (right) on evaporation time. Model vs Ref. [32]. On the figure: Water quantity vs time.

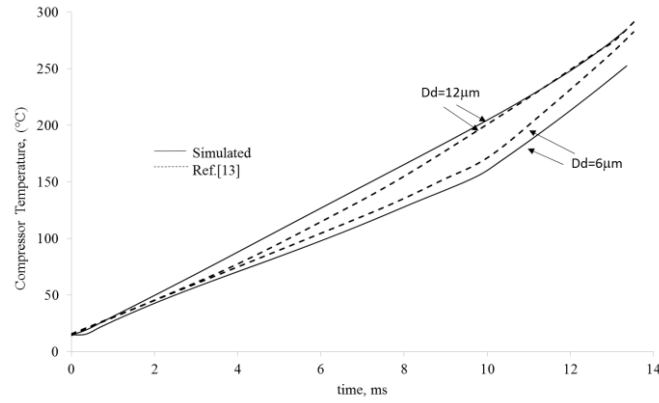


Figure A 2 Compressor Temperature increase for gas injected with different droplet diameters. Model vs Ref.[14]

Table A.1 compares the CDT reductions between this model and the compressor of Ref.[14] For different injection ratios. The model presented here seems to over predict the temperature reduction compared to Ref.[14]. This can be due to the assumption of constant water temperature as well as the fact that Ref.[14] Uses a different analytical model.

Table A 2 CDT reduction for different injection ratios. Model vs Ref [14]

f	CDT _{wet} /CDT _{dry}	CDT _{wet} /CDT _{dry}
	Simulated	Ref.[14]
0%	1.00	1.00
1%	0.87	0.91
2%	0.77	0.81
3%	0.68	0.72
4%	0.59	0.64

Appendix B. Calculation and Iteration Procedure

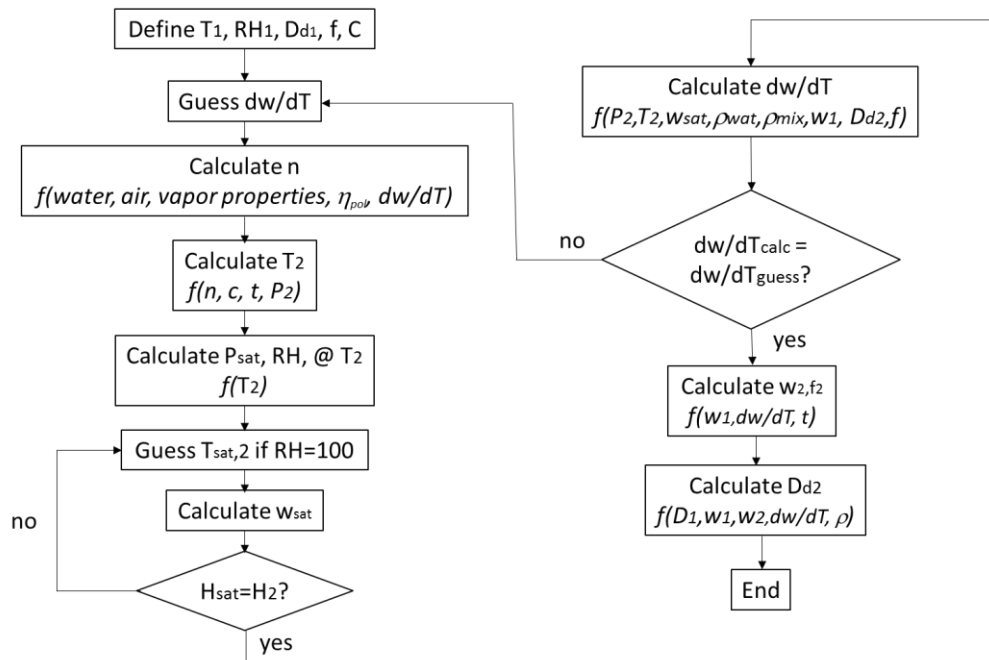


Figure B 1 Iteration Procedure followed for the compressor thermodynamic model

Appendix C. Variable vs Constant PR calculations

The following table shows the difference in compressor exit temperature and pressure between the stand-alone simulated compressor, and a compressor simulated as part of the complete gas turbine. When the stand-alone compressor was simulated, the pressure ratio was assumed to be constant with and without water injection. When this was integrated with the complete engine, it was seen that the rotational speed and mass flow changed, giving rise to a slight increase in pressure ratio. The difference in exit temperature is of interest here, as this is the boundary condition for the matching of the stand-alone compressor and the engine model presented in a subsequent study.

Table C 1 Differences in booster exit temperature and pressure ratio for stand-alone compressor model and engine simulation model at varied ambient temperatures

T (K)	Stand-alone compressor (constant PR)	Engine model (varied PR)	% error in Booster Exit Temperature	% error in Booster PR
278	370.46	369.18	-0.35%	2.80%
288	384.83	381.16	-0.96%	2.75%
298	400.78	395.35	-1.37%	2.67%
303	407.64	402.47	-1.28%	2.65%
313	421.9	416.31	-1.34 %	2.67%

References

1. ICAO- International Civil Aviation Organization. 2013 Environmental Report, Aviation and Climate Change. 2013.
2. Block N. DA., Igie U. Case For Exploring Compressor Water Injection For Airport Emission Reduction GT2017-64780. In: ASME (ed.) Asme turbo expo: Power for land, sea and air. Charlotte: American Society of Mechanical Engineers (ASME); 2017. p. TBC.
3. Daggett DL., Fucke L., Hendricks RC., Eames DJH. Water Injection on Commercial Aircraft to Reduce Airport Nitrogen Oxides. Nasa/Tm—2010-213179. 2010; (March).
4. Advisory Council for Aviation Research and Innovation in Europe A. Strategic Research & Innovation Agenda- Volume 1. 2012.
5. Nikolaidis T., Pilidis P. The effect of water ingestion on an axial flow compressor performance. *Journal of Aerospace Engineering*. 2014; 228(3): 411–423. Available at: DOI:10.1177/0954410012474421
6. AGARD. Recommended Practices for the Assessment of the Effects of Atmospheric Water Ingestion on the Performance and Operability of Gas Turbine Engines. Neuilly-Sur-Seine; 1995.
7. Roumeliotis I., Alexiou A., Aretakis N., Sieros G., Mathioudakis K. Development and Integration of Rain Ingestion Effects in Engine Performance Simulations. 2016; 137(April 2015): 1–11. Available at: DOI:10.1115/1.4028545
8. Liu C., Li X., Zhang H., Zheng Q. Heat and Mass Transfer Characteristics of Water Droplets in Wet Compression Process. ASME Turbo Expo 2017: Turbomachinery Technical Conference and Exposition. Charlotte; 2017. pp. 1–14.
9. Utamura M., Takehara I., Horii N., Kuwahara T. A New Gas Turbine Cycle for Economical Power Boosting. The American Society of Mechanical Engineers. 1997; 97-AA-142: 1–10.
10. Sexton MR., Urbach HB., Knauss DT. Evaporative compressor cooling for NOx Suppression and Enhanced Engine Performance for Naval Gas Turbine Propulsion Plants. The American Society of Mechanical Engineers. 1998; 98-GT332: 1–10.
11. White AJ., Meacock AJ. An Evaluation of the Effects of Water Injection on Compressor. ASME. 2004; 126(October 2004). Available at: DOI:10.1115/1.1765125
12. Zheng Q., Sun Y., Li S., Wang Y. Thermodynamic Analyses of Wet Compression Process in the Compressor of Gas Turbine. *Journal of Turbomachinery*. 2003; 125(3): 489. Available at: DOI:10.1115/1.1575254
13. Bagnoli M., Bianchi M., Melino F., Spina PR. Development and Validation of a Computational Code for Wet Compression Simulation of Gas Turbines. *Journal of Engineering for Gas Turbines and Power*. 2008; 130(1): 012004. Available at:

DOI:10.1115/1.2771563

14. Kim KH., Ko HJ., Perez-Blanco H. Analytical modeling of wet compression of gas turbine systems. *Applied Thermal Engineering*. Elsevier Ltd; 2011; 31(5): 834–840. Available at: DOI:10.1016/j.applthermaleng.2010.11.002
15. Kofar-bai DG., Zhang H., Zheng Q., Abdu S. Flow Assessment on the Effects of Water Droplets on Rotor Region of Wet Compression. *Transfer Phenomena in Fluid and Heat Flows III, Deffect and Diffusion Forum*. 2017. pp. 131–147. Available at: DOI:10.4028/www.scientific.net/DDF.374.131
16. Sun L., Zheng Q., Li Y., Luo M., Wang J., Bhargava RK. Numerical Through Flow Simulation of a Gas Turbine Engine With Wet Compression. *ASME Turbo Expo*. 2012. pp. 1–13.
17. Wang T., Khan JR. Overspray and Interstage Fog Cooling in Gas Turbine Compressor Using Stage-Stacking Scheme—Part I: Development of Theory and Algorithm. *Journal of Thermal Science and Engineering Applications*. 2010; 2(3): 031001. Available at: DOI:10.1115/1.4002754
18. Wang J., Zheng Q., Sun L., Luo M. The Effective Positions to Inject Water Into the Cascade of Compressor. *proceedings of ASME Turbo Expo*. Denmark; 2012. pp. 1–14. Available at: DOI:10.1115/GT2012-69158
19. Favorskii ON., Alekseev VB., Zalkind VI., Zeigarnik YA., Ivanov PP., Marinichev D V., et al. Experimentally Studying TV3 117 Gas Turbine Unit Characteristics at Superheated Water Injection into a Compressor. 2014; 61(5): 376–384. Available at: DOI:10.1134/S0040601514050024
20. Roumeliotis I., Mathioudakis K. Water Injection on Compressor Stage Operation. *Transactions of ASME*. 2007; 129(July): 778–784. Available at: DOI:10.1115/1.2718223
21. Schnitzler JP., von Deschwanen I., Clauss S., Berna F., Dohmen HJ., Werner K. Experimental Determination of a Four Stage Axial Compressor Map Operating in Wet compression. *ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*. Dusseldorf; 2014. pp. 1–10.
22. Kim KH., Ko HJ., Kim K., Perez-Blanco H. Analysis of water droplet evaporation in a gas turbine inlet fogging process. *Applied Thermal Engineering*. Elsevier Ltd; 2012; 33–34(1): 62–69. Available at: DOI:10.1016/j.applthermaleng.2011.09.012
23. Chaker M., Meher-Homji CB., Mee T. Inlet Fogging of Gas Turbine Engines- Part A: Fog Droplet Thermodynamics, Heat Transfer And Practical Considerations. *ASME Turbo Expo*. Amsterdam; 2002. pp. 1–16.
24. Sanaye S., Tahani M. Analysis of gas turbine operating parameters with inlet fogging and wet compression processes. *Applied Thermal Engineering*. Elsevier Ltd; 2010; 30(2–3): 234–244. Available at: DOI:10.1016/j.applthermaleng.2009.08.011
25. Zheng Q., Sun Y., Li S., Wang Y. Thermodynamic Analyses of Wet Compression

- Process in the Compressor of Gas Turbine. *Journal of Turbomachinery*. 2003; 125(3): 489. Available at: DOI:10.1115/1.1575254
26. Chaker M., Meher-Homji CB., Mee T. Inlet Fogging of Gas Turbine Engines- Part A: Fog Droplet Thermodynamics, Heat Transfer And Practical Considerations. *ASME Turbo Expo*. Amsterdam; 2002. pp. 1–16.
 27. Hill PG. Aerodynamic and Thermodynamic Effects of Coolant Injection on Axial Compressors. *The Aeronautical Quarterly*. 1963; November: 331–348.
 28. Meacock a. J., White a. J. The Effect of Water Injection on Multispool Gas Turbine Behavior. *Journal of Engineering for Gas Turbines and Power*. 2006; 128(1): 97. Available at: DOI:10.1115/1.2032432
 29. Roumeliotis I., Mathioudakis K. Water Injection on Compressor Stage Operation. *Transactions of ASME*. 2007; 129(July): 778–784. Available at: DOI:10.1115/1.2718223
 30. Daggett DL., Ortanderl S., Eames D., Snyder C., Berton J. Water Injection : Disruptive Technology to Reduce Airplane Emissions and Maintenance Costs. *SAE Technical Paper Series*. 2004; 01(3108).
 31. Roumeliotis I., Mathioudakis K. Evaluation of water injection effect on compressor and engine performance and operability. 2010; 87: 1207–1216. Available at: DOI:10.1016/j.apenergy.2009.04.039
 32. Roumeliotis I., Mathioudakis K. Evaluation of Interstage water injection effect on compressor and engine performance and operability. *Transactions of ASME Journal of Engineering for Gas Turbines and Power*. 2006; 128(4): 849–856. Available at: DOI:10.1016/j.apenergy.2009.04.039
 33. Saul A., Wagner W. International Equations for the Saturation Properties of Ordinary Water Substance. *Journal of Physics Chemistry*. 1987; 16(4): 893–901.
 34. Spalding DB. *Combustion and Mass Transfer*. 1st edn. London: Pergamon Press; 1979. 406 p.
 35. Eckert E., Drake RM. *Heat and Mass Transfer*. 2nd edn. New York: Mc Graw-Hill; 1959.
 36. Easa. EASA Type Certificate Data Sheet CFM56-5B and 5C Series engines. 2012.
 37. EASA. EASA Type Certificate Data Sheet Rolls Royce Trent 1000 Series Engines. 2013.
 38. Fishbeyn BD., Pervystin N V. Determination of the Effect of Atmospheric Humidity on the Characteristics of a Turbofan Engine. 1970.
 39. Samuels JC., Gale BM. Effect of Humidity on Performance of Turbojet Engines TN 2119. *Lewis Flight Propulsion Laboratory*, Cleveland Ohio; 1950.
 40. Bird J., Grabe W. Humidity Effects on Gas Turbine Performance. *The American Society of Mechanical Engineers*. 1991; 91-GT329: 7.

41. Sun L., Zheng Q., Li Y., Luo M., Wang J., Bhargava RK. Numerical Through Flow Simulation of a Gas Turbine Engine With Wet Compression. 2012; : 1–13.
42. Sun L., Sun T., Wang Y., Yang W. Numerical Simulation of Pollutant Emission of A Turbojet Engine with Water Injection. ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition GT2016. Seoul; 2016. pp. 1–9.
43. Daly M. Jane's Aero-engines. 2nd edn. IHS (ed.) Janes Information Group; 2015. 449 p.

V. Paper 4

Engine Models: 2 and 3 Spool.

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Aero Engine Compressor Cooling by Water Injection Part 2: Performance and Emission Reductions

David Alejandro Block Novelo and Uyioghosa Igie

School of Aerospace Transport and Manufacturing, Cranfield University, Cranfield, UK

Abstract

Take-off and climb up to 3,000 ft. are the flight segments in which the aero-engine experiences the highest operating temperatures, which are known to be accompanied by a high production rate of Nitrogen Oxides (NO_x). This contaminant has negative health implications on the human population, vegetation and wildlife that is in frequent proximity or exposure. Water injection into the compressor offers the possibility of reducing NO_x . Nevertheless, limited studies have focused on the emissions reduction potentials and the wider questions of the influence of engine type and of wide-ranging ambient conditions.

This study continues from the previous chapter and explores the implications of the studied ambient conditions on the overall respective engine systems and their consequent emission reduction. An in-house gas turbine performance simulation software has been implemented to model and simulate the engine performance. For the emissions estimation, correlations were made from the information provided by the Engine Emissions Data Bank to quantify the reductions in Nitrogen Oxides.

The 2 and 3-spool engine models investigated demonstrated significant reductions in compressor discharge and turbine inlet temperatures due to water injection. In this condition, the rotational speeds of the compressors are seen to be reduced to counter the mass flow augmenting effect of water injection and to satisfy the fixed thrust constraint. This along with lower compressor specific work brings about an improvement in the specific fuel consumption (5.3% and 7.8%, respectively) and general performance at low and high ambient temperatures. A higher advantage was seen for the 3-spool engine over the 2-spool as shown. Significant reductions in Nitrogen Oxide emissions of over to 50% are also demonstrated.

Keywords: Nitrogen oxides, compressor cooling, aero engine, performance, water Injection

1- Introduction

On a daily basis, more than 600 flights take-off from London Heathrow airport [1]. This can amount to an average of 30 take-offs per hour (accounting for the 6 hours of closure). The take-off phase in a flight is when the highest net thrust is reached, as well as the peak Turbine Inlet Temperature (TIT). The production of Nitrogen Oxides (NO_x) also peaks in this phase, that is related to high combustor temperatures, as also indicated by the International Civil Aviation Organization (ICAO)[2]. Heathrow airport report on Air Quality Strategy shows that departing aircraft is the main contributor of NO_x emissions around the airport [3], and this is revealed to be greater than that contributed by airport-related vehicle traffic, airport boiler plants and airside vehicles, all combined. In addition to this, the report indicates that 46% of the aircraft NO_x emissions at ground level are attributed to the take-off roll, while ICAO states this value can be as high as 70%[2].

The human population living in the locality of busy airports are predisposed to this pollutant and others, which has been proven to develop into respiratory illnesses as well as damage the local water quality and vegetation [4,5]. Regulatory authorities around the world are making efforts to mitigate emissions through the introduction of emission-based fees that are becoming more stringent. The European Strategic Research Innovation Agenda (SRIA)[6] target is to cut NO_x emissions by 90% in 2050 compared to 2000 levels. ICAO certified engines of today are required to produce up to 15% less NO_x than they did in 2005 [7]. In October 2017, Heathrow airport increased the emission-based charges to £15.96 per kg of NO_x compared to £8.15 implemented from October 2015, that is related to the Landing and Take-Off (LTO) cycle of an aircraft [8]. Some common technologies focused on reducing aircraft emissions, including combustion chamber design and new aircraft-engine configurations can be found in [9–12].

Water injection into the jet engine core flow after the fan has the potential of considerably reducing the combustor inlet temperature (i.e. compressor discharge temperature – CDT) as a result of the compressor air cooling effect that also augments the air density and mass flow. Although there are several studies of compressor water injection into axial flow compressors, only a few studies highlight the performance changes of a complete gas turbine engine system. Sun et al. [13,14] report 3D CFD through-flow method for a single spool turbojet engine with a 3-stage axial flow compressor. The simulations were conducted for different droplet diameters and injection ratios. At 2% injection ratio with $5\mu\text{m}$ droplets, the air mass flow (AMF) increased by 8% and the thrust by 12.5%, while the CDT, TIT, Specific Fuel Consumption (SFC) and NO_x reduced by 40 K, 75 K, 3.5% and 60% respectively. The work outlines the importance of droplet diameter and injection quantity as the two main variables but does not evaluate the impact of engine configuration or ambient conditions presented in this study. Favorskii et al. [15] present

an experimental analysis of a single spool engine with two droplet diameters, for constant TIT and constant power output. The investigations show a decrease in the compressor specific work accompanied by a 3.2% increase in mass flow for a 1.5% injection ratio. In addition to this, an 18% increase in power output was obtained, keeping TIT fixed. Utamura et al. [16] obtained 23% increase in power output with 2.3% injection ratio accompanied by a 2.8% increase in thermal efficiency, using an equilibrium analytical model. The results are confirmed with experiments of a single shaft gas turbine.

Sexton et al. [17] noticed reductions in SFC of up to 8.8% when 2.5% injection ratio was implemented. The application here was focused on potentially reducing the size of a naval gas turbine propulsion power plant by the use of water injection. The study also reports a decrease in NO_x by around 25% for a 0.45% injection ratio, at fixed TIT. A summary of the findings of 7 different studies comprising of CFD, experimental and analytical methods are shown and compared to the results of this study in [Appendix A](#).

With the exception of Daggett et al. [18] none of these studies, address the performance of multi-shaft engines, or the application of water injection into aero-engines at constant thrust. Although Meacock and White [19] is a study on 3-spool engines, the study was conducted only for the compressor and not the complete engine. This study intends to fill those gaps by outlining the importance of injecting water after the fan as opposed to at atmospheric conditions, pointing out the advantages in performance when operating at constant thrust. Two engine configurations (2 and 3-spool type) representative of modern high by-pass ratio turbofan engines is the focus of this work. Their stand-alone compressor section from the fan inlet to the intermediate compressors (booster or IPC) have been studied in [Part 1](#) [20], considering the influence of varied injection rate, droplet size, and ambient conditions on the intermediate compressors exit temperatures. These operating temperatures are used as boundary conditions for the engines in this second part, related to the water injection regime. Further to this, a correction is employed to account for the changes in gas properties (C_p and R)⁵ which cannot be applied in the simulating software TURBOMATCH. Details of this are provided in [Appendix B](#). This study's approach has provided the opportunity to study the evaporative process in greater detail and also overcome current limitations in capturing some of these effects using a well-established in-house gas turbine performance simulation code: TURBOMATCH.

⁵ The correlations are based on the results obtained to build Figure 4 on paper 2 (Chapter 3).

2- Methodology and Engines under Investigation

The performance of the 2 and 3-spool engine due to compressor water injection has been modelled and simulated using the zero-dimensional code. The design point calculation is achieved with initial user specification of ambient conditions, air mass flow, major component pressure losses and efficiencies, engine constraint (fixed net thrust in this case) etc. The code is embedded with standard compressor and turbine maps that allow for map scaling and combustion temperature rise chart for off-design calculations. Convergence is reached in the component matching after satisfying compatibility of non-dimensional rotational speed, work, and flow between the compressors and turbines. The program simulates the design and off-design performance of most gas turbine types using a modified Newton-Raphson method as the convergence technique. The iterative process involves several trials to ensure that the variables are consistent with the matching constraint. Further details of the methodology are provided in Macmillan [21] and Igie and Minervino[22]. Table 1 indicates the design point specification for both engine models at ISA cruise conditions. It can be observed that the cruise net thrust of the 3-spool engine is 2.6 times that of the 2-spool engine (this is due to the engines application rather than their different architecture). In addition to this, the take-off net thrust for both engines are 310kN and 133kN respectively and forms the reference point for all the simulations considered in this study. This is essential because the injection of water is considered only during take-off, nevertheless, such applications of jet engines are typically optimised for cruise operation and hence the design point is set at cruise condition. The relative error between the published values of SFC during take-off and the calculated off-design values of the model are 1.22% and 1.79% for the 2 and 3-spool engines respectively.

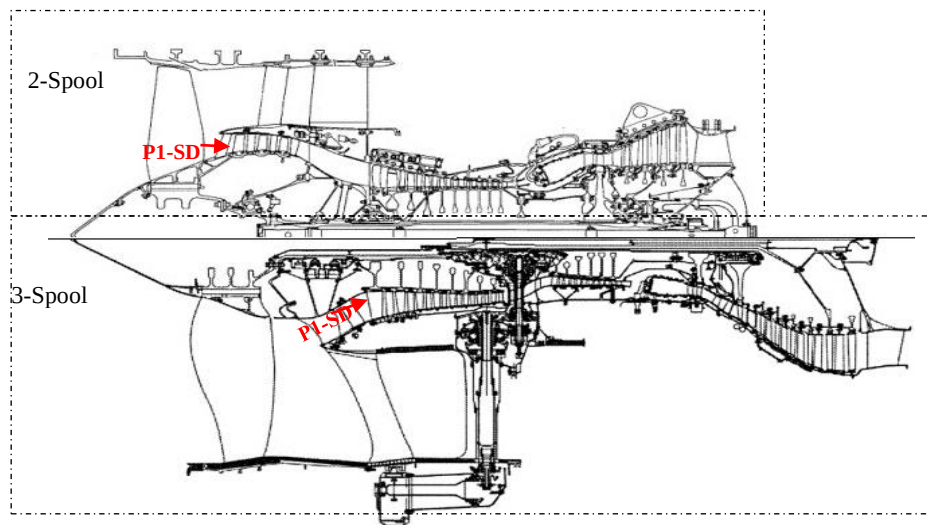


Figure 1 Architecture of the two and three-spool engines, Image adapted from [23]

A depiction of the relative difference in design architecture of both engines is shown in Figure 1. This diagram also points to the positions of water injection described in [Part 1](#) with the exception of the Position 2 – LD that has not been considered in this part of the study. This is due to similar changes in the IPC exit temperature due to water injection under the same conditions.

Table 1 Design point specification of engine models – Cruise ISA Altitude: 10,886, Ma=0.85

Parameter	2- Spool	3- Spool
Net thrust (kN)	26	67
Mass flow rate (kg/s)	172	540
BPR	5.48	10.7
OPR	31.6	50
Fan pressure ratio	1.64	1.65
Fan isentropic efficiency (%)	90	92
Booster/IPC pressure ratio	2.8	5.5
Booster/IPC isentropic efficiency (%)	88	90
HPC pressure ratio	6.86	5.52
HPC isentropic efficiency (%)	88	90
HPT cooling flow (%)	13	18
Cabin Press. Bleed (%)	2	2
Combustion efficiency (%)	99.9	99.9
Combustion chamber pressure loss (%)	5	5
TIT (K)	1439	1710
HPT isentropic efficiency (%)	90	90
IPT isentropic efficiency (%)	N/A	91
LPT isentropic efficiency (%)	93	93
SFC (g/kN*S)	16.98	14

2.1 Outline of the Model and Main Assumptions

The compressor evaporative model presented in the previous chapter was used as the basis for the point performance calculations used on this part of the study. It was assumed that the engine operates under take-off static conditions, and the boundary conditions for compressor pressure ratio, ambient temperatures and compressor efficiency were taken from the TURBOMATCH “dry” simulations. These values were then used to calculate the compressor behaviour in the stand-alone evaporative compressor model assuming a given injection ratio and droplet size. The Compressor Discharge Temperature (CDT) was calculated using the stand-alone model as explained in [chapter IV](#). The ambient temperature in TURBOMATCH was then reduced until the booster or IPC compressor discharge temperature matched the temperature calculated using the stand-alone compressor model. This was done by keeping the thrust of the engine always at the baseline “dry” value (at Take-off in this case). By matching the CDT of TURBOMATCH

with that of the evaporative model, it was ensured that the gas downstream of the “Turbomatch” compressor had similar conditions as those found on a water-injected engine. After the results were obtained for the “cooled” engine in TURBOMATCH, correction factors were applied to account for the gas property changes due to the presence of humidity, as explained in [Appendix B](#). In real conditions, dry air would get compressed through the fan at ambient temperature, and then it would be pre-cooled and inter-cooled inside the compressor by means of the injection of water droplets. The TURBOMATCH engine, however, operates under cold conditions from the fan entrance through to the booster / IPC exit. This leads to a mismatch in the power provided by the turbine. In the water injected case, for a 2-Spool engine, the low pressure turbine would provide power to drive a “dry” fan operating under ambient conditions, and an “intercooled-water-injected” booster. In the TURBOMATCH model, however, the LPT provides power to a “cooled” fan and a “cooled” booster. The turbine power rematch required in both types of engine (2 and 3 Spool) was estimated to be no more than 1% of the total engine power. This inaccuracy was termed as acceptable in comparison to other uncertainties that arise from modelling a turbofan engine with a 0-D code. The results presented in the [following chapter](#), consider an engine operating under different conditions from the start of the take-off run up to climb to 3,000 ft. The boundary conditions to simulate those cases are taken from the aircraft performance software as explained in the corresponding chapter.

3- Performance of Engines

The performance of the engines due to water injection is presented in this section for 5 μ m droplets and injection ratios of up to 3% for both engines. The ambient temperatures studied here are 278, 288, 298 and 303K with subsequent emphasis on the lowest and highest that represents common winter and summer temperatures. When water is injected into the compressor, this lowers the gas temperature, leading to an increase in its density. This causes a rise in the core Air Mass flow (AMF) shown in Figure 2 and a reduction in the Compressor Discharge Temperature shown in Figure 3. Fletcher and Walsh [24] recognise this fundamental characteristic of water injection and associate it to the increased air density rather than the added water mass flow. The increases in air mass flow at 2% injection ratio can be around 6% or 8% depending on the engine architecture as shown in Figure 2. The 3-spool engine shows a better improvement, influenced by a larger drop in the rotational speed of the HPC spool from 104% to 93% of its nominal take-off speed. This is to a lower extent for the 2-spool that is constrained by the fan on the same shaft as shown subsequently. These changes are also reflected in the CDT shown in Figure 3. In general, the figures show very little influence of ambient temperatures on the outcomes due to water being injected after the fan, as explained on Ref. [20]. The

higher reductions in CDT seen on the 3-spool engine are due to the water being injected at the entrance of the IPC which is a physically longer compressor with higher temperature and pressure ratio than that seen for the booster of the 2-spool engine. This allows for greater temperature reductions as the intercooling effect is larger. In the case of the 2-spool engine, for almost all the cases, there was unevaporated water at the exit of the booster that finished evaporating in the duct between the booster compressor and the HPC as shown in the previous [chapter](#).

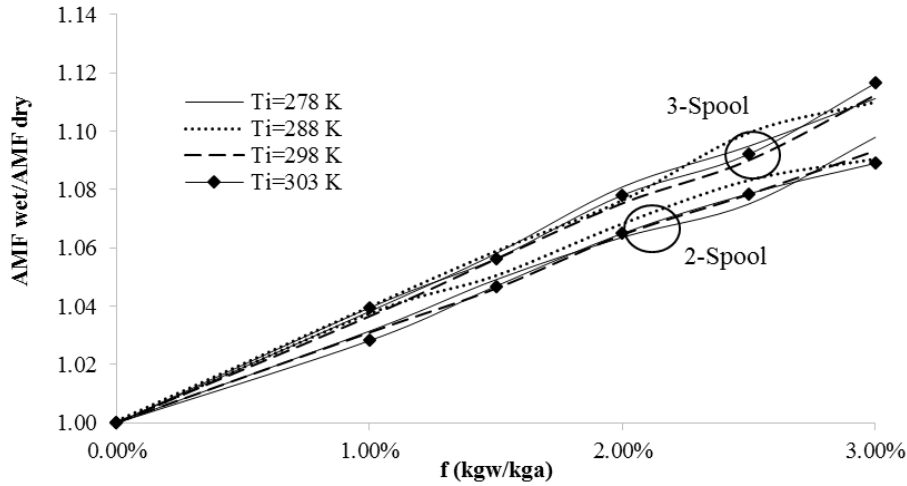


Figure 2 Increase in AMF as a function of water injection ratio for different ambient temperatures and 30% RH

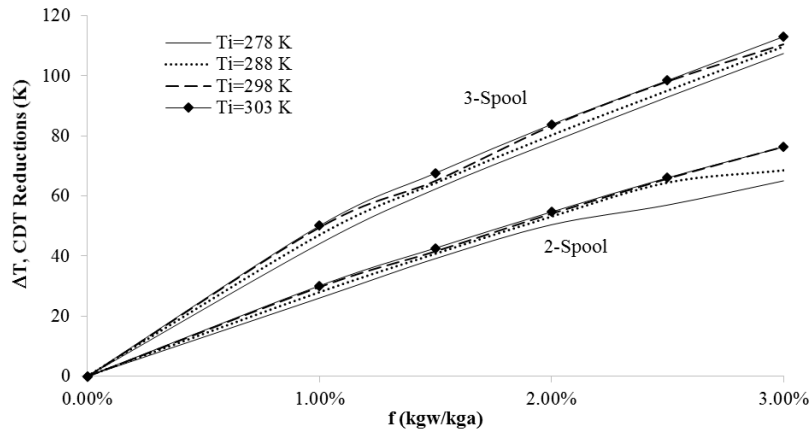


Figure 3 Drop in CDT as a function of water injection ratio for different ambient temperatures and 30% RH

The influence of droplet size on the increase in AMF is shown in Figure 4 for the case of the 3-spool engine. Smaller droplets, due to their larger surface area-to-volume ratio are more effective at cooling the air, and thus, for the same water quantity, they have a higher impact on increasing the density and in consequence, the AMF. The 2 and 5 μm droplets have the same effect, dominated by the evaporation in the duct before the compressor,

while the 10 μ m droplets tend to last for longer and to complete their evaporation in the later stages of the compressor. The 2-spool engine showed smaller AMF increases, due to smaller temperature drops, as seen in Figure 2, but not presented again for the presentation clarity of Figure 4. The droplet diameter, is a fundamental control variable, just as important as the water quantity, as this value determines the performance changes of the entire engine.

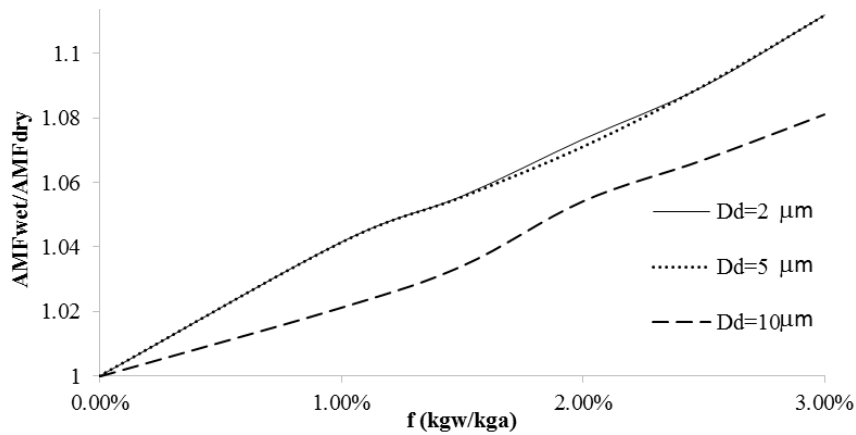


Figure 4 Increase in AMF as a function of water injection ratio for different droplet sizes and 30% RH

Figure 5 shows that the actual fuel utilised reduces further to achieve the same required thrust when the injection ratio increases. At 2% injection rate, this is possible due to the increased mass flow that is accompanied by an approximately constant Overall Pressure Ratio (OPR) as shown in Table 2. The increased mass flow is also counterbalanced by a reduction in the HPC rotational speed shown in the table, in order to achieve the required fixed thrust.

Table 2 Change in pressure ratios and rotational speeds at 2% injection rate and 303K

Parameters	2-Spool		3-Spool	
	Dry	Wet	Dry	Wet
OPR	30.9	31.3	42.4	42.9
Fan PR	1.62	1.63	1.499	1.5
Fan rotational speed	107%	102%	101%	93%
Booster/IPC PR	2.29	2.3	5.16	5.2
IPC rotational speed*	-	-	103%	96%
HPC PR	8.32	8.38	5.48	5.48
HPC rotational speed	109%	103%	107%	99%

* IPC and Fan rotational speeds are the same in the 2-spool engine

Figure 5 also shows the impact of ambient temperature on the fuel utilised, indicating generally better reductions at a lower temperature than at the higher temperature. This is mainly due to the improvement in the air density in lower temperature that begins from

the fan inlet. The corresponding re-matching of components as a result of this, which leads to subsequent changes of compressor air temperature is not entirely captured in the previous chapter [20] and hence, has a slight effect on the specification of the input boundary conditions in this part of the study. The figure also compares the 2 and 3-spool engines, indicating that the 3-spool engine fuel reductions are more significant due the temperature ratios accounted for in the compressor model in the previous [chapter](#) and consistent with the specification in Table 1. This is related to further evaporation and intercooling in the 3-spool engine, leading to higher specific work reductions as shown in Figure 6. For brevity, the impact of relative humidity is not included given discussions presented previously [20]. When water was implemented at 30% relative humidity, the reductions were less than 1% point difference better, as compared to water being implemented at 80% relative humidity, on the 2-spool engine. A lower relative humidity (drier day) allows for faster evaporation due to the lower water vapour mass concentration in the air. This finding on an engine system level is consistent with the relatively small changes discussed in the previous section. Figure 5 also shows that for the 2-spool engine, at 2% injection ratio and 303K, there is an upward deviation of the trend due to saturation conditions reached before the air gets to the booster.

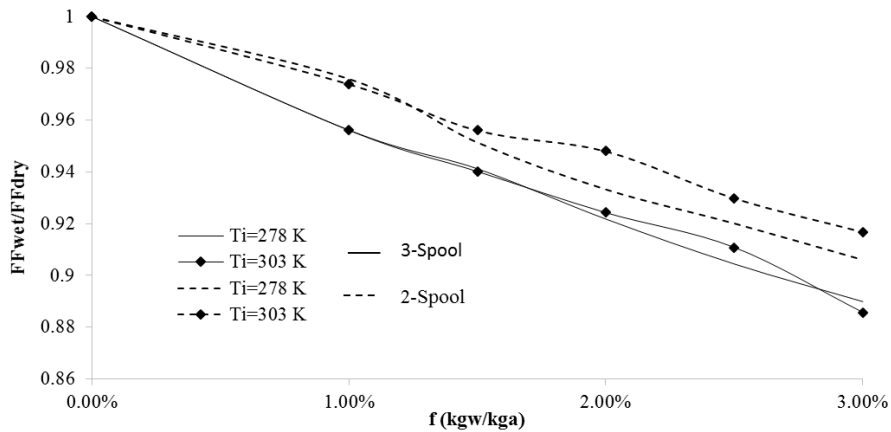


Figure 5 Fuel flow reductions versus injection ratio for different ambient temperatures and 30% RH

Further to the comments on the reductions in the specific work with injection ratio, a reduced specific compressor work or power translates to an improved available net power (Figure 6). As the thrust is kept constant in this study, a higher drop in the specific compressor work is expected when compared to a case of augmented thrust, and this is accompanied by a reduction in fuel flow as shown in Figure 5. The consequent TIT drop is shown in Figure 7, indicating that an increase in injection ratio causes an improvement in the turbine operating temperature for the same thrust setting. The reductions seen are an effect of the improved air mass to volume ratio that brings about the possibility to utilise less fuel. At 303K and 2% injection ratio, the 2-spool engine achieves a

temperature drop of 160 K (i.e. is close to 10% reduction), while the 3-spool engine attains a temperature drop of 240K (around 13% drop) as shown in Figure 7. This also shows that the changes are almost independent of the ambient temperatures. Daggett et al. [22] predicted close to 14% reduction with 2.2% injection ratio for a 2-spool aero-engine.

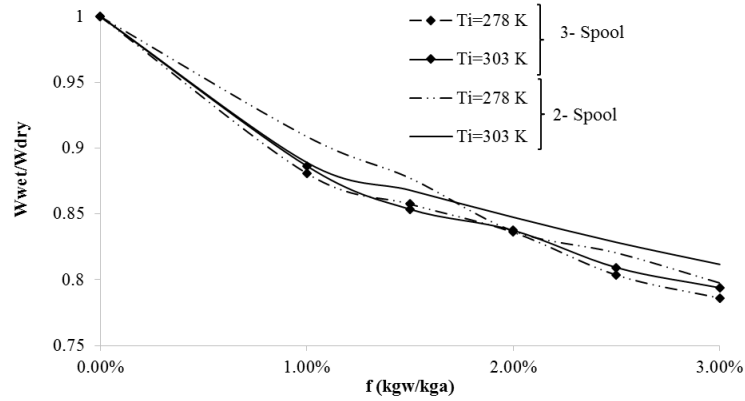


Figure 6 Compressor specific work versus injection ratio at different ambient temperatures and 30% RH

Generally, injecting water into the compressor has a similar effect on the engine performance as operations at low ambient temperatures (without water injection). For example, at 298K and 60% RH, injecting water at a ratio of 2%, would result in a TIT drop of 240K (13% decrease) for a 3-spool engine. This TIT drop can be achieved for the same thrust if the ambient temperature is dropped by 40K (i.e. 258K)⁶. According to Cumpsty [25], the TIT has been rising by an average of 8 K per year for a given manufacturer, over the past 20 years in the search for more fuel-efficient engines. This value, however, is limited by the materials of the hot section or the cooling technologies which are associated with lengthy and costly development times. The TIT reductions seen by compressor water injection offer interesting possibilities for existing engines in terms of creep life extension and possibly engine sizing for future engine and airframe. The former is particularly important as 36% of the life of a gas turbine is consumed during the take-off phase which only represents 1.6% of the on-time of the engine [22]. Cooling the flow during this critical phase will have considerable implications on life extension and maintenance cost savings [26]⁷.

⁶ The engines in Turbomatch were modelled using this approach. The ambient temperature was reduced until the compressor discharge temperature matched that calculated by the evaporative model at the same thrust. Then the correlations presented in the [appendix](#) were applied to account for gas properties changes.

⁷ A thesis outlining the potentials in life extension due to water injection, is presented by Ref. 26 in conjunction with this research.

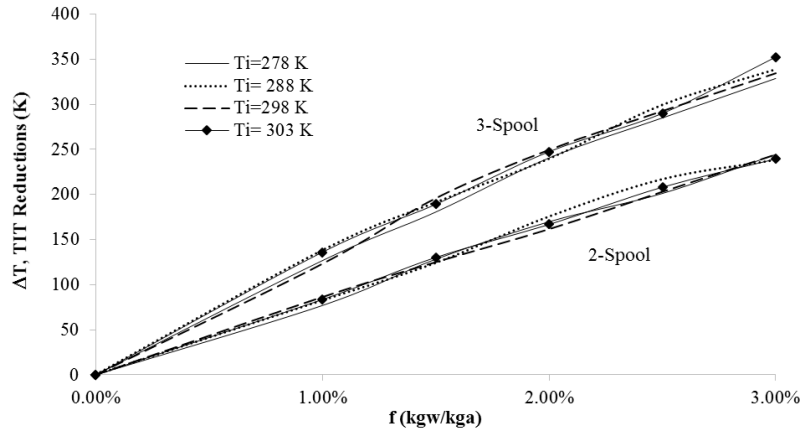


Figure 7 TIT drop versus injection ratio at different ambient temperatures and 30% RH.

4- Emission Reductions

It is well known that combustion NO_x emissions are dependent on flame temperature [4] OPR [27] and humidity [28]. Marchionna [28] proposed correlations to correct NO_x measurements to account for the presence of humidity. These correlations were later adopted by ICAO [7] and NEPAIR [27] as the industry standard for corrections. The need to account for pressure corrections is also well known and estimated to be in proportion to the OPR elevated to an exponent, n , with a value ranging between 0.4 - 0.8 depending on the combustion chamber design [4]. The methodology implemented in this study is that proposed by NEPAIR [27] and ICAO [29].

$$E\text{INO}_x_{\text{corrected}} = \frac{E\text{INO}_x}{\left(\frac{P_{\text{ref}}}{P}\right)^{0.5} * e^{(19*(w-w_{\text{ref}}))}} \quad (1)$$

The ICAO Engine Emissions Data Bank [2] consists of $E\text{INO}_x$ values related to the corresponding LTO power settings (7% for idle, 30% for approach, 85% for the climb and 100% for take-off). As such, the same power settings were simulated in TURBOMATCH, thereby using the obtained corresponding CDT or combustor inlet temperature to match the $E\text{INO}_x$. The CDT can be related to $E\text{INO}_x$ for water injection, and further to this, changes in pressure ratio and water vapour content were accounted for by applying Equ 1, leading to the final relationship shown in Figure 8 for the corrected $E\text{INO}_x$. This figure shows a close estimation in comparison to the ICAO data.

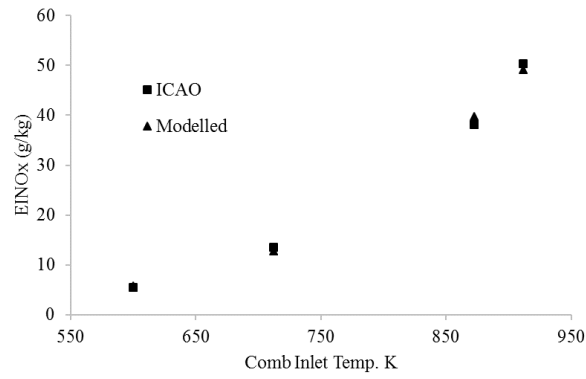


Figure 8 EINO_x versus Combustor Inlet Temperature - comparison between ICAO EEDB and the calculated value

Figure 9 and Figure 10 show the reductions in NO_x with injection ratio increase, focusing on the influence of ambient temperature and droplet size. The influence of ambient temperature is clearly shown to be negligible for these temperatures that bring about promising potentials for lower temperatures than initially thought. The reduction of NO_x is 49-54% (depending on the droplet diameter) at 2% injection ratio for the 2-spool engine. This compares well with Daggett [30] for the same engine design type that reports 47% reduction using a similar methodology at 2.2% injection ratio. Consistent with the other findings, the 3-spool engine promises better reductions as shown. The influence of droplet size for the same injection ratio shows to be more beneficial with smaller droplets as a result of the better mass flow augmentation obtained (as shown in Figure 4) from the more effective cooling explained in [Part 1](#).

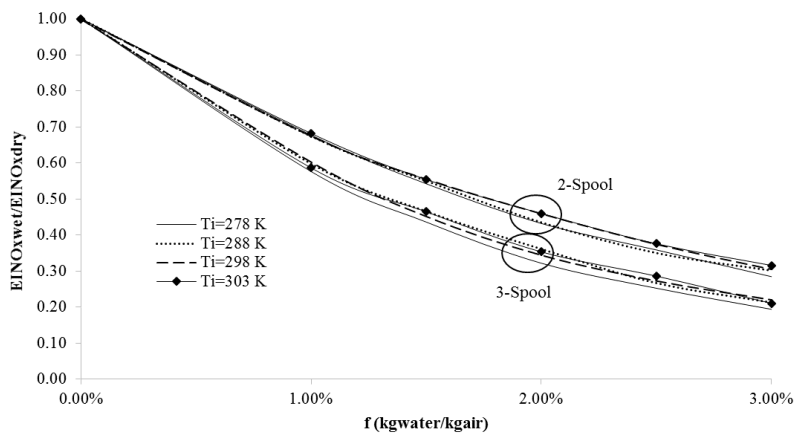


Figure 9 Effect of ambient temperature on Take-Off EINO_x for different injection ratios

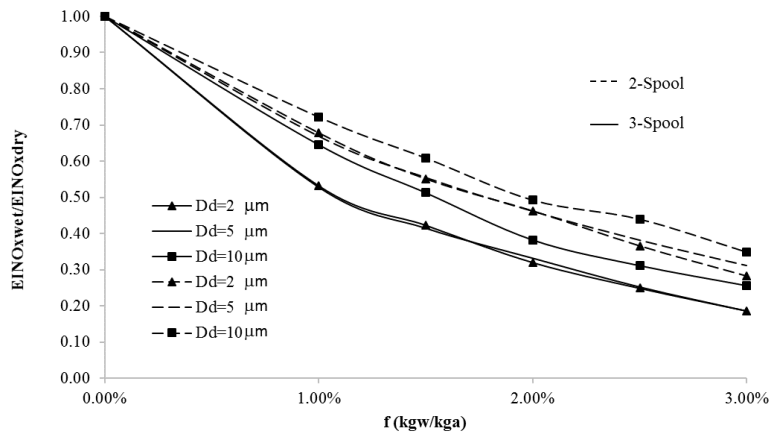


Figure 10 Effect of droplet size on Take-Off $EINO_x$ for different injection ratios

These NO_x savings can be considerable for both, an airport and an airline. A 2-spool engine such as the CFM56-5B quoted earlier, will produce 5.45 kg of NO_x , per take-off and climb to 3,000 ft. [2]. Which means an aircraft with this engine will pay Heathrow airport an environmental fee around £168 per cycle for a 2-engine aircraft based on charges published in [8]. The same case for a 3- spool engine would mean 14.99 kg of NO_x per engine, which would represent a charge of £462 per cycle (considering the 2017 charges), also for a 2-engine aircraft. Such a system applied to the core flow and behind the fan could cut these charges in 50-60%. Equally, an airport like Heathrow, which at the time of writing exceeds the annual average levels of $40\mu g/m^3$ of NO_x imposed by the European Union, could greatly benefit from this. With the same simplification, this can amount almost 3,000 kg less NO_x (if every engine taking-off from Heathrow airport was powered by a CFM-56 type 2-spool engine), improving the air quality of the surrounding neighbourhoods. In terms of regulations, if the reductions seen in Figure 9 are applied to two typical engine configurations analysed, for the 2 and 3-spool engines, LTO NO_x emissions can be cut by 42 and 51% respectively. This can be plotted against the ICAO regulations, set by the CAEP[7] meetings, as shown in Figure 11. The figure shows how the Trent1000G engine (certified in 2011), has to comply with the CAEP/8 (2014) regulations. Implementing water injection would make this engine comply with the long-term goal 2026 of ICAO. In order to reduce NO_x emissions in high-pressure ratio (and thus, high temperature) engines, manufacturers have to invest a lot of time in redesigning the combustion chamber to create staged, lean or quenched combustion. The NO_x reductions by water injection, however, can be achieved without a combustion chamber re-design, and at a lower development and manufacturing cost. The CFM56-5B engine (Certified in 1995) complies with CAEP/6 but not with CAEP/8. Water Injection would not only make this engine comply with the latest regulation but would also achieve the mid-term ICAO goals. [Appendix C](#) presents a summary of all the performance parameters

and emissions corresponding to both engines with different water injection ratios and for two droplet diameters.

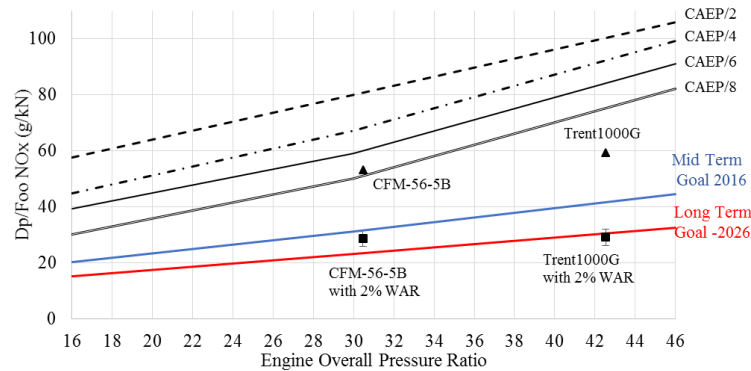


Figure 11 2 and 3-spool engine NOx reductions plotted against CAEP regulations and goal

5- Conclusions

This study has explored aero engine compressor cooling by water injection indicating the potential benefits when the droplet atomisation is implemented behind the fan. The clear benefits for constant thrust operations are as follows:

- Reduction in the fuel flow, hence SFC as much as 5.3% and 7.8% for the 2 and 3-spool engines at 2% injection ratio with 5 μ m, during take-off operations
- Decrease in NOx emissions by 63% and 54% for both engines respectively at mentioned injection ratio and droplet size
- Drop in TIT by 247 K and 167 K respectively
- Further improved benefits in performance and emissions when the injection ratio is increased to 3%
- Better performance when using relatively smaller droplets with the higher surface area-to-volume ratio.

Nevertheless, the difference between the benefits in SFC and NO_x reductions alongside a drop in TIT for 5 and 10 μ m makes the latter worth considering due to practical reasons associated with generating fine droplets. For the 3-spool engine using 10 μ m at 2% injection ratio, these reductions are 4.5%, 56%, and 198 K respectively. The 2-spool engine shows comparable similarity with regards to these two droplet sizes. Further details are provided in [Appendix C](#).

Both engines significantly benefit from water injection, nevertheless, the 3-spool engine has an advantage over the 2-spool engine that has been attributed to the higher operating temperature and mass flow. The influence of ambient temperature is generally small when 5 μ m droplet is considered as shown.

These findings indicate the promise of this technology that can be fitted to existing engines with relatively small adaptations in the current infrastructure when compared to other concepts focused on mitigating emissions. This can bring about a tangible and realistic reduction in the environmental footprint of airports if deployed by airlines in good numbers, apart from the direct benefit it offers to the airline in terms of fuel cost reduction and creep life extension of turbine blades. The actual reductions in fuel utilised for the same net thrust bring about a direct reduction in CO₂ emissions, expected to be in the same order of magnitude of fuel flow reductions.

Acknowledgments

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Nomenclature

CO ₂	Carbon Dioxide	m	air mass flow
CDT	Compressor Discharge Temperature	NO	Nitrogen Oxide
CFD	Computational Fluid Dynamics	NO _x	Nitrogen Oxides
C _p	Specific Heat (J/kgK)	PR	Pressure Ratio
EEDB	Engine Emissions Data Bank	r	Pressure Ratio
EINO _x	Emission Index of NO _x	SD	Short Duct
γ	specific heat ratio	SFC	Specific Fuel Consumption
η	efficiency	SRIA	Strategic Research and Innovation Agenda
HBPR	High By-Pass Ratio	TIT	Turbine Inlet Temperature
ICAO	International Civil Aviation Organization	C _w	Specific Compressor Work
IPC	Intermediate Pressure Compressor	LPC	Low-Pressure Compressor
LD	Long Duct	LTO	Landing and Take-off Cycle

Appendix A - Comparison against other studies

Seven publications are compared to the findings of this article for different engine configurations and different techniques for water injection simulation. The references are listed chronologically from Sexton et al. (1998) to the release of this study

Table A 1 Comparison Between this study and open-literature

	Water to Air ratio (f)	Droplet Dia (μm)	Technique	CDT	TIT	Power/ Thrust	Efficiency	NOx	Mair	Engine Config
Sexton et al.	2.5%	10.0	Analytical	-15.0%	-	34.0%	8.8%	-25% (f=0.45%)	5.0%	1-Spool
Utamura et al.	2.3%	-	Experimental/ Analytical	5% (f=0.5%)	-	23.0%	2.8%	-	-	1-Spool
Dagget. Et al.	2.2%	-	Analytical	-14.0%	-14.0%	Constant	3.5%	-47.0%	-	2-spool
Sanaye et al.	2.0%	20.0	Analytical/ CFD	-19.0%	unchanged	18.0%			5.0%	1-Spool
Sun et al.	2.0%	5.0	3D Throughflow	-7.7%	-7.7%	11.4%	3.5%	-60.0%	8.0%	1-Spool
Favroskii et al.	1.5%	-	Experimental/ Analytical	-	-	const/+ 18%	-	-	3.2%	-
Luo et al.	2.0%	5.0	CFD	-17.0%	-	-	-	-	4.0%	1-Spool
This study 2-s	2.0%	5.0	Analytical	-13.0%	-10.0%	Const. Thrust	5.2%	-55.0%	6.5%	2-spool
This study 3-s	2.0%	5.0	Analytical	-14.0%	-13.0%	Const. Thrust	7.7%	-65.0%	7.8%	3-spool

Appendix B - Humidity Corrections

As an alternative to re-calculating the gas properties to account for humidity, correlations were derived similarly to those found in Ref. [31] for each engine model to correct the results for the “dry” engine, and account for the presence of humidity. This was done because although the evaporative model was coupled to the performance software to modify the compressor discharge temperature, the latter doesn’t have a module to specify the absolute humidity at the exit of the compressor. To derive the correlations, the engine model was run under the same conditions but for varying inlet relative humidity. The performance was then correlated to the water-to-air content of the air. These correlations (Equations B.1- B.8) were then applied to the “dry” engine output parameters to account for the varying gas properties leading to the “Corrected with correlations”. These two curves correspond to “Corrected with correlations” and “Modified Gas Properties” on Fig.B1. The values corrected by means of the Agard correlations in Ref. [31] are also shown for comparison. On Fig.B1, only the mass flow was plotted by means of Eq.(B.a). Note that the changes are very small, and the errors even at high humidity or water vapour are below 0.25% for the Agard correlation.

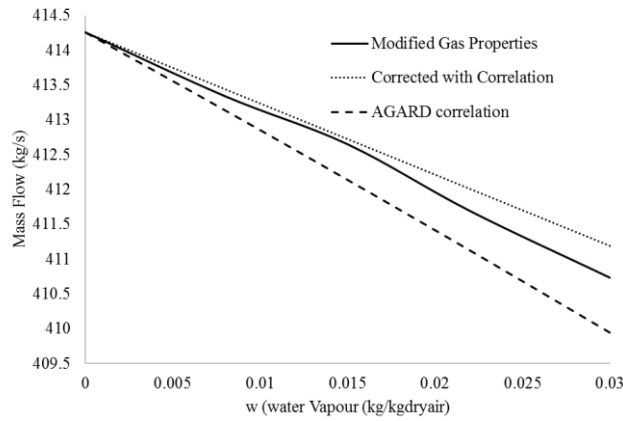


Figure B 1 Mass Flow Corrections for Humidity

Curves like Fig. B1 were developed for each performance parameter (and engine); correlations were made to adjust the dry values for those with an increased level of water vapour.

2- Spool engine at Constant Thrust:

$$M_a' = M_{aDRY} * (1 - 0.247 * w) \quad (B.1)$$

$$OPR' = OPR_{DRY} * (1 - 0.390 * w) \quad (B.2)$$

$$TIT' = TIT_{DRY} * (1 - 0.240 * w) \quad (B.3)$$

$$SFC' = SFC_{DRY} * (1 + 0.568 * w) \quad (B.4)$$

3- Spool engine at Constant Thrust

$$M_a' = M_{aDRY} * (0.311 * w^2 - 0.294 * w + 1) \quad (B.5)$$

$$OPR' = OPR_{DRY} * (0.856 * w^2 - 0.535 * w + 1) \quad (B.6)$$

$$TIT' = TIT_{DRY} * (0.780 * w^2 - 0.461 * w + 1) \quad (B.7)$$

$$SFC' = SFC_{DRY} * (-0.237 * w^2 + 0.555 * w + 1) \quad (B.8)$$

Appendix C – Summary of Results

A summary of all the performance parameters for both engines is presented below. The results include water injection with 5 and 10 μ m droplets and with 1, 2 and 3% water-to-air ratio.

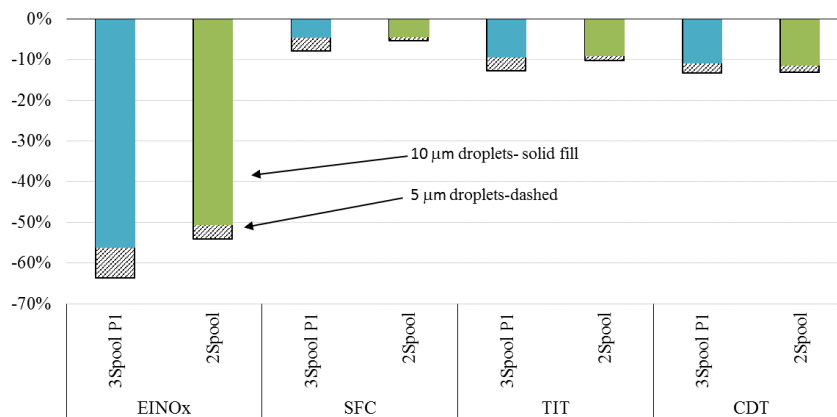


Figure C 1 EINOx, SFC, TIT, CDT reductions for 2% injection ratio at two droplet diameters (298K, 30% RH)

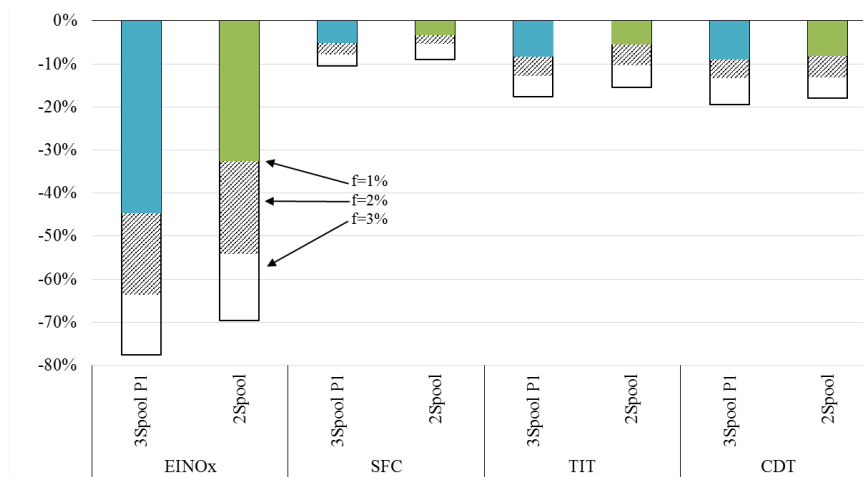


Figure C 2 EINOx, SFC, TIT, CDT reductions for 5 μ m droplets and 1,2,3% injection ratio (298K, 30% RH)

References

1. Heathrow Airport Limited. Heathrow Airport Facts and Figures. 2017. Available at: <http://www.heathrow.com/company/company-news-and-information/company-information/facts-and-figures> (Accessed: 7 August 2017)
2. ICAO. ICAO Engine Exhaust Emissions Data Bank. 2013. Available at: <https://www.easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank#6>
3. Heathrow Airport Limited. Heathrow Air Quality Strategy Report 2011-2020. 2011.
4. Lefebvre AH., Dilip RB. Gas Turbine Combustion Alternative Fuels and Emissions. 3rd edn. New York: CRC Press; 2010. 560 p.
5. EEA (European Environment Agency). Nitrogen Oxides (NOx) Emissions. 2016. Available at: <http://www.eea.europa.eu/data-and-maps/indicators/eea-32-nitrogen-oxides-nox-emissions-1/assessment.2010-08-19.0140149032-3> (Accessed: 5 July 2016)
6. Advisory Council for Aviation Research and Innovation in Europe A. Strategic Research & Innovation Agenda- Volume 1. 2012.
7. ICAO- International Civil Aviation Organization. 2013 Environmental Report, Aviation and Climate Change. 2013.
8. Heathrow Airport Limited. Heathrow Airport Limited Conditions of Use including Airport Charges from 1 January 2017. 2017.
9. Liu Y., Sun X., Vishal S., Nalianda D., Li Y-G., Wang L. Review of Modern Low Emissions Combustion Technologies for Aero Gas Turbine Engines. Progress in Aerospace Sciences. 2017; 94(2017): 12–15.

10. Grönstedt T., Rolt A., Tantot N., Xisto C., Donnerhack S., Schmitz O., et al. Ultra Low Emission Technology Innovations for Mid-Century Aircraft Turbine Engines. ASME Turbo Expo: Turbomachinery Technical Conference and Exposition. 2016. pp. 1–13.
11. Kyprianidis KG., Dahlquist E. On The Trade-off Between Aviation NO_x and Energy Efficiency. Applied Energy. Elsevier Ltd; 2017; 185(x): 1506–1516. Available at: DOI:10.1016/j.apenergy.2015.12.055
12. Schäfer AW., Evans AD., Reynolds TG., Dray L. Costs of Mitigating CO₂ Emissions from Passenger Aircraft. Nature Climate Change. 2016; 6(April). Available at: DOI:10.1038/NCLIMATE2865
13. Sun L., Zheng Q., Li Y., Luo M., Wang J., Bhargava RK. Numerical Through Flow Simulation of a Gas Turbine Engine With Wet Compression. ASME Turbo Expo. 2012. pp. 1–13.
14. Sun L., Sun T., Wang Y., Yang W. Numerical Simulation of Pollutant Emission of A Turbojet Engine with Water Injection. ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition GT2016. Seoul; 2016. pp. 1–9.
15. Favorskii ON., Alekseev VB., Zalkind VI., Zeigarnik YA., Ivanov PP., Marinichev D V., et al. Experimentally Studying TV3 117 Gas Turbine Unit Characteristics at Superheated Water Injection into a Compressor. 2014; 61(5): 376–384. Available at: DOI:10.1134/S0040601514050024
16. Utamura M., Takehara I., Horii N., Kuwahara T. A New Gas Turbine Cycle for Economical Power Boosting. The American Society of Mechanical Engineers. 1997; 97-AA-142: 1–10.
17. Sexton MR., Urbach HB., Knauss DT. Evaporative compressor cooling for NO_x Supression and Enhanced Engine Performance for Naval Gas Turbine Propulsion Plants. The American Society of Mechanical Engineers. 1998; 98-GT332: 1–10.
18. Daggett DL. Water Misting and Injection of Commercial Aircraft Engines to Reduce Airport NO_x. 2004.
19. Meacock A. J., White A. J. The Effect of Water Injection on Multispool Gas Turbine Behavior. Journal of Engineering for Gas Turbines and Power. 2006; 128(1): 97. Available at: DOI:10.1115/1.2032432
20. Block Novelo DA., Igie U. Aero Engine Compressor Cooling by Water Injection - Part 1: Compressor Model. Applied Thermal Engineering. 2018;
21. Macmillan WL. Development of a Modular Type Computer Program for the Calculation of Gas Turbine Off Design Performance- Phd. Thesis. Cranfield Institute of Technology; 1974.
22. Igie U., Minervino O. Impact of Inlet Filter Pressure Loss on Single and Two-Spool Gas Turbine Engines for Different Control Modes. Journal of Engineering for Gas Turbines and Power. 2014; 136(9): 091201. Available at:

DOI:10.1115/1.4027216

23. Daly M. Jane's Aero-engines. 2nd edn. IHS (ed.) Janes Information Group; 2015. 449 p.
24. Walsh PP., Fletcher P. Gas Turbine Performance. 2nd edn. Oxford: Blackwell Science; 2004. 646 p.
25. Cumpsty N. Jet Propulsion a Simple Guide to the Aerodynamic and Thermodynamic Design and Performance of Jet Engines. 1st edn. Cambridge: Cambridge University Press; 1997. 279 p.
26. Vallina Torralba M. Life Analysis of Water Injected Commercial Aircraft Engines. Cranfield University; 2018.
27. Norman P., Lister D., Lecht M., Parl K., Penanhoat O., Plaisance C., et al. Development of the technical basis for a New Emissions Parameter covering the whole Aircraft operation: NEPAIR. NEPAIR/WP4/WPR/01. 2003. Available at: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Development+of+the+technical+basis+for+a+New+Emissions+Parameter+covering+the+whole+AIRCRAFT+operation#0>
28. Marchionna NR. Effect of Inlet-Air Humidity on the Formation of Oxides of Nitrogen in a Gas-Turbine Combustor- TMX-68209. Ohio; 1973.
29. ICAO-International Civil Aviation Organisation. Environmental Protection, Annex 16, Volume II Aircraft Engine Emissions. Chicago; 2008.
30. Daggett DL., Ortanderl S., Eames D., Snyder C., Berton J. Water Injection : Disruptive Technology to Reduce Airplane Emissions and Maintenance Costs. SAE Technical Paper Series. 2004; 01(3108).
31. AGARD. Recommended Practices for the Assessment of the Effects of Atmospheric Water Ingestion on the Performance and Operability of Gas Turbine Engines. Neuilly-Sur-Seine; 1995.

VI. Paper 5

Aircraft Models: Narrow and Wide-Body.

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On-Board Compressor Water Injection for Civil Aircraft Emission Reductions: Range Performance with Fuel Burn Analysis

David Alejandro Block Novelo, Uyioghosa Igie and Devaiah Nalianda

School of Aerospace, Transport and Manufacturing, Cranfield University,

Abstract

The performance benefit of compressor water injection for a stand-alone jet engine has been investigated in previous work conducted by the authors, as well as other studies. For the same required thrust, the benefits include reduced specific fuel consumption, turbine inlet temperature and NO_x emissions. The additional weight implication for aircraft (narrow and wide-body type) with their typical engine type (two and three-spool) for the varied range is investigated here. The emphasis of this study is to establish whether the performance benefit restricted to take-off and parts of the climb, offsets the additional weight penalty of the water injection system, onboard the aircraft. An in-house aircraft performance tool has been used and the changes in performance due to water injection are determined by an evaporation model previously developed. This study shows that the shortest range of 4 missions offers small overall fuel savings of 0.42% per flight cycle. The longest mission, in which the injection equipment is carried for longer (though mostly empty water tank), brings about an overall increase in fuel consumed, by about 0.05%. For the same range, the aircraft powered by a three-spool engine shows better performance. However, both aircraft equally benefit from landing and take-off NO_x emission reductions of around 43%. Water Injection is shown to result in similar performance benefits as 25% take-off derate but without the penalties in fuel burn or increased take-off and climb times. Reductions in turbine inlet temperature obtained are worth considerable attention as a means of decreasing the direct operating costs of an airline.

Keywords: NO_x emissions, Aircraft performance, emissions reductions, water injection. Derated take-off

1- Introduction

Rising levels of air pollutants around airports have become more of a concern and it is a direct consequence of higher air traffic influenced by the increased demand of air travel estimated at 5.3% per year [1]. Block and Igie [2] shows that few measures aimed at reducing airport emissions seem to tackle Nitrogen Oxides (NO_x), and most of them are focused on reducing fuel burn and consequently carbon emissions. The latter can be achieved by reducing the on-time of the engines by means of technological or operational

improvements. NO_x reductions, however, are more challenging to tackle as they depend on the temperature and residence time of the gas in the primary combustion zone. During take-off, which is when the highest engine power/thrust is required, NO_x emissions will peak. To limit this, the combustion temperature needs to be lowered. One approach to this is redesigning the combustion chamber to reduce the residence time or the temperature of the combustion process. Modern aero-engines with higher pressure ratios (PR) and Turbine Inlet Temperatures (TIT) give rise to more NO_x emissions. However, advances in combustion chamber design have managed to keep the Emission Indices (EI) within acceptable levels. For instance, staged combustion offers around a 40-50% reduction in NO_x , compared to conventional burners, and Rich-Burn Quick-Quench Lean combustors offer improvements in the range of 50-60% [3,4]. Liu et al. [3] is a comprehensive overview of modern combustion chamber designs, their improvements in NO_x and their development challenges.

Nevertheless, regulations on aero-engine pollutants are becoming more stringent. The sole focus on combustion chamber design improvement is not likely to be sufficient to comply with ICAO long-term emission targets of 60% NO_x emissions reductions by 2026 (compared to 2004)[1]. ICAO forecasts that to keep aircraft emissions within acceptable levels, technological, operational and regulatory improvements, all need to occur simultaneously to counteract the growth of the civil aircraft fleet [1]. Reduced thrust take-off is an operational measure which can also lead to improved take-off NO_x emissions. It has been shown that reducing the take-off thrust can lead to reductions of NO_x emissions estimated at 31%, compared to full thrust take-off [5,6]. Other studies [7,8] suggest reductions of 0.7% NO_x for every 1% of derate, meaning the highest reductions achievable, corresponding to 25% derate (maximum reduction allowed by authorities) would be 17.5%. However, this can come with a fuel burn penalty due to longer take-off and climb times, and it is restricted by the runway length and environmental conditions [6]. An alternative solution analysed here is aimed at reducing emissions by cooling the core flow of the engine by means of injecting atomized water droplets into the intermediate pressure compressor (IPC) of the engine. The thermodynamics of compressor performance with water injection has been studied by Refs.[9–11]. Refs. [12–15] offer analytical and experimental performance studies of single-spool gas turbines. However, to the knowledge of the authors, only one group of study incorporates this to aircraft performance. These papers [16,17] analyse a system for a Boeing 747, flying one mission under one ambient condition. The study concludes that misting the compressor with water could lead to NO_x reductions of up to 47%, and this is compared to combustion chamber water injection that offers a greater reduction in NO_x but with a penalty in fuel burn. The aircraft studied in the report represents only 1% of the wide-bodied aircraft (WBA) order backlog as can be observed from Ref [18] for a B747. Based

on the fleet and aircraft demand presented on the airliner census [18], operators seem to prefer 2-engine aircraft due to their lower operating cost. The research presented here expands the investigation into two different types of aircraft, both with twin-engines. Also, the influence of range is taken into account by considering missions ranging from 500 to 11,000 km. The narrow-bodied aircraft (NBA) studied here is representative of around 90% of the narrow-body order backlog and used for the short-haul mission (SHM) and medium-haul mission (MHM). The WBA investigated is applicable to long-haul missions (LHM) and MHM, and is representative of nearly 30% of the order backlog for the WBA type aircraft. It is important to highlight that the mode of engine control considered in this study is to keep the required thrust during water injection the same as in the dry case. As such, the potential thrust augmentation does not occur. In another approach which can involve a constant TIT, the fuel flow is expected to rise to maintain the same TIT. As such, higher pressure ratios occur, the Specific Fuel Consumption (SFC) is also reduced as relatively less fuel is used to generate the higher thrust. As TIT is unchanged, the NO_x is expected to remain approximately constant. This approach is not considered here as it does not offer a reduction in NO_x and brings about an increase in the absolute value of fuel used, leading to more CO_2 .

2- Methodology

2.1 Aircraft Performance

The aircraft performance tool implemented here is *Hermes*, a Cranfield University in-house code. The calculation of aircraft performance is based on the Total Energy Model methodology for aircraft performance[19,20]. The inputs for the program are the geometry of the aircraft (airframe length and diameter; span, thickness to chord ratio and aspect ratio of the wings and high lift devices configuration), the weight, and the mission specifications. The mission profile is calculated based on defined speeds and altitudes. It solves Newton's second law of motion for the aircraft, equating the propulsive force to the drag (estimated based on the given geometry) and the acceleration. The lift force (calculated from wing geometry) is equated to the weight (airframe, engines, payload, and fuel). *Hermes* runs the engine performance tool, *Turbomatch* to calculate the thrust required at each segment, and thus the SFC of the engines and total fuel consumption for the mission. The simplified forces of the aircraft at any flight segments are represented in Figure 1.

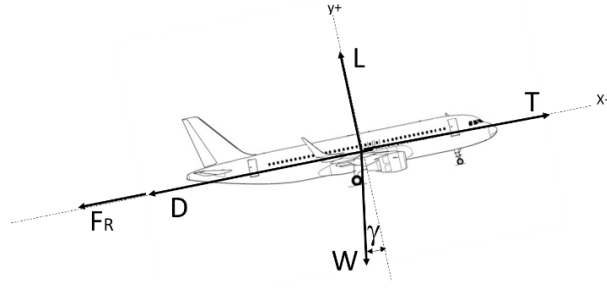


Figure 1 Forces on an Aircraft

Solving the forces on the free body diagram of Figure 1, two equations can be derived,

$$\Sigma F_x = T - D - F_R - W \sin \gamma = m \left(\frac{dv_x}{dt} \right) \quad (1)$$

$$\Sigma F_y = L - W \cos \gamma = m \left(\frac{dv_y}{dt} \right) \quad (2)$$

T: Is the total aircraft thrust and represents the thrust per engine, multiplied by the number of engines, $T = F_n * n$. This thrust is calculated by an integrated engine performance simulation code: *Turbomatch* by varying the TIT or fuel flow for the different off-design points at which the engine is operating, to satisfy Eq. (1). The thrust value will be maximum at take-off and climb, and minimum at idling and descend. For the cruise condition, the simulations show that cruise thrust is between 15 to 20% of the maximum static take-off thrust value.

D: is the aerodynamic drag and is calculated by adding the zero-lift and lift-induced drag coefficients of each flying element, as explained in Ref. [21]. *Hermes* considers skin friction, interference drag, and profile drag. All the previous is calculated by means of the input geometric parameters and flight conditions. The drag term will always be present as long as the aircraft is moving.

FR: is the rolling friction coefficient and can be computed by multiplying the rolling resistance μ_R , by the aircraft reaction R . When the aircraft is on the ground the reaction to the weight is the weight itself (W), so $R = W$ and thus $F_R = \mu_R W$. The rolling resistance μ_R is 0.02 on a paved runway; other values for μ_R can be found in Ref.[20]. Once the wheels leave the ground, this term becomes zero, since the ground reaction gets substituted entirely by the lift force.

W siny: In Figure 2, the axis has been tilted to be aligned with the aircraft trajectory. The aircraft's weight thus has an angle γ with respect to the ground known as climb gradient. When the aircraft is in cruise or taxiing, γ is zero and this term disappears. The climb

gradient can also be defined by the ratio of vertical to horizontal speeds where dh is the change in altitude,

$$\sin \gamma = \frac{\left(\frac{dh}{dt}\right)}{V_x} \quad (3)$$

$m \left(\frac{dv_x}{dt}\right)$: is the acceleration term only relevant while the aircraft changes its speed during the take-off roll or descend. During cruise, this term is zero along with $\sin \gamma$ and F_R so that the only two forces in the horizontal plane (x) are the thrust and the drag.

L: Is the lift force, calculated from the geometric parameters of the wings and the defined flight velocities. The lift is dependent on the lift coefficient of the wings, the density of the air, the area of the wings and the flight speed. The aerodynamic efficiency of the lifting surfaces will be evaluated by the lift to drag ratio C_L/C_D .

W cos γ : is the weight component on the vertical axis, for cruise condition or when the aircraft is rolling on the runway, γ is zero, so $W \cos \gamma$ becomes simply W , and the lift force (or ground reaction if the aircraft is on the ground) equals the weight of the aircraft.

$m \left(\frac{dv_y}{dt}\right)$: This term defines the vertical acceleration of the aircraft. Usually the aircraft will climb at a constant rate, so the variation of vertical speed with time is very small or zero.

The general case of equations (1) and (2) can define any of the 6 defined flight phases [20]:

- Start-up and Taxi out
- Take- Off and initial climb to 3,000 ft.⁸
- Climb from 3,000 ft. to cruise altitude
- Cruise at selected speed and altitude
- Descend to 3,000 ft.
- Taxi-in.

Based on Eqs. (1) and (2), *Hermes* iteratively calculates the aircraft performance for a given range or fuel capacity, by performing aerodynamic calculations while using appropriate values of thrust for the corresponding engines. Further details of this methodology can be found in Refs.[19,22,23]. Igie et al. [16] highlights the different modules of *Hermes*, showing their interactions, with details of the calculation procedures.

⁸ Normally initial climb is taken to an altitude of 1,500 ft. but in this analysis 3,000 ft. is considered as water is injected from 0-3,000 ft.

2.2 Aircraft Selection and Specification

The NBA chosen and modelled was based on the design of the Airbus A320-200 (CEO) and applicable to SHM and MHM, while the WBA applicable to the MHM and LHM was simulated based on the Boeing 787-9. To date, the A320 is the most common aircraft in the world, and hence the selection. The A320 design has undergone improvements over the years but still represents a modified version of an aircraft which was first flown in 1987. On the other hand, the B787 represents more design modifications: 50% of its weight is from composite materials [24]. It also comprises more flexible and thinner wings at the tip and new engines with higher by-pass and pressure ratios. All of these combined makes the 787 up to 20% more fuel efficient than its predecessor. Double floor airliners like the Airbus A380 or the Boeing 747 were not considered, as they only represent 5% and 1% respectively, of the WBA order backlog, in contrast to the 28% that the Boeing 787 represents [18]. The information to model both aircraft is summarized in Table 1 and was obtained from official documents and reports [25–29]. The payload-range diagram for the NBA was obtained and compared to published data for an A320-200 weight variant 15 with no extra central tanks [27].

Table 1 Aircraft specification and limit requirements

	NBA (A320-200)	WBA (787-9)	Source
Fuselage Length (m)	37.57	62.8	[28]
Wing Span (m)	34.09	60.12	[28]
Empty Weight (kg)	42,200	128,850	[27][29]
MTOW (kg)	78,000	254,011	[27][29]
Max Payload (kg)	20,400	52,587	[27][29]
Max Fuel (kg)	18,729	101,456	[27][29]
Ferry Range (km)	6,667	17,223	[27][29]
Max PL Range (km)	3,815	9,722	[27][29]
Max Passengers	180	381	[27][29]
Order Backlog Share	44% narrow-body	28% wide-body	[18]
Engines	CFM-56-5B	Trent 1000-G	[28]
First Flight	1987	2009	[28]

The validation is achieved by means of Figure 2 where the performance of the aircraft under different payloads is evaluated. The numbers represent the relative error between the modelled aircraft and the source. This shows a maximum error of about 3.6% overestimation at 20,400 kg, which is the maximum payload. The main implication of this is on the fuel estimation, however, does not have a significant influence when comparing the wet and dry cases, where deltas and percentage changes are of interest.

Similarly, the model for the WBA was developed and compared to a Boeing 787-9. The differences were of similar magnitude as follows: 5.2% at point B, -2.1% at point C and -6.9% at point D.

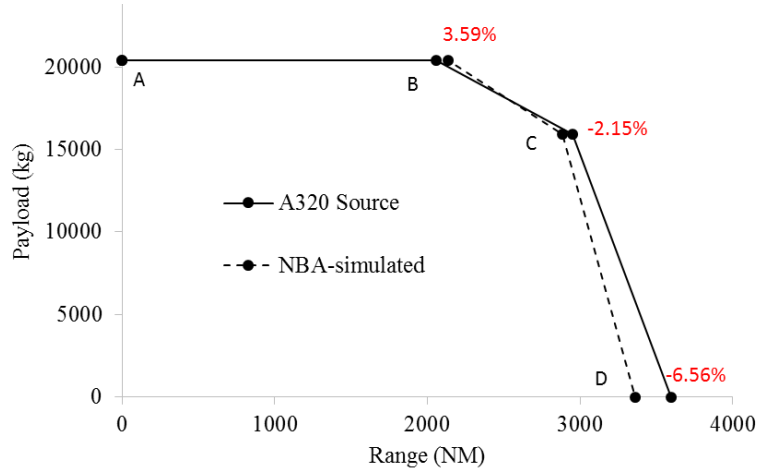


Figure 2 Payload-Range Diagram for NBA

2.3 Added Weight due to the Water Injection System:

An estimation of the water injection system's weight was subsequently calculated and added to the original aircraft weight. A system design was developed based on the assumptions found in Daggett [17]. The study indicates a detailed analysis of water injection design for a Boeing 747-400ER. The weight of the pipes and tanks in the present study were scaled based on the required water volume and the wingspan of each aircraft. It was initially assumed that the amount of required water was 2% of the core air mass flow at full thrust, applied for 2.9 minutes (0.7 for take-off and 2.2 minutes for the initial climb) according to ICAO EEEDB [31]. This is a conservative assumption as the thrust for take-off and climb will be below the maximum take-off thrust. As such, the air mass flows are actually lower. In absolute terms, the amount of water will be also lower when using the water-to-air ratio relationship. According to Ref. [31], the climb segment occurs at 85% of the maximum thrust. For the case of the NBA, the initial calculation showed that 500 kg of water were needed to cool the engine during take-off and early climb. However, when the simulations were performed on *Hermes* for the aircraft operation, it was shown that this value is, in fact, closer to 300 kg. The lower value is a consequence of the thrust of the engine being below 100% for the segments going from 0-3,000 ft. Regardless of this, the water weight on the simulations was kept constant and assumed to be 500 kg to keep the estimations conservative (allowing for an additional 200 kg of equipment). The weights of the pumps were calculated by analysing the specifications of fuel pumps for different aircraft [32]. The final weight breakdown is given in Table 2, where the original system for the B747 is compared.

Table 2 Water Injection system weight

	Original System 747 [17]	System for NBA	System for WBA
No. of engines	4	2	2
Pump (per engine) (kg)	12.47	10	14
Tanks and mounts (kg)	79.38	26.27	42.69
Valves, wires, tubes(kg)	151.95	69.74	93.49
Hydraulic accessories*(kg)	25.40	25.40	25.40
System weight - empty (kg)	306.63	141.41	189.58
Water, Max (kg)	1514.16	501.12	814.32
Total Extra Weight (kg)	1820.79	642.53	1003.9

* Includes, distribution valves, manifold, water mixers, flow meters, pressure gauges etc.

The weight of the empty tank system is added to both aircraft in the form of extra payload for simulation purposes. It is assumed that at the beginning of the take-off roll, the system is full of water and thus the weight increase will be 642 kg and 1,003 kg respectively for the NBA and WBA. The water will be consumed during take-off and climb, up to 3,000 ft. As the gradual/momentary reduction in weight due to the water being consumed cannot be simulated in *Hermes*, it is assumed that from 0-3,000 ft., the aircraft carries the full weight of the system (plus the water). From 3,000 ft. onwards, only the weight of the empty system is accounted for. Simulations were done for the take-off roll, with and without the water weight, but considering the system weight. This was done to evaluate the error in assuming that the water is suddenly consumed at 3,000 ft., rather than being gradually used. These did not cause a considerable error when calculating fuel consumption difference between the two cases (0.9% for that segment). The total increase in weight is only 0.99% for the NBA considering the longest mission studied. For the WBA, it is 0.46% for the longest mission. The auxiliary power required to drive the water pumps at the required pressure and flow rates is estimated to be 17 kW per pump for the WBA and 10kW per pump for the NBA. This is assuming a water flow rate equivalent to 2% of the core air mass flow of the engines during take-off, operating at a pressure of 55 Bar as suggested in [17]. The implications of this additional electrical power requirement is not considered in the simulations.

2.4 Performance of Aircraft with Compressor Water Injection

The performance of the aircraft for water injection was calculated by coupling three platforms: the stand-alone compressor evaporative model [33], the stand-alone engine

performance model [34] and the aircraft model introduced in this paper. The simulation procedure for the aircraft with water injection is as follows:

- 1- A baseline mission with the unmodified aircraft is calculated and used as a reference as shown in Figure 3 from left to right of the figure.
- 2- Another identical mission is calculated for the aircraft with the extra system weight.
- 3- The thrust values required, along with the environmental conditions and compressors pressure ratios and efficiencies of step 2 are recorded and used as boundary conditions for subsequent steps (stand-alone engine). This is conducted only for the take-off roll and climb up to 3,000 ft.
- 4- The performance of the stand-alone compressor (with evaporation model - under the same operating conditions as step 3) is calculated assuming water injection at a rate of 2% of the compressors air mass flow with 5 μm droplet size. The compressor discharge temperature (CDT) change is computed using the [methodology](#) found in [33]. This is the boundary condition required for the engine model for water injection in the next step.
- 5- The outcome of step 4 is imposed on the engine model to account for water injection and the performance of the water injected engine is computed using *Turbomatch*, following the [methodology](#) found in [34]. This is also achieved keeping the thrust consistent with step 2 and 3.
- 6- The difference in performance between the “dry” and the “water injected” engine is recorded and applied to step 2.

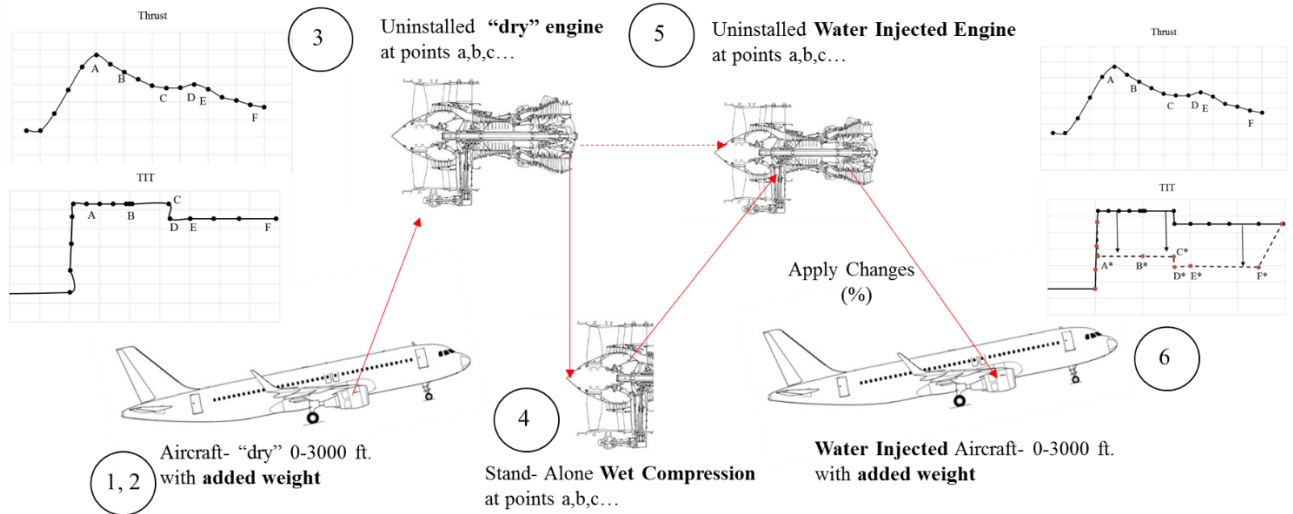


Figure 3 Simulation procedure for the aircraft with water injection

Further information about the compressor and the engine models can be found in Refs. [33,34], that consist of the same conditions of water injection investigated here. Details of the engines design and off-design points and their comparison against available data for similar engines can be found in [Appendix A](#).

2.5 Emission Modelling- Landing and Take-Off Cycle.

The primary aim of water injection at the start of the investigation from the previous works [33,34] has been to reduce NO_x emissions. These emissions reductions and associated fuel savings are obtained only during take-off and early climb. In this section, the attention is on the Landing and Take-Off (LTO) Cycle that focuses on the emissions around the proximity of an airport. Correlations of emission indices of NO_x to combustor inlet temperature were created based on the experimental results published by ICAO [31] and following the [methodology](#) found in Refs. [35,36]. For the 2-spool engine installed on the NBA and based on the CFM56-5B engine:

$$EINO_{x,calc} = 0.000175 * Tb^2 - 0.14809 * Tb + 35.09184 \quad (4)$$

That of the 3-spool engine installed on the WBA, based on Trent 1000-G engine is:

$$EINO_{x,calc} = 0.00039 * Tb^2 - 0.43532 * Tb + 126.99 \quad (5)$$

Where, Tb is the combustor inlet temperature, which was obtained from simulating the engines performance at 7%, 30%, 85% and 100% of the maximum take-off thrust, corresponding to the four power settings defined in the ICAO EEEDB [31]. The correlations were then validated for both engines against the published data of Ref. [31] as shown in Figure 4.

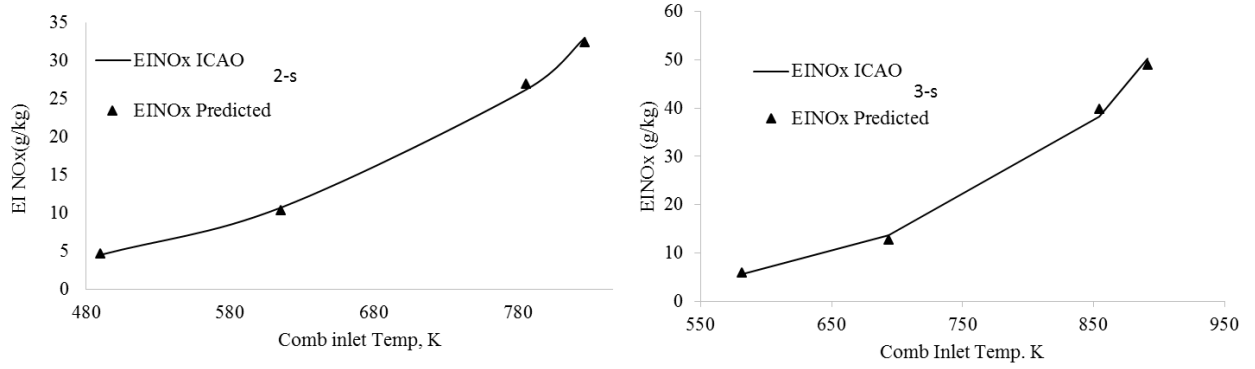


Figure 4 Prediction of NO_x for the 2-spool (left) and 3-Spool engine (right)

Unlike a stand-alone engine study as in Ref [34] for the aircraft-engine configuration, the Mach number, altitude and thrust levels of the engine will change with time. Equations 4 and 5, can account for the engine operating point changes by adjusting T_b , however, they need correction for the change in humidity and pressure with altitude as shown in Eq. 6 [36].

$$EINOx_{corrected} = EINOx_{calc} * \left(\frac{P_{ref}}{P}\right)^{-0.5} * e^{-(19*(w-w_{ref}))} \quad (6)$$

Here w is the humidity content of the air, defined as the mass of water vapour (in kg) per kilogram of dry air. P_{ref} and w_{ref} are the combustor inlet pressure and ambient specific humidity for the engine running at maximum thrust on ISA sea level conditions of 288 K and 60% RH.

For the water injection conditions, w is the sum of the atmospheric water vapour, plus the injected water. The injected water is constant and for the cases studied, has been defined as 0.02 kg of water per kg of air (2%). The atmospheric absolute humidity is defined by the ambient temperature and relative humidity and it decreases with altitude [35]. A relationship was derived based on the information found in Ref [35] to consider the variation of humidity with altitude up to 3,000 ft. More details of the calculations of the atmospheric humidity can be found in [Appendix B](#).

The total NO_x can be calculated by multiplying the Emission Index (grams of NO_x per kg of fuel) by the fuel used in that segment, mf as indicated in Eq.7. The summation of the different segments, i , will give the total NO_x emissions per flight phase.

$$mNOx(g) = \sum_{i=1}^n (Mf_i) * (EINOx_i) \quad (7)$$

2.6 Missions and Engines Investigated

Five missions have been considered as shown in Table 3. Short and Medium-Haul missions (SHM, MHM) are applicable to the NBA, and Medium and Long-Haul missions (MHM, LHM) are applicable to the WBA. The range classification is based on Eurocontrol; short-haul: airport to airport distance is less than 1,500 km; medium-haul: distance more than 1,500 km but less than 4,000 km; and long-haul, distance is more than 4,000 km [37]. The justification for these missions is to investigate the influence of water injection on mission duration or range. This is of interest as water injection is shown to improve fuel efficiency [14,16,34] but the overall impact of carrying the empty injection system and its implication on mission performance are of interest here. It is also of interest to see if the fuel savings identified in the previous studies [34] offset the expected weight penalty that will be worsened by increased distance. Table 3 indicates the engine models used. These engines are also applicable to the respective aircraft type in actual practice. The referred studies [33,34] shows the impact of water injection on the stand-alone engine and the case applied in this study is that of ISA conditions (288 K, 60% RH).

Table 3 Missions Investigated

Case	Mission	Distance (km)	Aircraft	Engine Model*
1	SHM (e.g. London to Paris)	522	NBA	2-Spool [34]
2	SHM (e.g. London to Barcelona)	1,249	NBA	2- Spool [34]
3	MHM (e.g. London to Beirut)	4,054	NBA	2- Spool [34]
4	MHM (e.g. London to Beirut)	4,054	WBA	3-Spool [34]
5	LHM (e.g. London to Tokyo)	11,349	WBA	3-Spool [34]

3- Results

3.1 Impact of WI on Take-off Performance

The impact of water injection on take-off performance is investigated in this section. Figure 5 shows the net thrust, TIT and the corresponding altitude throughout a complete flight mission. This mission relates to Case 3 of Table 3. This is the baseline aircraft with no water injection with a full payload of 20,400 kg. The highest level of net thrust (134.2 kN) is seen to occur at the beginning of the take-off roll when the aircraft experiences the highest acceleration. As the altitude increases, the net thrust decreases due to the

decreasing air density (along with aerodynamic drag). The climb segment is regulated to a fixed calibrated airspeed (CAS) and climb rate, to keep the noise levels down as in practice. As shown for the climb, the TIT is kept constant, allowing for this decreasing thrust with altitude. The maximum values for the engine operating temperature are restricted in both, the temperature itself, and the duration. When the aircraft reaches the cruising altitude of 10,886 m (35,700 ft.), the net thrust levels are seen to be considerably reduced as the thrust required at this stage is only that needed to overcome the drag, at this segment of the flight the aircraft is not accelerating nor climbing. At descent, the thrust levels are generally lower than any segment of the mission, as the gravity term in Eq. 1 and 2 is now in the direction of travel, and adds to the thrust term. As the aircraft descends in altitude, the air density and thus mass flow into the engine will rise. The latter effect should cause an increase in net thrust that is not observed here due to the reduction in the power setting of the engine by means of fuel flow reductions (and thus TIT). After touchdown, the thrust reverser is deployed to decelerate the aircraft, this is represented by the peak seen just after the 300th minute of the mission.

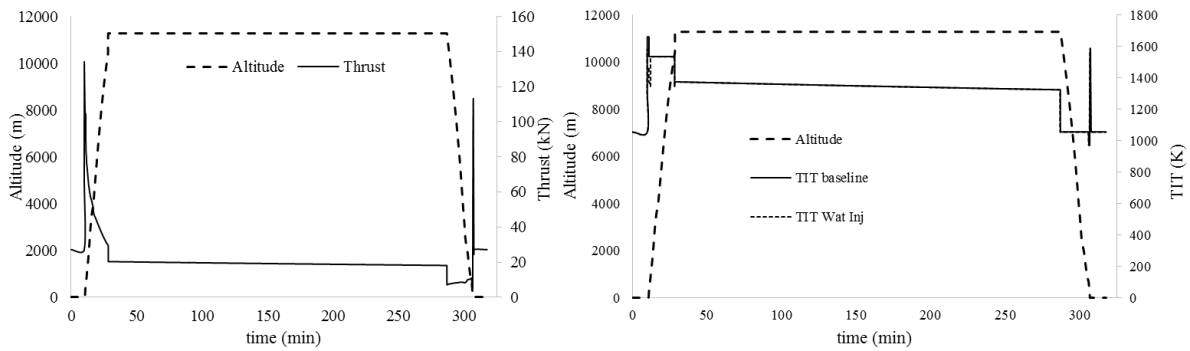


Figure 5 Left: Altitude and Net Thrust vs time. Right: TIT and altitude vs time for complete mission – Case 3

For water injection (applicable to all cases simulated in this study) the baseline net thrust is maintained and so the effects of injecting water will be reflected in a lower engine operating temperature and lower fuel consumption. The calculations involving the water injection case are obtained from the individual point calculations, arising from the specific altitude, ambient condition and the power setting of the baseline case. These individual point calculations are signified on Figure 6 by markers and are obtained as explained in the previous section. Using Eq. 8, the additional fuel flow as an effect of the extra weight can be calculated for [case 3](#). If the aircraft had the extra weight (water + system), but the water system was turned off, during the take-off segment (up to 3,000 ft.) the extra fuel required amounts to 3.5 kg (+1.27%). For the entire mission, this is 24 kg, noting that beyond 3,000 ft., only the system weight without water is the penalty. Hence, the effect of the added weight though small as indicated has been accounted for. Since the “water

injected” aircraft is slightly heavier than the baseline, the take-off and climbing duration is expected to be longer, though observed to be insignificant (this is 2 and 3 seconds for the NBA and WBA, respectively). This marginal increase in time will have a small impact on the fuel utilised, also accounted for. The segment fuel is calculated by means of Eq. 8, which represents the summation of the fuel flow at each segment multiplied by the segment duration. Where M_f is the total fuel weight, FF is the fuel flow and can be obtained by multiplying the SFC by the thrust of each engine, t is the segment time and n is the number of engines.

$$M_f = \sum_{i=1}^n \frac{1}{2} (FF_i + FF_{i+1}) * (t_{i+1} - t_i) * n \quad (8)$$

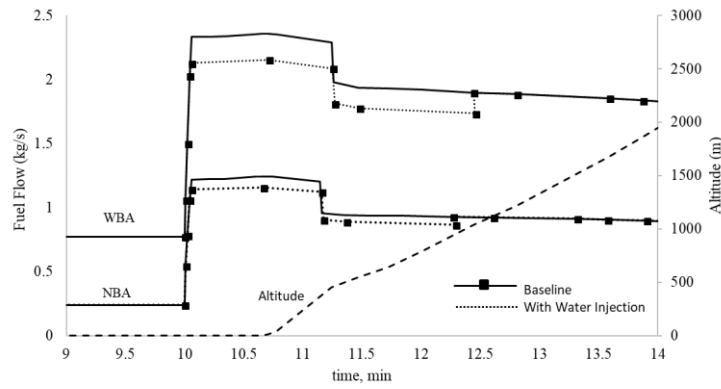


Figure 6 Fuel flow vs time for take-off and initial climb - Case 3 and 4 (NBA and WBA)

Figure 6 indicates the fuel flow during the take-off and early climb segment for Case 3 and 4 applicable to both aircraft. As shown in the figure, when the engine runs at full thrust, the water injection system is turned on, resulting in reduced fuel flow for the segments going from 0 to 1,000 m or just above 3,000 ft. This reduced fuel flow reflects an increase in the thermal efficiency of the power plant for a constant thrust. This has been influenced by a reduction of the specific compressor work by means of the intercooling effect of the evaporating water that increases the air mass flow. Once the aircraft climbs above the regulated emission altitude of 3,000 ft. (after 12 mins, including taxiing) the system is turned off, also assuming all the water is consumed. Figure 6 also indicates that a reduction in fuel flow is higher for the WBA than for the NBA. This higher reduction is due to the different engine architecture found on each aircraft. Block and Igie [34] explains the justification of this, indicating the advantage of WBA engine of three-spool design over the two-spool in the NBA engine, is the higher operating temperature and pressures, overall leading to faster evaporation. As a result of this effect, in absolute terms for the take-off roll, water injection would result in 14.8 kg less of fuel used for the NBA ([Case 3](#)) compared to 48 kg for the WBA (Case 4). The difference in

engine compressor architecture and pressure ratio leads to different temperature reductions when injecting the same water-to-air ratio. This is reflected in the specific compressor work reduction which directly impacts the fuel flow, and is also reflected in the Compressor Discharge Temperature (CDT) as shown subsequently.

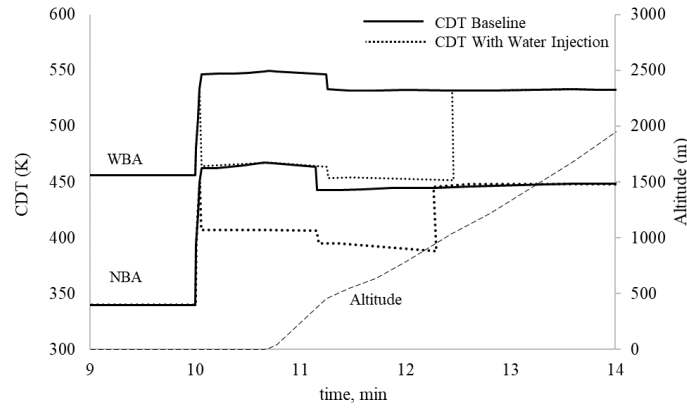


Figure 7 Intermediate CDT for take-off and initial climb - [Case 3](#) and 4 (NBA and WBA)

Figure 7 shows the resulting intermediate CDT due to water injection compared to the baseline case for both aircraft. A drop of 60 K and 82 K is seen for the NBA and WBA respectively. The lower temperature gas delivered into subsequent components of the engine will result in an overall reduced temperature operation. As indicated in Figure 8, the WBA engine has a take-off TIT almost 200 K greater than the NBA engine for baseline operation (due to higher pressure ratios). However, similar to the CDT reductions, the TIT reductions are greater for the WBA than for the NBA. This is a 195 K and 250 K drop in TIT for the NBA and WBA aircraft respectively. These reductions are consistent with Daggett et al. [38] and Sun et al. [14] for engine point calculations. From the figure, it can also be inferred that injecting water into the compressor allows for a larger margin between the operating temperature and the maximum allowable TIT. These improvements suggest that that aircraft will be able to take-off in hot conditions without the need of reducing the payload.

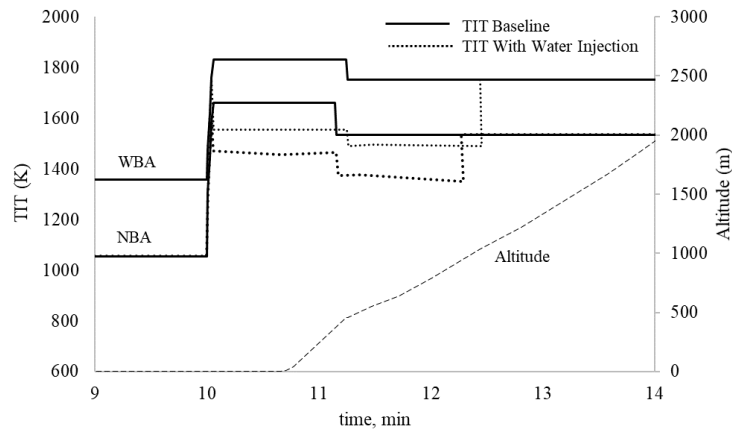


Figure 8 TIT for take-off and initial climb - Case 3 and 4 (NBA and WBA)

3.2 Influence of mission range

The take-off segment fuel savings seen in Figure 6 are counteracted by a fuel penalty derived from carrying the extra weight of the empty water injecting system throughout the rest of the mission. The longer the range of the mission, it is expected that the penalty will increase. The balance between the fuel savings (during take-off and climb) and the fuel penalty is of interest, and all cases indicated in Table 3 are presented here. The fuel changes for each segment of the flight are shown in Figure 9, as well as the total or overall effect, compared to a baseline case that flies the same mission but does not have water injection. The columns in the figure for each [case \(1-5\)](#) represent the fuel changes at each flight segment: 0- 3,000 ft.; 3,000 ft. to cruise; cruise, descend, and finally the combined effect. Similar to previous simulations, the payload is unchanged and the water injecting system is an extra weight to the aircraft baseline take-off weight. This weight is estimated from the sum of the reported aircraft and engine weight [27,29], the maximum payload weight, the water injection system, and the fuel weight. The latter is iteratively calculated by *Hermes* so that only the fuel required for the mission, plus the contingency fuel is considered. From 0 to 3,000 ft., there is a considerable fuel saving in all the cases despite the extra water weight. This reduction in segment fuel is a consequence of the reduced compressor work discussed in earlier sections. The reduction generally increases with mission range as seen; though, for the WBA, its MHM shows a marginally higher reduction than the LHM. [Case 3](#) shows a higher fuel reduction (during take-off) than case 2, and case 2 larger than case 1. This increasing trend has to do with the aircraft taking off heavier, due to more fuel required to complete a longer mission. Since the maximum thrust that the engines can output is the same in all the cases, a heavier aircraft will take longer to take-off and climb. For this reason, water will be injected for a longer period of time, hence the apparent higher fuel reductions seen in case 3 (-5.07%) compared to case 1 (-4.43%).

Beyond 3,000 ft. to maximum climb or start of cruise, it can be seen that there is a fuel penalty. This increases gradually with range from case 1 to case 3 (for the NBA) due to an increase in the duration of this segment with an increase in range. Case 2 to 5 reflects an increase in cruise duration leading to an increase in the penalty of fuel flow. In case 1 there is a reduction in cruise fuel flow. This apparent reduction is a consequence of a slightly longer take-off time (due to the extra weight), which means that the cruising time in this mission is shorter than the baseline. Since other missions have longer cruising times, this effect of reduced cruise time is only perceivable on the shortest mission. The overall impact is depicted in the last column of each case, and observed to be most favourable for the shortest duration – case 1 with 0.42% reduction in fuel, and the worse for case 3, which is slightly penalized with 0.04% increase in fuel. When comparing the same range as case 3 and 4 applicable to the 2 and 3-spool or NBA or WBA respectively, the latter outperforms. This is attributed to the better efficiency of the engine as discussed in Ref [34]. Cases 4 and 5 applicable to the WBA also highlights the favourability of shorter range with regards to the impacts of water injection. The penalty during the cruise for the WBA ([Cases 4 & 5](#)) is seen to be small, since this is a heavier aircraft and the proportion of the water injection system weight, compared to the aircraft weight is much smaller (0.1% of the Take-Off Weight) than what was seen for the NBA.

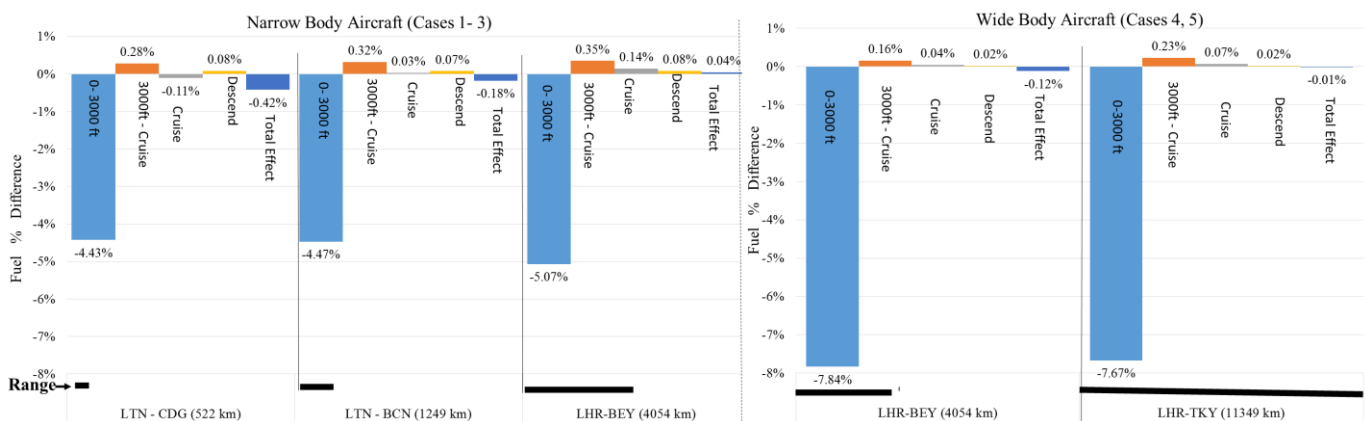


Figure 9 Impact of water injection additional weight on the range fuel flow per flight segment and overall mission

Table 4 shows the baseline and water injection total mission fuel burn for each case. The Carbon Dioxide (CO₂) emissions are also displayed by assuming that 1 kg of kerosene generates 3.16 kg of CO₂ [39]. Case 2 approximates to the average sector length of most European low-cost airlines. For this case, 29 kg of CO₂ would be saved per flight. Considering that a narrow body aircraft operator like EasyJet has, on average 1,000 flights per day, the numbers start becoming significant.

Table 4 Total Fuel Burn and Carbon Dioxide emissions per mission

	Case 1 522 km	Case 2 1,249 km	Case 3 4,054 km	Case 4 4,054 km	Case 5 11,349 km
Fuel (kg) Baseline	2,898	4,766	12,765	28,430	77,915
Fuel (kg) Water Injection	2,886	4,757	12,770	28,397	77,907
CO ₂ (kg) Baseline	9,158	15,061	40,337	89,839	246,211
CO ₂ (kg) Water Injection	9,120	15,032	40,353	89,735	246,186

Further context to be noted with regards to the assumption of a constant payload in this study that does not involve the reduction of passengers to accommodate for the added weight of the injection system is as follows:

- An Airbus A320-200 (NBA here) is certified to evacuate 180 passengers [25] and the cabin of the A320 fleet used by the low-cost carrier EasyJet is configured to maximize the passenger utilization. The load factor of this specific airline for the years ending 2016 and 2017 is of 91.55% on average [40]. Based on a yearly average, the aircraft are 15 passengers short of their full capacity. In addition, a NBA like the A320 or the B737 is normally used for short-haul trips, for which the take-off fuel is below the maximum fuel weight allowance. EasyJet's average sector distance in 2017 was 1,050 km, that is one-quarter of the aircraft maximum-payload range [41]. For these reasons, it is unusual that these NBA will take-off at their MTOW; an observation also made by Koudis et al. [6] where the take-off weights and thrust settings for more than 3 thousand flights are reported. The article shows that these types of aircraft usually take-off around 85-95% of their full weight capacity. If there were ever 100% of MTOW, 8 passengers would have to be removed (constituting 4% decrease in capacity) from the aircraft for it to comply with the original take-off weight (assuming that an average passenger with carry-on bag will weigh 83 kg [42] to make up for the 642kg indicated on Table 2).
- For the WBA, the extra weight at take-off would be 1,004 kg if allowed, which equates to 12 passengers with no check-in baggage (that is unlikely on a long-haul flight). A 787 on a MHM and LHM considered here is certified to evacuate 381 passengers [26]. Hence a reduced number of passengers would represent 3% of its maximum capacity. However, the passenger load factor for a long-haul airline carrier like British Airways is 81.2% (2016) [43]. This translates to 72 passengers for an aircraft like a 787-9. Despite the fact that the fuel capacity might be at its maximum weight for long-haul flights, the 2, 3 or 4 class cabin configuration

means the aircraft is unlikely to carry the maximum number of passengers that it is certified for. The 787-9 used by British Airways (4 class configuration) can carry a maximum of 216 passengers which is 165 less than the maximum aircraft capacity.

From these considerations, it appears less likely that a situation would present itself in which passengers would have to be let off the flight to accommodate for the water injection system to avoid exceeding the MTOW. However, if this situation arises, the estimates indicate that the aircraft would have a total mission fuel savings between 0.5 and 1%, depending on the aircraft type and the range. These values are obtained by reducing the aircraft payload in an amount equal to the weight of the water plus the equipment. The values are more optimistic than those seen in Figure 9 since the aircraft would be flying lighter than the baseline presented in this study. For example, if the water and equipment weight is 1,000 kg, and 12 passengers are taken off the flight, the take-off weight at the beginning of the take-off run would be the MTOW; but after the aircraft passes 3,000 ft., it would be flying 812 kg lighter than its baseline case, since the water would be consumed.

An alternative solution commonly used by airline operators to reduce emissions and engine operating temperature (and thus maintenance costs) is reduced-thrust take-off. To achieve this, the pilot enters on the aircraft flight computer an ambient temperature above the actual Operating Ambient Temperature (OAT); the aircraft then restricts the maximum take-off thrust so that the Exhaust Gas Temperature (EGT) margin is respected at this virtual OAT [44]. This reduction in thrust is restricted by the civil aviation authorities to 25% of the maximum thrust [45], and it is limited by the runway conditions (wet, ice or contaminated), the ambient temperature, the wind intensity and direction, the airport altitude and the aircraft weight.

Calculations for take-off derate of 10% and 25% were done for both aircraft ([cases 3 & 4](#)) and are presented in [Appendix C](#). Results show that the reductions in temperature obtained from water injection are comparable to those obtained by a 25% reduction in take-off thrust. However, reducing the take-off thrust was seen to increase the take-off and climb times in up to 30%. This time increase has been observed to result in a fuel penalty for certain missions. Koudis et al.[6] Observed that although operators can apply a take-off thrust reduction of up to 25%, most pilots will not exceed 10-15%, and the highest reductions in thrust were only seen when the aircraft weight was about 30% under the MTOW. Water injection could offer similar performance benefits as high take-off derates but without the higher fuel penalties and the restrictions of reduced thrust take-off.

3.3 Impact on Emissions for Different Aircraft

The take-off NO_x reduction seen for [cases 3 and 4](#) are indicated in Table 5 and Table 6 respectively. The first column represents the NO_x emissions emitted considering the ICAO standard times of 0.7, 2.2, 4, and 26 minutes for take-off, climb-out, approach, and taxi, at the corresponding published fuel flows and Emission Indices [31]. The second column is the proportion of NO_x emission that each segment emits, compared to the total LTO emissions. On the next columns, the same parameters are shown but this time for the NO_x calculated on the simulation for the baseline case. The last two columns represent the mass of NO_x obtained from injecting water, and the reductions compared to the baseline case (column 3). These reductions are only seen during 0- 3,000 ft., which is when the system is used. There is also a small increment of 0.2% (Table 5) compared to the baseline case during approach and landing, attributed to the extra weight of the aircraft.

Table 5 LTO NO_x reductions with water injection for NBA –Case 3

	NO _x (g) (ICAO)	% of Total	NO _x (g) Calc. dry (baseline)	% of Total	NO _x (g) Wat.Inj.	Changes compared to baseline
Taxi	1544.4	10.9%	1238.3	11.3%	1238.3	0.0%
0-3,000 ft.	10907.7	76.7%	8337.1	76.1%	3731.8	-55.2%
Approach and Landing	1771.9	12.5%	1386.3	12.6%	1389.5	+0.2%
Total LTO	14224.0		10961.8		6359.6	-42.0%

The take-off and climb-out NO_x reductions (0- 3,000 ft.) are a lot higher for the WBA (Table 6). This is attributed, to the higher temperature reductions obtained for this engine type and hence the sensitivity of EINO_x to Tb. The overall reduction in LTO emissions, however, seems to be almost the same for both cases, between 42-43%. This is attributed to the different weights and configurations of each aircraft which result in different take-off, climb-out, and approach times (taxi times are the same in both cases).

Table 6 LTO NO_x reductions with water injection for WBA – Case 4

	NO _x (g) (ICAO)	% of Total	NO _x (g) Calc. dry (baseline)	% of Total	NO _x (g) Wat.Inj.	Changes compared to baseline
Taxi	4182.9	10.9%	12423.2	26.6%	12423.2	0.0%
0-3,000 ft.	29983.6	78.1%	28494.4	61.0%	8358.7	-70.7%
Approach and Landing	4236.7	11.0%	5819.2	12.5%	5824.3	+0.1%
Total LTO	38403.2		46736.8		26606.2	-43.1%

This suggests that assuming the ICAO LTO cycle to evaluate this technology in both types of aircraft would be an overestimation. The NB-aircraft, according to the ICAO cycle (Table 5), will produce 76% of its NO_x from 0- 3,000 ft., 12.5% on approach and 10.9% on taxiing. This proportion matches well with the simulations. In the dry simulated case, 76.1% of the total NO_x emissions occur during take-off, 12.6% during approach, and 11.3% during taxi. The absolute total NO_x values, however, are slightly different because the flight segment times are different; while ICAO assumes prescribed times per segment, for the simulation, these times depend on the environmental conditions, weight and geometry of the aircraft. For the simulated WBA case (Table 6), the segment corresponding to 0- 3,000 ft. produces only 61% of the NO_x , while taxi accounts for 26.6% and landing to 12.5%. The substantial difference in the distribution of NO_x emissions with segment means that a higher reduction in take-off NO_x , on this aircraft is required to match the overall LTO NO_x emissions reductions seen in the NBA.

Figure 10 is an integration of the NO_x emission indices to the mission profile for the segments going from the take-off roll to 3,000 ft. The figure shows the NO_x Emission Indices for the two aircraft with and without water injection (NBA- Left and WBA- Right). The water injection quantity has been added on the secondary axis to show when the water is turned on and off. The high reductions seen for the WBA become evident in this figure. According to the ICAO emissions certification sheets, the maximum EINO_x for the take-off of the engine installed on the WBA aircraft is 50.3, and 33 on the NBA. The maximum values reported on the figure are similar, corroborating the validation done in Figure 4. When the WBA aircraft operates with water injection, the NO_x Emission Indices are even lower than the dry-case of the NBA aircraft, despite the fact that the engines on the WBA are rated to almost 3 times the thrust and 1.6 times the pressure ratio.

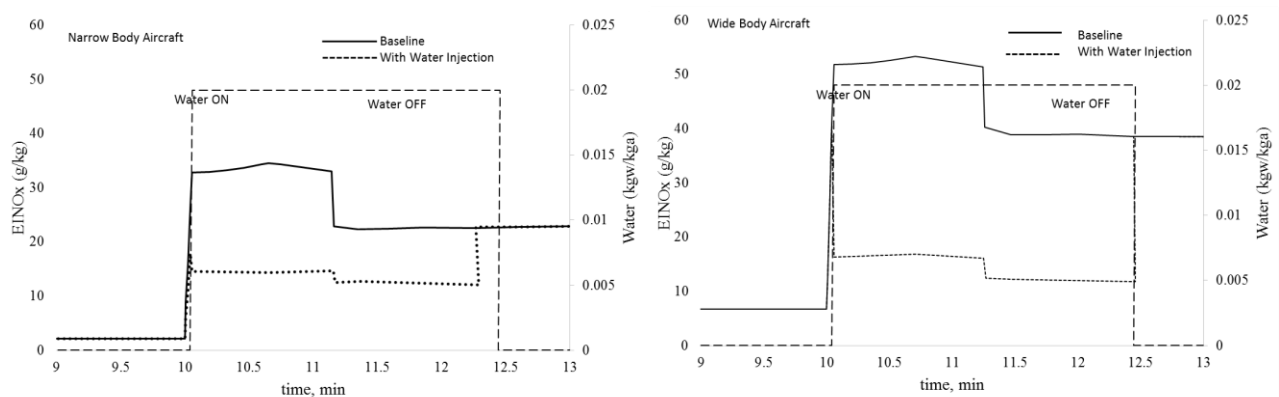


Figure 10 EINO_x with and without water injection for NBA (Left) and WBA (Right)

4- Conclusions

The implications of water injection on aircraft performance have been analysed on this study. The case presented here is to maintain the aircraft payload and avoid any thrust augmentation, thereby dropping the specific fuel consumption during water injection. The outcomes of the work have shown that for 2% injection ratio and 5 μ m droplet size:

- The penalty of the additional weight of the injection system leading to an increase in fuel burn can be overcome for the shortest range missions up to 1,249 km. These are ranges in which the take-off and climb segments last for a significant amount of time, in relation to the entire mission duration; as such, shorter cruise. However, this can be extended up to a range of 4,054 km using a WBA powered by a three-spool engine.
- All periods of water injection for any range see a benefit in fuel reduction for their take-off and climb segment up to 3,000 ft. In these instances, the fuel reduction due to water injection outweighs the additional weight. From 3,000 ft. to maximum climb the opposite is true for all cases of range that water injection is not applied.
- Landing and Take-off (LTO) emissions for NBA or WBA reduces around 42 to 43% for the same MHM.
- Water injection provides similar NO_x and core temperature reductions as a 25% derated take-off, however, it will reduce fuel burn without penalizing the take-off and climb times, and does not have the operational restrictions that reduced-thrust take-off has.
- A positive effect of water injection is the considerable reduction in core temperature. For the NBA, it is a drop in the intermediate CDT and TIT of 60 K and 195 K respectively. For the WBA, it is 82 K and 250 K respectively. These temperature reductions can have significant maintenance costs savings for airline operators as a result of the potential extended creep life of hot the section components.

The take-off time and distance will be influenced by the additional weight of the system. The extra runway length needed for this was evaluated to be no more than 20 m for the NBA and 30 m for the WBA (0.5%-0.75%, considering runway 09L/27R at Heathrow which has a length of 3.9 km).

The droplet diameters considered in this study are 5 μ m. In practice, a spraying plume consists of a distribution of droplets of different sizes. As such, the predictions done here are expected to be more optimistic. Doubling the droplet size to 10 μ m, assuming no

distribution in droplet size, decreases the effectiveness of water injection. Previous work shows a reduction in NO_x decrease from 54 to 50%.

In practice, a Sauter Mean Diameter droplet of 5 μm would be challenging to achieve with conventional injection systems, due to the high water pressure requirements and specialized nozzle design.

Acknowledgements

This work was supported by the Mexican National Council for Science and Technology (Conacyt) and by the Centre for Propulsion of Cranfield University.

Nomenclature

CDT	Compressor Discharge Temperature	MTOW	Maximum Take Off Weight
CEO	Current Engine Option	n	
D	Drag Force	NBA	Narrow Body Aircraft
EEEDB	Engine Exhaust Emission Data Bank	NO_x	Nitrogen Oxides
EI	Emission Index	P	Pressure
FR	Friction Force	SET	Small Emitters Tool
g	climb gradient	SHM	Short-Haul Mission
h	altitude	t	time
HPC	High-Pressure Compressor	T_b	Combustor Inlet Temperature
ICAO	International Civil Aviation Organization	TIM	Time In Mode
IPC	Intermediate Pressure Compressor	TIT	Turbine Inlet Temperature
L	Lift Force	TO	Take Off
LHM	Long-Haul Mission	V_x	Axial Velocity
MHM	Medium-Haul Mission	W	Weight
m	mass	w	specific humidity
M_f	Fuel Mass	WBA	Wide Body Aircraft

Appendix A – Engines used for the Aircraft Models

Table A 1 2-Spool engine simulated vs CFM-56 at DP and OD (NBA aircraft)

Flight Phase, [ref]	Parameter	Value	% Error with Ref.
Cruise (DP) [46]	Thrust (kN)	25.98	4.67%
	SFC	16.98	-0.29%
Take-Off [31,46,47]	Thrust (kN)	133.50	0.19%
	OPR	30.47	-0.45%
	Air Mass Flow (kg/s)	427.70	-1.48%
	Fuel Flow (kg/s)	1.30	1.22%
Top of Climb [46]	Thrust (kN)	28.56	0.91%
	OPR	34.40	-0.48%
Climb to 3,000 ft. [31]	Thrust (kN)	113.48	0.13%
	Fuel Flow (kg/s)	1.06	3.12%
Approach [31]	Thrust (kN)	40.05	-0.42%
	Fuel Flow (kg/s)	0.35	3.21%
Idle [31]	Thrust (kN)	9.35	-0.91%
	Fuel Flow (kg/s)	0.11	-6.15%

Table A 2 3-Spool engine simulated vs Trent1000 at DP and OD (WBA aircraft)

Flight Phase [ref]	Parameter	Value	% Error with Ref.
Cruise (DP) [46]	OPR (kN)	50	0.19%
	SFC	14.33	-5.35%
Take – Off [31,48]	Thrust (kN)	323.70	-0.66%
	OPR	42.53	-1.45%
	Air Mass Flow (kg/s)	1211.00	0.09%
	Fuel Flow (kg/s)	2.40	1.79%
Top of Climb [46]	Thrust (kN)	-	-
	OPR	52.00	-0.44%
Climb to 3,000 ft. [31]	Thrust (kN)	275.15	-0.95%
	Fuel Flow (kg/s)	1.97	2.35%
Approach [31]	Thrust (kN)	97.11	0.59%
	Fuel Flow (kg/s)	0.65	0.71%
Idle [31]	Thrust (kN)	22.66	1.32%
	Fuel Flow (kg/s)	0.24	-9.24%

Appendix B- Ambient Humidity correlations

The correlation used to calculate ambient humidity has been compared to that found in the ISO5878 standard as shown in Fig. B1. and also available in Ref.[35]. The range

considered for the calculations corresponds to 0-10 km of altitude and the maximum error of any individual point within this range reported in Fig.B1 was 0.4%, at 10km of altitude. This correlation is only valid for the ground level relative humidity of 60% (ISA conditions).

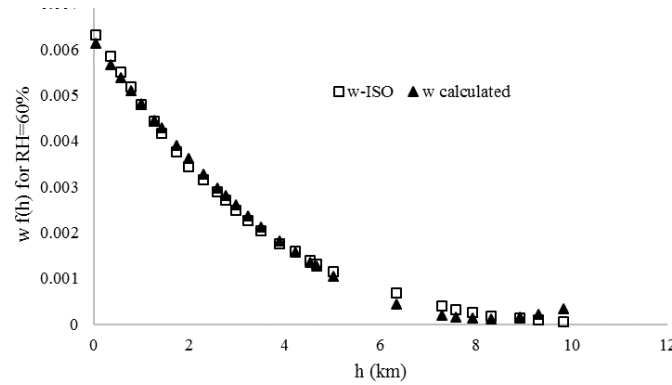


Figure B 1 Variation of absolute humidity with altitude

Appendix C – Reduced Thrust Take-Off vs Water Injected Take-Off

Water Injected (WI) take-off is compared here to reduced thrust take-off (10 & 25%). WI seems to achieve the highest TIT reductions, -196K compared to -165K for the most extreme derate condition. This represents a 12 and 10% reduction, respectively compared to the maximum TIT. Mishra and Beura [49], predicted a 13% reduction in TIT for a 25% derate operation (-228K) with a 2-spool engine installed on a WBA. Hanumanthan et al. [50] report a reduction in Exit Gas Temperature (EGT) of -127K (-11.1%) for a 25% derated take-off on a narrow body aircraft with a 2-spool engine, similar to the one considered here.

Table C 1 Water Injection vs reduced take-off (NBA, case 3)

Average values	10% derate	25 % derate	W. I. (2%)
TIT, ΔT (K)	-69	-165	-196
TIT, %	-4%	-10%	-12%
EGT, ΔT (K)	-31	-70	-104
EGT %	-4.0%	-8.8%	-13.1%
Fuel Flow, (%)	-12%	-28%	-7%
TIM change (%)	11%	36%	1%
TO Fuel change (kg)	-4.58	-5.27	-8.93
TO NO _x change (%)	-20.4%	-43.1%	-58.5%

For the case studied, reducing thrust in 25% would reduce the Take-off (TO) fuel flow by 28%, however it would increase the TO time in mode (TIM) in 36%. This would lead

to a total TO fuel saving of -5.27 kg (-4.58 for 10%). Water Injection, despite the extra weight of the water and the system would achieve a TO fuel flow reduction of 7% (4 times less than derated take-off) but no penalty on take-off time, having as a consequence a higher TO fuel saving of -6.9 kg. Some studies, however, report that operations under reduced take-off might incur in fuel penalties associated to the longer take-off and climbing times also seen here [44]. A study made on a fleet of Boeing 777, concluded that a 10% derate could lead to 5.5% increased fuel, and this value can be as high as 15% if full derate (25%) is applied [7]. In terms of NO_x, water injection also seems to deliver higher reductions than reduced take-off. This comes about as a consequence of the high-temperature reduction and the fact that the TIM is not altered with water injection. Table C2, presents a similar case related to a WBA with a 3-spool engine⁹.

Table C 2 Water Injection vs reduced take-off (WBA, case 4)

<i>Average values</i>	10% derate	25 % derate	W. I.
TIT, ΔT (K)	-61.84	-160.61	-274.78
TIT, %	-3.4%	-8.8%	-15.0%
EGT, ΔT (K)	-19.99	-49.99	-130.26
EGT %	-2.5%	-6.3%	-16.5%
Fuel Flow, (%)	-7.09%	-17.79%	0.36%
TIM change (%)	12.2%	41.2%	0.6%
TO Fuel change (kg)	-4.18	1.27	-26.96
TO NO _x change (%)	-19.9%	-43.0%	-69.0%

References

1. ICAO. ICAO Environmental Report 2016- Aviation and Climate Change. 2016.
2. Block N. DA., Igie U. Case For Exploring Compressor Water Injection For Airport Emission Reduction GT2017-64780. In: ASME (ed.) ASME turbo expo: Power for land, sea and air. Charlotte: American Society of Mechanical Engineers (ASME); 2017. p. TBC.
3. Liu Y., Sun X., Vishal S., Nalianda D., Li Y-G., Wang L. Review of Modern Low Emissions Combustion Technologies for Aero Gas Turbine Engines. Progress in Aerospace Sciences. 2017; 94(2017): 12–15.
4. Wulff A., Hourmouziadis J. Technology Review of Aeroengine Pollutant Emissions. Journal of Aerospace Science and Technology. 1997; (8): 557–572.
5. Koudis GS., Hu SJ., North RJ., Majumdar A., Stettler MEJ. The impact of aircraft

⁹ An analysis on engine Life was presented by Vallina (2018) (Reference 26 on the previous chapter) in which the gains in engine life due to water injection are compared to those obtained from reduced thrust take-off. The Analysis is done with the same NBA presented here.

- takeoff thrust setting on NO X emissions. *Journal of Air Transport Management*. 2017; 65(X): 191–197.
6. Koudis GS., Hu SJ., Majumdar A., Jones R., Stettler MEJ. Airport emissions reductions from reduced thrust takeoff operations. *Transportation Research Part D*. The Authors; 2017; 52: 15–28. Available at: DOI:10.1016/j.trd.2017.02.004
 7. King D., Waitz I. Assessment of the effects of operational procedures and derated thrust on American Airlines B777 emissions from London ' s Heathrow and Gatwick airports. Massachusetts; 2005.
 8. Ashok A., Balakrishnan H., Barrett SRH. Reducing the air quality and CO2 climate impacts of taxi and takeoff operations at airports. *Transportation Research Part D*. 2017; 54: 287–303.
 9. Zheng Q., Sun Y., Li S., Wang Y. Thermodynamic Analyses of Wet Compression Process in the Compressor of Gas Turbine. *Journal of Turbomachinery*. 2003; 125(3): 489. Available at: DOI:10.1115/1.1575254
 10. Bagnoli M., Bianchi M., Melino F., Spina PR. Development and Validation of a Computational Code for Wet Compression Simulation of Gas Turbines. *Journal of Engineering for Gas Turbines and Power*. 2008; 130(1): 012004. Available at: DOI:10.1115/1.2771563
 11. Meacock A. J., White A. J. The Effect of Water Injection on Multispool Gas Turbine Behavior. *Journal of Engineering for Gas Turbines and Power*. 2006; 128(1): 97. Available at: DOI:10.1115/1.2032432
 12. Utamura M., Takehara I., Horii N., Kuwahara T. A New Gas Turbine Cycle for Economical Power Boosting. *The American Society of Mechanical Engineers*. 1997; 97-AA-142: 1–10.
 13. Sexton MR., Urbach HB., Knauss DT. Evaporative compressor cooling for NOx Suppression and Enhanced Engine Performance for Naval Gas Turbine Propulsion Plants. *The American Society of Mechanical Engineers*. 1998; 98-GT332: 1–10.
 14. Sun L., Zheng Q., Li Y., Luo M., Wang J., Bhargava RK. Numerical Through Flow Simulation of a Gas Turbine Engine With Wet Compression. *ASME Turbo Expo*. 2012. pp. 1–13.
 15. Favorskii ON., Alekseev VB., Zalkind VI., Zeigarnik YA., Ivanov PP., Marinichev D V., et al. Experimentally Studying TV3 117 Gas Turbine Unit Characteristics at Superheated Water Injection into a Compressor. 2014; 61(5): 376–384. Available at: DOI:10.1134/S0040601514050024
 16. Daggett DL. Water Misting and Injection of Commercial Aircraft Engines to Reduce Airport NO x. 2004.
 17. Daggett D. Water Injection Feasibility for Boeing 747 Aircraft. Nasa Cr-2005-213656. 2005; Available at: <http://gltrs.grc.nasa.gov/reports/2005/CR-2005-213656.pdf>

18. Flight Global. World Airliner Census 2016. 2016.
19. Nalianda DK. Impact of Environmental Taxation Policies on Civil Aviation. A Techno-Economic Environmental Risk Assessment, PhD. Thesis. Cranfield University; 2012.
20. Jenkinson L., Simkin P., Rhodes D. Civil Jet Aircraft Design. 2009.
21. Igie U., Goiricelaya M., Nalianda D., Minervino O. Aero engine compressor fouling effects for short- and long-haul missions. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2016; 230(7): 1312–1324. Available at: DOI:10.1177/0954410015607897
22. L. J., Simkin P., Rhodes D. Civil Jet Aircraft Design. 2009. Available at: <http://booksite.elsevier.com/9780340741528/appendices/data-b/default.htm> (Accessed: 26 September 2016)
23. Igie U., Goiricelaya M., Nalianda D., Minervino O. Aero engine compressor fouling effects for short- and long-haul missions. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2016; 230(7): 1312–1324. Available at: DOI:10.1177/0954410015607897
24. Boeing. 787 Dreamliner Family. 2017. Available at: <http://www.boeing.com/commercial/787/#/route-map> (Accessed: 6 November 2017)
25. EASA. Airbus A318-19-20-21 Type Certificate Data Sheet. Blagnac; 2017.
26. EASA. Boeing 787-8, 787-9 EASA Type Certificate Data Sheet. 2017.
27. Airbus. Aircraft Characteristics Airport and Maintenance Planning A320. FRANCE;
28. Jackson P. Jane's All The World's Aircraft 2015-2016. IHS; 2016.
29. Boeing Commercial Airplanes. 787 Airplane Characteristics for Airport Planning 787. 2015.
30. Eurocontrol. Small Emitters Tool (SET). 2018. Available at: <https://www.eurocontrol.int/small-emitters-tool> (Accessed: 5 November 2018)
31. ICAO. ICAO Engine Exhaust Emissions Data Bank. 2013; 0: 2013.
32. EATON. Main Gear Fuel Pumps Manual. Devon: EATON Fuel System Division; 2008. p. 20.
33. Block Novelo DA., Igie U. Aero engine compressor cooling by water injection - Part 1: Evaporative Compressor Model. Energy. 2018; 160: 1224–1235. Available at: DOI:10.1016/j.energy.2018.05.171
34. Block Novelo DA., Igie U. Aero engine compressor cooling by water injection - Part 2: Performance and emission reductions. Energy. 2018; 160(x): 1236–1243. Available at: DOI:10.1016/j.energy.2018.05.171

35. Norman P., Lister D., Lecht M., Parlk K., Penanhoat O., Plaisance C., et al. Development of the technical basis for a New Emissions Parameter covering the whole Aircraft operation: NEPAIR. NEPAIR/WP4/WPR/01. 2003.
36. Marchionna NR. Effect of Inlet-Air Humidity on the Formation of Oxides of Nitrogen in a Gas-Turbine Combustor- TMX-68209. Ohio; 1973.
37. EUROCONTROL. EUROCONTROL Glossary for Flight Statistics & Forecasts. 2005.
38. Daggett DL., Ortanderl S., Eames D., Berton JJ., Snyder CA. Revisiting Water Injection for Commercial Aircraft. World Aviation and Exposition. Reno, USA; 2004.
39. Future AS. ICAO Environmental Report 2016. 2016;
40. Easyjet. Easyjet Traffic Statistics. 2017. Available at: <http://corporate.easyjet.com/investors/traffic-statistics/2017/english> (Accessed: 9 August 2017)
41. EasyJet. EasyJet plc Results for the year ending 30 September 2017. 2017.
42. FAA. Advisory Circular- Aircraft Weight and Balance Control. Aviation. 2005. Available at: DOI:10.1177/004728757301200242
43. British Airways Plc. Annual Report and Accounts Year Ended 31 December 2016. London; 2016. Available at: file:///C:/Users/s241630/Downloads/British Airways Report and Accounts year ended 31 December 2016.pdf
44. Ting D. Reduced and Derated Thrust- Operations Course. 2009.
45. FAA. Reduced and derated ,takeoff thrust (power) procedures- AC25-13. 1988.
46. Daly M. Jane's Aero-engines. 2nd edn. IHS (ed.) Janes Information Group; 2015. 449 p.
47. Easa. EASA Type Certificate Data Sheet CFM56-5B and 5C Series engines. 2012.
48. EASA. EASA Type Certificate Data Sheet Rolls Royce Trent 1000 Series Engines. 2013.
49. Mishra R., Beura C. Life Consumption Assessment of a Large Jet Engine. Journal of Failure Analysis and Prevention. 2014; 14: 519–529. Available at: DOI:10.1007/s11668-014-9842-2
50. Hanumanthan H., Stitt A., Laskaridis P., Singh R. Severity Estimation and Effect of Operational Parameters for Civil Aircraft Jet Engines. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2011; 226(12): 1544–1561. Available at: DOI:10.1177/0954410011424854

VII. Paper 6

Experimental Investigation: Spray Fog Analysis and Gas Turbine Water Injection

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Experimental Investigation of Gas Turbine Compressor Water Injection for NO_x Emission Reductions

David Alejandro Block Novelo, Uyioghosa Igie*, Vinod Prakash, Artur Szymański

School of Aerospace Transport and Manufacturing, Cranfield University, Cranfield, UK

*u.igie@cranfield.ac.uk

Abstract

The global rising demand for civil air travel shows good prospects for the industry, however, this growth is inevitably matched with higher levels of emissions and fuel consumption. In this study, demineralised water injection is presented as an alternative to reduce NO_x emissions and enhance engine performance. The experimental study firstly presents the droplet size characterisation of a spray nozzle. This is done for varied injection pressure, water temperature and at varied axial and radial locations using an impaction pin nozzle. The single-shaft *Artouste* engine is used in conducting the compressor water injection test with water-to-air ratios of 0.5, 1 and 2%. The water droplet diameter, engine gas path and exhaust emissions are all monitored in real time. For the engine tests, droplets are measured at the spraying point and correlations are used to account for the droplet size at the inlet of the compressor due to measurement difficulties in this region. The test showed a reduction in compressor discharge temperature by up to 34 K and a NO_x decrease by 25%. Nevertheless, the higher reductions in NO_x at higher water-to-air ratios are attributed to a predominant cooling in the combustor because of unevaporated water in the compressor. At 0.5% water-to-air ratio, the drop in NO_x is mainly due to compressor cooling and signified by the only case in which the fuel-to-air ratio reduces. The study presents evidence of the combined effects of compressor and combustor water ingestion. The CO is seen to increase significantly and associated with reduced combustor efficiency.

Keywords: water injection, engine experiment, compressor, combustor, NO_x

1- Introduction

There are more aircraft flying today than ever before and civil air transportation is still expected to double within the next 14 years [1]. The promise of more accessible air travel has come with increasing concern about the effects of jet-engine pollutants at ground level and during flight. The increase in aircraft fleet has led to aviation-borne Nitrogen Oxide (NO_x) emissions doubling between 1990 and 2014, while Carbon Dioxide (CO₂) emissions increased by 80% [2]. Currently, only ground-level emissions (considered

below 3,000 ft.) are regulated, by limiting the maximum levels of pollutants that aircraft produce during take-off, climb, approach and idle. The regulated emissions are NO_x, Carbon Monoxide (CO), and unburned hydrocarbons (UBH) that are controlled through the International Civil Aviation Organization (ICAO). Airports have also attempted to mitigate this problem by charging airliner operators an environmental fee, based on the mass of pollutants that aircraft engines produce. In the pursuit of meeting these regulations, engine manufacturers and operators have implemented programs to reduce exhaust emissions and fuel burn. The most common approaches for ground-level fuel reductions are limiting the on-time of the engines. These are: by deploying single engine taxiing, towing vehicle- taxiing, queue management or by limiting the use of the Auxiliary Power Unit (APU) [3–5].

Nitrogen Oxide emissions formed in the combustion chamber at high temperatures are especially relevant during take-off when the turbine inlet temperature (TIT) peaks. These emissions are harder to control as they depend on the engine pressure ratio and temperature (which has been rising to attain superior fuel efficiency) and on the residence time of the gas in the primary combustion zone. For this reason, research has been conducted in redesigning the combustion chamber to cool down the operation, burn the fuel-air mixture in a lean way, or modify the gas residence time [6]. Fuel efficiency and emissions reductions have also been achieved through the improvements in the design or modification of other main engine components like the compressor and turbine. Significant advancements have been achieved in this area by deploying multiple spools, employing variable stators, implementing better blade profiles and advanced cooling, all of which have resulted in reaching peak component efficiency and on expanding the range of safe operations.

Despite this, the maximum thermal efficiency of the cycle is about 41% and one of the major sources of entropy generation according to Grönstedt et al. [7] is the core exhaust loss. The loss is associated with the thermal energy lost to the surroundings and in the exhaust flow of the engine. In stationary gas turbines, this heat can be recovered through steam generation to drive a steam turbine to achieve up to 60% plant efficiency. A promising alternative that could tackle both (emissions and core exhaust losses) when constrained to just the engine as in the case of jet engines is through intercooling the compressor. This will reduce the cycle temperature (and thus wasted heat energy at the exit) for the same thrust settings, allowing for similar or greater compressor exit pressures accompanied by lower exit temperatures throughout the engine and the exhaust. The focus of this study is on injecting atomized water into the compressor of the gas turbine to reduce NO_x emissions and improve the performance of the engine. The small size of the engine used, and hence operating temperatures and pressures have brought about an added

opportunity to also examine the effects of combustor water injection that is known to be more promising at reducing NO_x emissions.

Compressor water injection: Previous analysis based on analytical or numerical methods predict that the core air mass flow can be cooled by 12% [8,9] and as a consequence reduce NO_x emissions by up to 50% [9–12]. To the knowledge of the authors, only a few experimental studies have been performed in this area. Utamura et al. [13,14] show the promise in reducing the compressor exit temperature and specific compressor work. The study predicts up to 10% increase in power output with only 1% water-to-air ratio. The study is compared to analytical predictions. Jolly [15] presents very similar figures as the previous study and reports changes in temperature (-7.4%) and pressure (+3.2%) of a 35 MW industrial installation under inlet fogging conditions (1% of the air flow). These engine-based studies show the performance changes due to compressor water injection but do not include droplet size distribution analysis and the corresponding exhaust emissions. Other experimental studies involve the work of Roumeliotis and Mathioudakis [16] for a single stage compressor which highlights the aerodynamic implications of water injection. The study shows an increase in the amount of compressor power consumed for the same throttle position. No significant changes in the flow pattern, stall margin or pressure rise were observed for up to 2% water-to-air ratio investigated. The study focuses on the stand-alone compressor component and does not provide details about the droplet size distribution. Schnitzler et al. [17] extended the problem to a multistage stand-alone compressor. The work includes droplet measurements and concludes that injecting water into the compressor can improve the efficiency of the turbo component. A recent experimental study also on a stand-alone multi-stage compressor was also presented by Munari et al [18]. The study examines an axial-centrifugal compressor operating under steady state, surge and rotating stall conditions. The investigation concludes that water injection has no considerable negative effect on the surge margin under the conditions examined.

Combustor water injection: Bahr and Lyon [19] experimentally investigated the implications of water injection into LM2500 and LM5000 land-based gas turbine combustors. The study shows that injecting water directly in the combustor can reduce NO_x emissions by up to 90%. The engine with the lowest compression ratio (LM2500) was penalized with a sharp increase in CO emissions due to a reduction in combustion efficiency. Although combustion water injection has a great promise in reducing NO_x emissions, it does not provide the advantage of reduced compressor work and is often associated with an increase in Specific Fuel Consumption (SFC) [13]. Walsh and Fletcher [20] indicate that a water-to-fuel ratio of 1 could increase the SFC of an engine by 6-8% while producing a three-fold increase in CO emissions. Shahpour and Houshfar [21]

present a numerical model of a conventional combustor operating with humid air (only water vapour) and water injection. The study also noticed a rise in CO with direct water injection, but a decrease with humid air. In both cases, the NO_x emissions were reduced, though this reduction was more significant with direct water injection. The developments of Dry Low Emission combustors that deploys lean premixed combustion has brought about a significant reduction in NO_x emissions for power generation applications. However, for jet engines, diffusion combustors produce higher levels of NO_x but generally more stable and efficient combustion at wider operating envelopes. Daggett [11,22] reports the last application of wet combustion for the early 747-100 and 747-200 using a Pratt & Whitney JT9D-3AW and 7AW series engines. Problems related to the poor temperature distribution in the high-pressure turbine and hotspots are indicated by the author. The study also indicates that this problem was resolved in the industrial application. The referred study also provides evidence of the impact of combustor water injection at different water-to-fuel ratios, through simulations. At 0.5 ratio for constant thrust operation, there is a 50% reduction in NO_x emission, 80 K drop in TIT and about 2% increase in SFC. Wilkes [23] shows the case of increased power (3.3% rise) at the same water-to-fuel ratios. The NO_x reduction is shown to be about 50% and around 1.5% decrease in thermal efficiency (that is an increase in SFC). Blazowaki [24] shows that for the same water-to-air ratio, the combustor water injection is more promising for NO_x reduction, thereby inferring relatively less water required for the same decrease. Despite the advantages, as would be observed in the present study, the negative effects on increased fuel burn, CO/ hydrocarbon emissions, and soot is still to be addressed.

Droplet Characterisation: Extensive experimental work on the science of water misting or water injection has been conducted by Chaker et al. [25–28]. Most of the published work is based on droplet dynamics and the methodology for measuring fogging sprays. These studies do not include engine performance analysis and are entirely based on inlet fogging for industrial gas turbines. Droplet measurements were performed using fogging nozzles with a diffraction laser tracking the spray plume axially and transversally, and this approach forms the basis of the present work. Savic et al. [29] studied nozzle sprays for different flow velocities and considering different nozzle orientation (in line with the flow, cross flow and opposite to the flow direction). The investigation provides valuable information about nozzle and droplet interaction. The influence of ambient conditions (temperature and relative humidity) as well as water temperature, measuring position and injection pressure on droplet size was also studied and presented by Chaker et al. [26]. The study concludes that the environmental conditions have a minor effect compared to the injecting properties (when studying droplet decay and temperature reductions of the surrounding air).

The present investigation corroborates some of the results obtained in Refs. [25,28,29] for single impaction pin nozzle, and subsequently applies the fogging nozzles to the inlet of a gas turbine. This nozzle type was chosen over other types of nozzles (flat spray and hollow cone) as they are characterised by smaller droplet sizes without compromising the water flow delivery, as noted by Ref. [25]. A parametric analysis is presented considering varying injection pressures, identical nozzles and varied distances from the nozzle exit: axially and radially. The droplets were measured by means of laser diffraction, using a Malvern Spraytec laser equipment. For the engine test, the nozzle manifold was installed in front of the engine bellmouth. Due to the difficulty in measuring the droplet size at the entrance of the compressor, empirical correlations from Ref. [30] were used to account for the droplet size between the measuring station and the compressor intake. The results presented here bring together the estimated droplet size at the intake of the engine with the performance and emissions changes during water injection. Though the water injection takes place in the compressor section, the study brings together the combined effects of evaporation in the compressor and combustor, as a result of incomplete vapourisation of the former. This is directly due to the small size of the engine that is associated with lower operating temperatures and pressures. The achievement of this study, therefore, is to provide evidence for the implications of injecting water into a gas turbine, with the combined water effects from both components, in an area dominated by analytical and numerical studies which do not often capture some of the practicalities of deploying this technology. The change in gas path performance (temperatures, pressures and flows), as well as the exhaust emissions and the water droplet size, are monitored in this study by means of experimental tests performed on a single-spool engine.

2- Methods: Droplet Measurements in Still Air

2.1 Experimental set-up

A nozzle spray consists of a distribution of particles or droplets of different sizes. The interaction between the droplets (break-up, coalesce, bounce) makes it impossible to produce a homogenous droplet size composition. For this reason, when measuring a spraying plume at a given location, a number that represents the droplet size distribution is used rather than the actual particle size (explained subsequently). In this study, the instrument used to measure the droplets size is light diffraction Helium-Neon Laser (wavelength: 632.9 nm, power <5mw) capable of measuring particles from 0.1 to 2000 μ m. The laser emits a 10 mm diameter beam, which is scattered by the particles. This scattered light is collected into an array of detectors located on the receiver lens as depicted in Figure 46. The angle of the light diffraction is inversely proportional to the droplet size. As such, the laser equipment measures the angle at which the light is

diffracted and not the droplet size directly. This instrument subsequently applies Fraunhofer approximation and Mie theory to translate the scattering pattern into particle size distributions, on the basis that each droplet will distribute the light at a specific angle depending on its size [31].

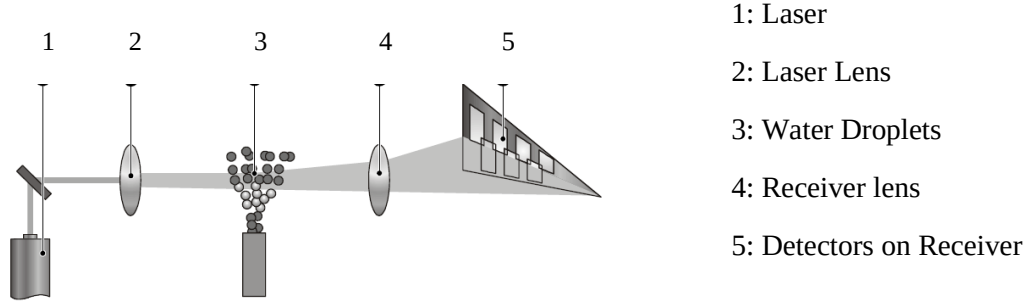


Figure 46 Laser scattering mechanism [31]

The presented method is well established for measuring droplet sprays and it has been previously applied in Refs. [25,27,29]. It also complies with the ASME standard for spray measurement [32] and according to the manufacturer, has a repeatability in measurement and an accuracy better than $\pm 1\%$ [31]. The numbers used to represent the sprays are the Sauter Mean Diameter (SMD) also referred to as D_{32} , and the Dv_{XX} , where XX can take the value of 10, 50 or 90. The Dv_{90} , for example, means that 90% of the volume of the spray is distributed in droplets of the specified diameter or smaller. The SMD, on the other hand, is a diameter that has the same volume-to-surface-area ratio as the average volume-to-surface-area ratio of all the droplets in the spray. This diameter is of high relevance for evaporative cooling applications because it expresses how much surface area of water is exposed to the air. The SMD values tend to be smaller than the Dv_{90} , since the Dv_{90} is an expression of the largest particle size present in the spray, while the SMD refers to a representative diameter. Further details of the other diameters used to characterize the size distribution of a spray can be found in Ref.[33]. For this analysis, the spray was characterized by the Dv_{90} and SMD parameters. These values are a time-average of each measurement at each position and at the specified operating pressure. The time considered for each measurement was about 2 minutes and the droplet size is based on the following parameters:

- Operating Pressure (69 and 138 bar)
- Nozzle (multiple identical impaction nozzles were tested)
- Water Temperature (288- 323K)
- Water type (demineralized and tap water)
- Axial positions from the nozzle tip (50 – 250 mm)
- Radial positions for a given axial location from the nozzle tip

The 138 bar operating pressure produces smaller droplet size distribution as seen subsequently and hence implemented in the engine analysis. The experimental setup for the droplet study consists of 4 units as indicated in Figure 2. In the figure, number 1 is the water injection skid consisting of a tank, a water pump, an electric motor and a pressure control valve. Number 2 refers to the impaction pin nozzle also shown in Fig. 3. The laser unit used to monitor the droplet diameter is labelled as 3. Droplet size measurements were taken at different positions along and across the plume. For these positions to be consistent, a 3-directional Parker-Hannifin® daedal positioning mounting was used. This mechanism labelled in Figure 2 as 4, has a readability of 0.1 mm and a straight-line accuracy of 0.01%.

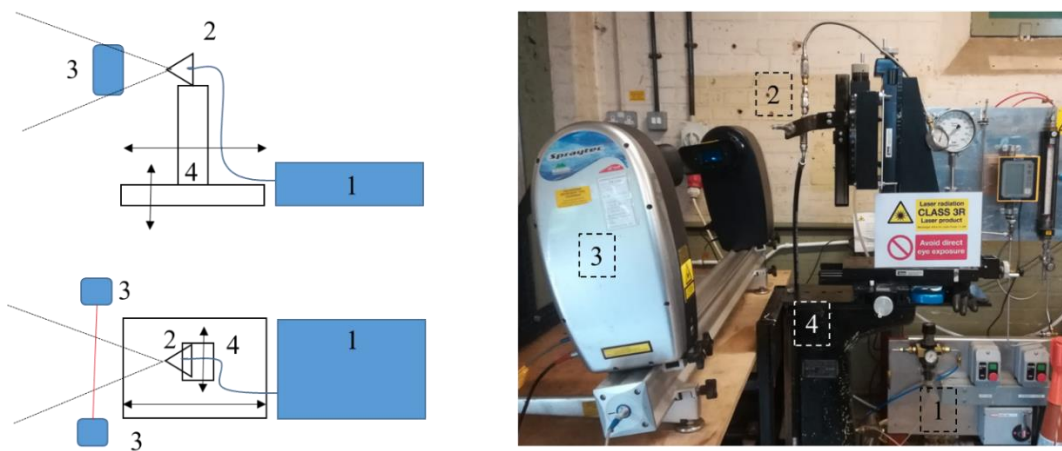


Figure 2 Experimental set-up for single nozzle testing



Figure 3 Impaction pin nozzle

2.2- Uncertainty

Controlling the nozzle orientation proved challenging because the thread on the nozzle and that on the pressure fitting did not always align to give the same nozzle orientation, and the pressure fitting could not be rotated. Impaction pin nozzles do not produce a symmetrical spray, however, Chaker [34] evaluates the effect of this asymmetry at

different pressures and flow rates and concludes that at high pressures, the droplet distribution is independent of the nozzle orientation. The current test set-up, did not allow for this to be confirmed, as there was no way of rotating the nozzle. For multi-point measurements, the nozzle was moved up and down with respect to the laser, so that the plume measurements could be taken at the “top”, “bottom” and “centre” of the spray. When the nozzles were replaced, these measuring positions were repeated and controlled to an accuracy of ± 0.1 mm. Despite this, the fog produced by the spraying nozzle slightly varied in shape. Some nozzles produced a plume with a slightly wider spray angle. Hence, the relative position between the laser and the “top” or “bottom” of the spray was not always the same. The thermocouples and pressure transducers used have an accuracy of 0.75% and 0.5% respectively, and that of the water flow meter is 2%. The temperature of the water and the air was constantly monitored to ensure that the difference between them stays within an acceptable range ($<10^{\circ}\text{C}$). The temperature and humidity effects were studied by Chaker et al. [26] and concludes that the ambient conditions have minimal effect on droplet size decay and that this is rather dominated by the coalescence and break-up of the water droplets. The ambient temperatures at which the tests were conducted in the present study were in the range of 16- 19 $^{\circ}\text{C}$.

2.3- Considerations for Single Nozzle Testing

The tests in the first part were conducted for single nozzles spraying water into the still air. Since the intention is to subsequently use the nozzles in a manifold for the engine test, 8 identical nozzles were tested individually to quantify the similarity between them to characterize the spraying fog. The initial measurement position was taken at centreline and traversed in 50 mm intervals, going from 50 mm away from the nozzle up to 700 mm. No significant change in droplet diameter was observed beyond 150 mm from the nozzle. This is in agreement with Chaker et al.[26,30]. In both studies, the droplet size was reported to stabilize after 100 mm. The standard for inlet fogging [32] recommends the readings to be taken at 75 mm away from the nozzle. However, the droplet size distribution was seen to increase beyond 75 mm; stabilization of the measurements was only observed at 100 mm and beyond. For this reason, the initial measurements were taken as close as possible from the nozzle (50 mm) similar to Ref.[35]. The measuring distance was then increased to 150 mm and 250 mm. The vertical distribution of the plume was also varied, considering 2 other radial positions other than the centre position: + 20 and - 20 mm at the point closest to the nozzle. This distance was increased as the measuring position moved away from the nozzle tip, to follow the conical shape of the fogging plume. This is applicable for all the axial positions and controlled for an accuracy of 0.1 mm. Since commonly used injection pressures in industrial systems are between 69 and 138 bar, only this range is considered here.

Water injection causes an increase in the humidity of the surrounding air that subsequently has a higher index of refraction than dry air. This causes extra light diffraction, which leads to the receiver reading high light incidence angles. The consequence of this is a larger estimation of droplet sizes than they actually are. This phenomenon is known as beam steering [31] and the ASME standard for water spray measurement [32] recommends restricting the droplet diameter range to 200 μm , to reduce the influence of this effect. However, the laser manufacturer recommendation is to identify the detectors in the receiver that are affected by beam steering and turn them off. The light scattering pattern will change as a result of this. However, the processing software is embedded with an algorithm that corrects for the missing detectors; the exact details of this correction are not provided by the manufacturer. Both approaches were tested to evaluate the influence on the results, as presented subsequently. For both approaches, a background reading of the media (air) and ambient light is taken prior to the start of the spraying and droplet measuring.

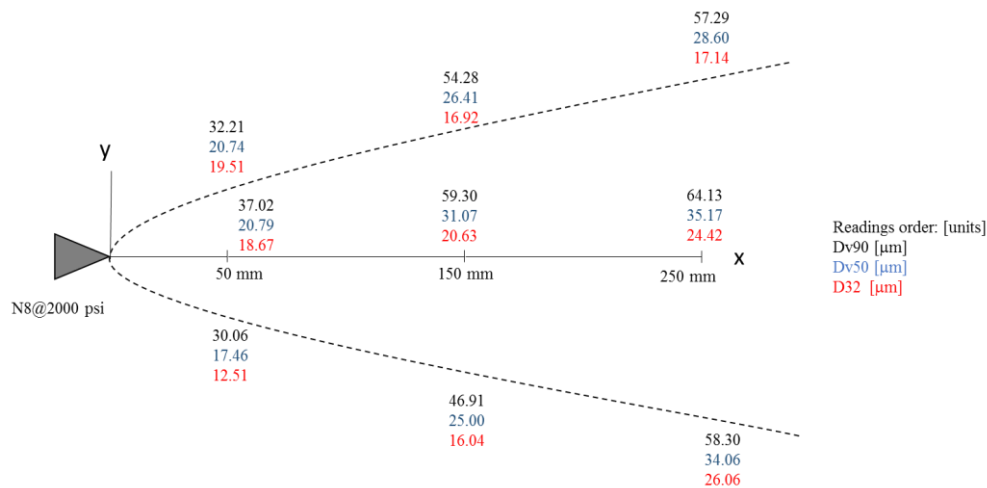


Figure 4 Droplet distribution across the plume at 138 bar

Figure 4 depicts the measurements taken at the 9 locations in the x (50, 150, 250 mm) and y coordinates, for one of the nozzles tested at 138 bar. The figure shows a general increase in the droplet diameter with an increase in axial distances away from the nozzle exit. Although the size diameters are similar between the axial locations, the figure shows the importance of measuring at different points across the plume. Some studies have identified smaller droplets at the “centre” of the plume, and larger droplets at the edges [35]. This is not the case observed in this study due to the presence of the spray cone edges as shown in Figure 4. The first set of readings from the left (Figure 4), taken at 50 mm away from the nozzle shows a Dv_{90} of $37.02\mu\text{m}$ at the centre, but $32.21\mu\text{m}$ and $30.06\mu\text{m}$ at the top and bottom of the spray. When measuring the conical-shaped spray at any “y” position, the laser travels through the edges and centre of the plume, penetrating

the cloud across the “z” direction as illustrated in Fig. 5. This means that the readings taken will account for the edges and the “core” of the conical spray. To mitigate this effect and account for a more indicative reading at the core or centre of the spray, a separate set of measurements was taken by “shading” the edges of the spray, using an obstruction as shown in Figure 5. For a given (x, y) position of (50, 0) mm, the droplet diameters (D_{v90}) measured at the core of the plume were about 45% smaller than those seen when the measurements were conducted without the obstruction of the spray cone. This observation served to explain the findings of smaller droplets at the core of the plume, obtained in other studies. Nevertheless, in the present study, these “core” readings were not used for further analysis, as the measurement taken with full cone penetration provide a more indicative sizing of the droplet diameter in this region.

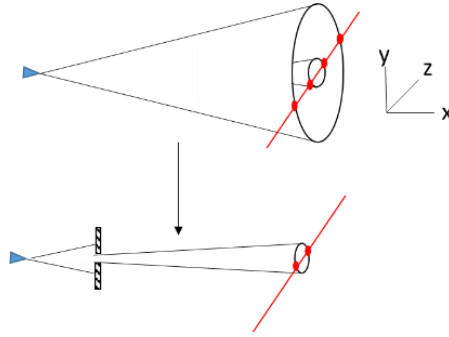


Figure 5 Spray without and with shading/obstruction of the edges

3- Results for Droplet Size Analysis

If the transversal values of Fig.4 (y_1, y_2, y_3) are weight averaged, the plume can be characterized by only three values for the 3 axial distances from the nozzle (50, 150 and 250 mm). Figure 6 shows the influence of varying measurement distance for the case of 5 nozzles. As expected, the droplet size increases with increasing distance from the spraying point. This behaviour was noted by Refs. [30,36] and it is attributed to droplet coalescence and the evaporation of smaller droplets. On average, a smaller increase in droplet size is seen to occur when moving from 150 mm to 250 mm.

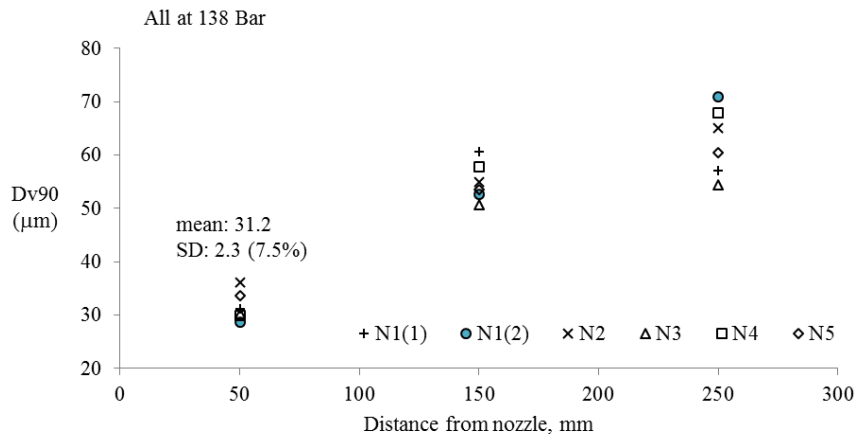


Figure 6 Influence of measuring distance on droplet size

The figure also shows the cases for which the droplet size diameter is restricted N1 (1) and when the detectors are turned off N1 (2). No significant difference was noticed between the methods, and so the latter was selected. The apparent decrease in diameter of N1 (1) when moving from 150 to 250 mm has to do with the coalescing and bouncing phenomenon. Since evaporation has stopped in this region due to the saturation of the air and extinction of small droplets, from 150 mm onwards the droplet size is governed by the droplets braking, merging or bouncing that is a stochastic process. In the case of N1, it is possible that the measurement taken at 250 mm was in a region where droplet merge was less dominant; hence the distribution shows a slight decrease in droplet size. Initially, all droplets exit the nozzle at the same speed, but as they travel away from the injection point their speed reduces due to a loss in momentum caused by a reduced mass that is accompanied with a continuous air drag resistance. Hence, initial smaller droplets slow down faster than larger droplets due to a lower initial momentum. The low-energy droplet impacts that occur in the region away from the nozzle are responsible for droplet coalesce rather than bounce. This phenomenon is responsible for the higher droplet sizes observed (with larger deviations) farther away from the injection point.

The measurement of all the particle sizes had a standard deviation of 2.3 μm at 50mm from the nozzle, and 5.1 μm and 5.3 μm at 150 and 250 mm respectively. Considering the mean diameters of 31, 56 and 63 μm , the standard deviation (SD) at any one point is below 10% of the mean. This was considered acceptable for the current set-up, in agreement with the ASME standard for fogging nozzles [32]. Results of the mean values of all the nozzles at the three distances are presented in Figure 7 for pressures of 69 and 138 bar, with the corresponding error bands. The SD presented in the figure as a percentage, (7.5, 9.2, and 8.5%) is applicable to the 138 bar case. It can be noted that doubling the pressure has a small effect on the droplet diameter reduction as observed by Refs [30,37]. According to Ref. [37], impaction pin nozzles have much less influence

from injection pressure than pressure swirl nozzles. In the study, the authors report a 20% reduction in diameter for a three-fold increase in injection pressure. For a similar kind of nozzle at 138 bar and at 50 mm away from the nozzle, the study reports a mean diameter of 29.8 μm (2% smaller than the mean reported here, but still within the range of the SD). Chaker [30] reports a smaller Dv_{90} of around 28 μm but with an airspeed of 1 m/s. The SD for the 69 bar case for the three points analysed here were 9.4, 9.5 and 6.5% respectively.

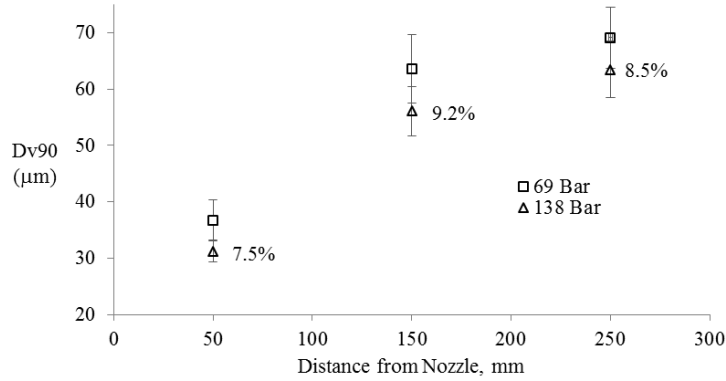


Figure 7 Droplet Diameter with distance for different injection pressure - mean values presented

The investigated effect of water temperature is shown in Figure 53. The figure indicates the minimal influence of water temperature on droplet diameter, as also observed by Ref. [27,36]. These Dv_{90} and D_{32} measurements were taken at 150 mm from the nozzle, over a period of 10 minutes by spraying water as it was gradually heated. The interest of this was to identify any favourable temperature that can bring about a further reduction in the droplet sizes.

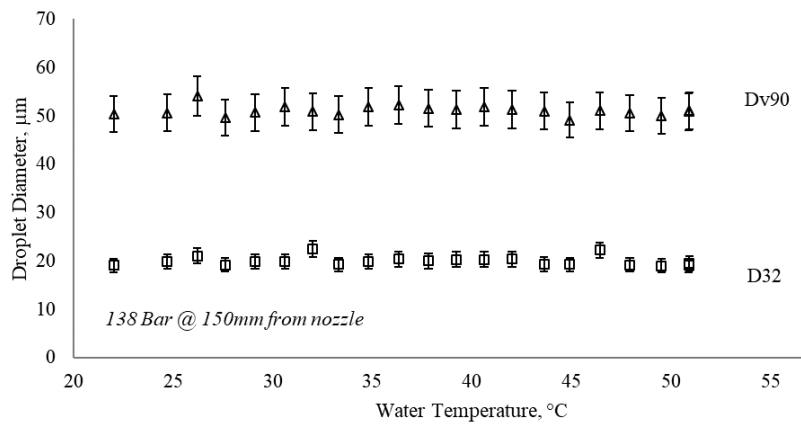


Figure 53 Influence of temperature on droplet size

This first part served as a basis for understanding the droplet size distribution and behaviour for a single nozzle before progressing to the case of a multi-nozzle arrangement

that is necessary to achieve the required water-to-air ratio. Other efforts made to arrive at the selected injection pressure and nozzle type are indicated in Fig A1 of Appendix A. The figure shows the relationship between the nozzle type and injection pressure. The requirement for smaller droplet formation allows for better intercooling inside the compressor thereby reducing the temperature of the gas path of the engine. This relatively cooler operation reduces the endothermic NO_x emissions as explained by Block and Igie.[12]. Smaller droplets also reduce the risk of blade impingement which could lead to surface erosion and a loss in the aerodynamic efficiency.

4- Gas Turbine Engine Testing

4.1 Experimental Set-up

The water injection rig along with the laser and a multi-nozzle manifold was then installed in front of a single shaft gas turbine engine as shown in Figure 9. The figure depicts the engine intake (1), the laser (2) and the spraying nozzles (3). Water was injected into the engine at varying water-to-air ratios (f) but at a fixed injection pressure of 138 bar. The water quantity was controlled by the number of nozzles; 1 nozzle delivers water at 0.166% of the air mass flow, while 3, 6 and 12 nozzles amount to 0.5%, 1% and 2% respectively.

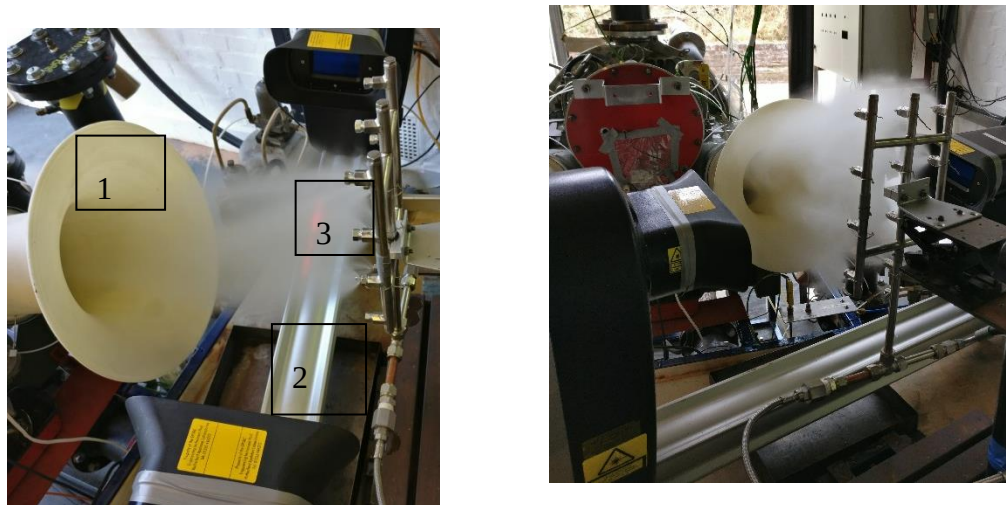


Figure 9 Photograph of the experimental set-up. Engine Intake (1), Laser (2), and Nozzles (3)

The Rolls Royce *Artouste* gas turbine engine was deployed to investigate the effects of compressor water injection. This type of auxiliary power unit (APU) was used to provide compressed air to start the main aircraft engines like the Rolls-Royce Conway – the first turbofan to enter into service- that powered some versions of the Vickers VC10 and Boeing 707-420 [38]. The *Artouste* engine as described in Figure 10 consists of a single-stage centrifugal compressor (on the right-hand side of the figure), an annular combustion chamber and a two-stage axial flow turbine that is directly coupled to the centrifugal

compressor on the same shaft. Some measured and calculated performance parameters of the “dry” engine condition are presented in Table 1. This includes the total inlet air temperature (T_{in}) and pressure (P_{in}), Compressor Discharge Temperature (CDT), Exhaust Gas Temperature (EGT), air mass flow, (m_{air}), Fuel Flow (FF) and Pressure Ratio (PR) for which the measurement stations are depicted on Figure 10. The table shows on the left-hand side column the averaged performance parameters corresponding to the “dry” tests, and on the right-hand side, the corresponding averaged and corrected values. The latter is the result of averaging over 7,000 readings over a period of time and then correcting them to ISA temperature and pressure (Eq.2) [20,39].

$$\theta = \frac{T}{288.15} \quad \delta = \frac{P}{101.325} \quad (1)$$

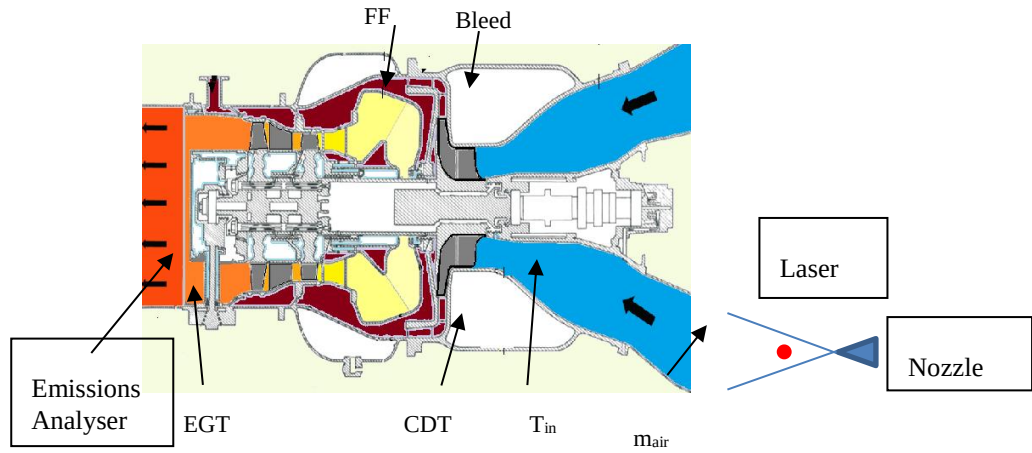


Figure 10 Gas Turbine Experimental Set-Up. Adapted from [40]

The temperature and pressure based corrections do not account for the relative humidity (60% used for sea level stationary gas turbines). Igie et al.[41] devise an extended correction accounting for relative humidity effects. This shows that the influence is very small for the range of temperatures investigated in this study and hence can be neglected for the data correction. In this investigation, the engine is operating without any load or driven equipment and hence there is no power requirement or demand. It is also important to mention that the performance of this engine is unlikely to exactly match the manufacturer's design specification even at the same ambient conditions and rotational speed. This is mainly due to mechanical wear and tear and refurbishments over the years of service. As such, the reference conditions applied here for water injection are corrected conditions before and after water injection is applied.

Table 1 Performance at dry engine condition (averaged, and corrected values to ISA 288K and 101325Pa)

	Averaged Measurements	Averaged Measurements corrected to ISA
Tin (K)	303.3	288.0
P in (kPa)	100.6	101.3
CDT(K)	471.9	449.0
EGT(K)	795.3	756.0
FF (kg/s)	0.034	0.0332
n (RPM)	33096.0	32261.0
Ma (kg/s)	3.2	3.3
PR	3.4	3.4
Cw (kW)	172.6	164.2
Measured Dry Emissions	NO _x : 40.28 ppm CO:446.57 ppm CO ₂ : 3.23%	
Fuel Type:	Kerosene	

This experimental gas turbine is equipped with five k-type thermocouples; two at the intake, two at the compressor discharge and one at the turbine exit. The temperature measured by the thermocouples is the mixture temperature, as there was no way to condense the extra water. Pressure transducers were used to evaluate the static and total pressures at the same stations (the compressor inlet and bleed duct) using a pitot-static tube. At the exit of the compressor, pressure tapings are installed to a manometer that measures the gauge pressure. As such, the absolute pressure is calculated to obtain CDP. These readings were used to calculate the parameters on the bottom columns of Tab. 1. The accuracy and errors of the instruments are the same as for section 2.2. At the exit of the turbine, a Protea ProtIR 204M ® emission analyser was installed as highlighted in Figure 10. This analyser is based on the Fourier Transform Infrared (FTIR) technology for stack emission testing. It has a resolution for NO, NO₂, CO and CO₂ of 0.9, 0.3, 0.2 and <2 ppm respectively. As a reference comparison, ICAO [42] recommends resolutions better than 1 ppm for NO_x, 2 ppm for CO and 100 ppm for CO₂, when measuring aircraft engine emissions. The emissions were collected by means of a probe installed at the exit of the engine. A suction pump collects a sample of the gas and mixes it in a dilution chamber prior to analysing the composition of the mixture. The analyser takes six readings before giving an output and this whole process lasts for around 60 seconds. The user can track this process and read each point measurement as well as track the history of each gas species. During the tests, the engine was left with unchanged conditions for a period of time long enough for the readings to stabilize, as the species of each gas changed when water was injected.

4.2 Water Droplet Measurements at the Engine Intake

The spraying nozzles were located 290 mm away from the compressor intake and the droplet diameter readings were taken at a distance of 50 mm away from the nozzle. Due to the presence of the engine bellmouth, the entrance of the compressor was inaccessible to the laser. As such, the water droplet diameters were measured at the exit of the nozzle and the change in size from the measuring point to the compressor inlet was estimated. Two approaches were selected to approximate the change in size from the nozzle exit to the compressor inlet: an empirical [30] and an analytical method [8]. The work presented by Ref [30] shows empirical correlations to predict droplet size change as a function of pressure, measuring position, airflow or water mass flow. The correlation presented in Eq. 2 is derived from experiments and depends on empirical parameters and a nozzle constant, k . The empirical constants were set to $\mu=0.23$, $\delta=0.14$, $\pi=0.16$, $\omega=0.14$, as recommended by Chaker [30]. A similar correlation for the D_{32} can be found in the referenced study. In the stand-alone nozzle test (section 3), and for the position of 50 mm at 138 bar and at a given mass flow, a droplet size was calculated using Equ.2. This value was compared against the experimental readings taken at the same position. The difference between these two values determines the nozzle constant, k . An average was then made between all the measurements and k was chosen to be 491 for this type of nozzle. The correlations lead to errors mostly between 1.8 and 10% (and in a few cases up to 20%) when comparing the predictions with the actual measurements. The same maximum uncertainty of 20% was applied to predict the droplet sizes at the compressor entrance.

$$Dv_{90} = k \frac{m_w^\mu D^\delta}{\Delta P_w^\pi V_a^\omega} \quad (2)$$

When analysing droplet decay at still air and different air flow velocities, refs. [29,30,36] noticed that the size stabilizes after 10-12 m/s and also after 100 mm of leaving the nozzle. This is due to the air being saturated (no further evaporation) as well as the fact that the effect of coalescence and break up is diminished after the primary breakup phase. When applying Eq. 2 to moving air at 12 m/s and 50 mm away from the nozzle, a D_{v90} of $30 \pm 6 \mu\text{m}$ is obtained. This compares well with the measured readings while the engine was running, which gave a D_{v90} of $35 \pm 2 \mu\text{m}$. The distribution obtained at the measuring station also showed that 50% of the volume had droplets of $22 \pm 1 \mu\text{m}$ or smaller ($D_{v50}=22$) and 10% of the volume was distributed in droplets of $13 \pm 1 \mu\text{m}$ or smaller (D_{v10}). The stated distribution implies that 40% of the volume is represented by large droplets of size between 22 and 35 μm , which are not expected to fully evaporate in the compressor.

The values obtained at the measuring point were set as boundary conditions and applied to Equ.2 to predict the droplet size at the compressor inlet, 240 mm away from the measuring station. It was predicted that the droplets would have a Dv_{90} of $36 \pm 7 \mu\text{m}$ and a D_{32} of $16 \pm 3 \mu\text{m}$. The droplet size was also estimated by means of a physics-based evaporative method [8,43]. These methods assume that the droplets evaporate until the air is saturated. Once saturation occurs (100% relative humidity) no further evaporation is possible. The analytical model does not consider coalescence or breakup and predicted a droplet size of $27 \mu\text{m}$ based on mass transfer-driven evaporation only. It can be noted that since the analytical model does not account for droplet coalescence, a lower droplet diameter is predicted. Details on the diameter reduction of an isolated droplet based on mass diffusion theory can be found in Ref. [43].

When using the maximum number of nozzles (12) corresponding to a water-to-air ratio of 2%, the fogging plume was too thick for the laser to achieve full penetration. Measurements were only possible for the configurations with 1, 3 and 6 nozzles, corresponding to water-to-air ratios of 0.13, 0.5 and 1%. There was a small increase in droplet diameter when using multiple nozzles attributed to the increased number of collisions between the droplets, leading to higher droplet coalescence. This increase is already accounted for in the size distribution discussed.

4.3 Engine Performance with water injection

The engine measurement data have been obtained simultaneously (including droplet size and exhaust emissions) and continuously as shown in Figure 11 for each set of experiments. After the engine was operated under dry conditions, different amounts of demineralised water were introduced ranging from 2% to 0.5% of water-to-air ratio. The engine was initially allowed to warm up for about 7 minutes before introducing water; this is well within the start-up time recommended by the manufacturer that suggests 40 seconds. Since the engine pressures and temperatures were recorded in real-time, it was straightforward to identify the stabilization of the readings before the water injection.

In reference to Figure 11, after minute 7, a quantity of water equivalent to 2% of the inlet-air-mass flow was injected into the compressor. The figure shows the changes in the four parameters mentioned in Tab. 1, when the engine is injected with 2%, 1% and 0.5% of water. Figure 11 also shows the raw data (fluctuating lines) and the time averages for each quantity. At each engine operating condition, around 700 individual readings for pressure and temperature were taken. The mean of these values (presented as a continuous line superimposed on the raw data) and standard deviation (SD) were computed. The SD seen for each set of readings was noticed to be below 1% of the mean. Further statistical analysis of the raw data is presented in Appendix B.

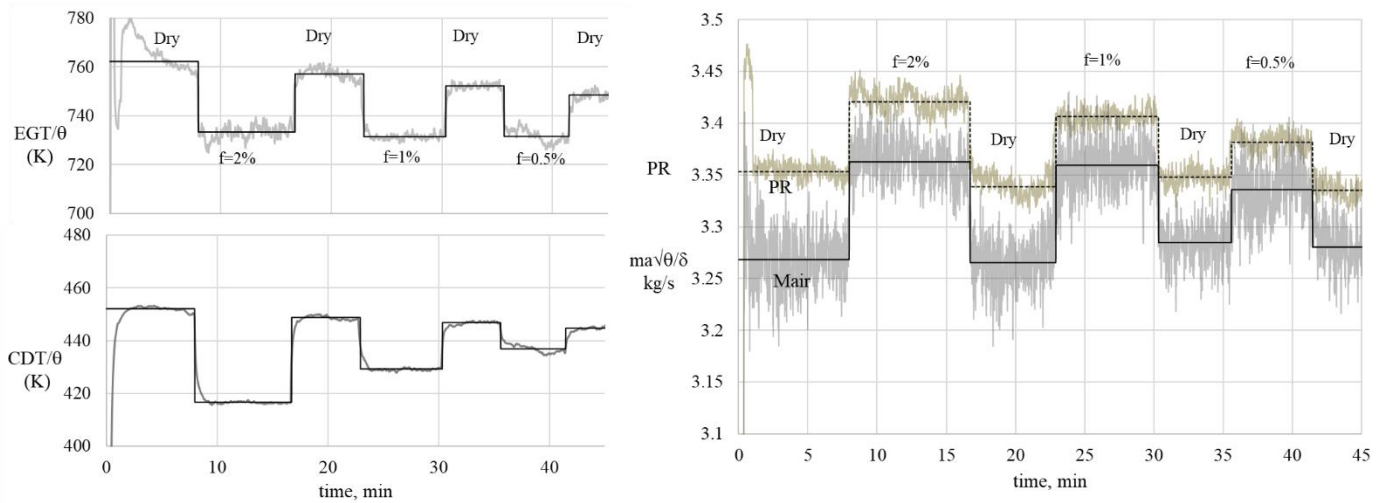


Figure 11 Raw and time-averages of CDT, EGT, PR and mass flow

Figure 11 shows a significant decrease in CDT and EGT immediately after the injection was initiated. For 2% injection, this amounts to average values of 36 K and 29 K respectively. These reductions in temperatures increase the air density which in turn increases the air mass flow rate (continuous line) and pressure ratio (dashed line) indicated in Figure 11- Right. For the interpretation of the results, it is important to indicate that the engine is operating at an approximately constant rotational speed; as a result, the shaft torque will increase with air and fuel flow increases. Subsequent injection of water at reduced injection rates shows similar benefits but at a lower magnitude of change. It is important to note that a reduction of injection rate by half does amount to almost half the benefit of performance improvement. For example, the drop in corrected CDT of 2%, 1% and 0.5% are: 36 K, 19 K and 10 K. That of the rise in corrected mass flows is 3.1%, 2.8% and 1.5% respectively, with the reference dry condition being that prior to the injection of water for each case.

Only the key investigation of 2% injection rate was conducted with the most number of runs – 7 experimental cases - as indicated in Table 2. The values are computed from averaging each reading during the time that water was injected, and comparing this with its corresponding “dry” value. The table shows the changes in performance parameters, inclusive of the specific compressor work for all the experimental runs. The corrected compressor work reduces as shown in Tab. 2 and the calculation is explained subsequently. Also presented are the mean values of the readings and their standard deviation. Considering that the thermocouples and pressure transducers can give measurement errors of 0.75% and 0.5% respectively, the variation seen between each experiment is acceptable.

Table 2 Changes in Engine Parameters with 2% water injection ratio

	CDT/ θ (K)	EGT/ θ (K)	$m_a\sqrt{\theta}/\delta$ (%)	PR (%)	C_w/θ (%)
Exp 1	-32.0	-33.7	3.9%	2.9%	-10.0%
Exp 2	-32.0	-37.7	3.0%	2.2%	-8.5%
Exp 3	-38.3	-33.1	2.8%	2.5%	-10.3%
Exp 4	-33.0	-37.2	3.0%	1.9%	-8.1%
Exp 5	-34.6	-23.9	3.0%	2.4%	-9.4%
Exp 6	-35.5	-28.8	2.9%	2.0%	-9.7%
Exp 7	-32.6	-26.8	2.8%	2.2%	-11.4%
Mean	-34.0	-31.6	3.0%	2.3%	-9.6%
SD +/-	2.2	4.9	0.3%	0.3%	1.0%

The specific compressor work (C_w) presented on Tab.2 and subsequent figures are the comparison between the “wet” and “dry” specific compression work. These two are calculated in a different way and arise from different assumptions. When water is injected, the pressure ratio will increase, along with the mass flow. The wet compression work thus has to be compared to the dry compression work but at the new pressure ratio (and mass flow for compressor power). To do this, the compressor inlet, outlet temperatures and pressure ratio are used to calculate the polytropic efficiency of the compressor. Then, assuming the efficiency stays constant, the dry work is re-calculated at the “wet” pressure ratio but assuming “dry” compression. This value is then corrected to account for inlet temperature variations by using the dimensionless factor, θ (Eq.1).

The wet compression work is calculated by adding the enthalpy changes of water vapour, dry air and liquid water as seen on Eq. 3.

$$(\dot{m}_a h_a + \dot{m}_v h_v)_1 + \dot{m}_{w1} h_{f1} + w_c = (\dot{m}_a h_a + \dot{m}_v h_v)_2 + \dot{m}_{w2} h_{f2} \quad (3)$$

The wet compression work (C_w) is then defined by,

$$C_w = C_{pa}(T_2 - T_1) + w_2(C_{pv}T_2 + h_{fg}) - w_1(C_{pv}T_1 + h_{fg}) + f_2 C_{pf}T_2 - f_1 C_{pf}T_1 \quad (4)$$

Where subscript 1 and 2 denote the entry and exit of the compressor respectively. T is the measured total gas temperature, w, the entry and exit water vapour content (specific humidity) of air, f, the liquid water-to-air ratio. $C_{pa,v,f}$ are the specific heat capacities of air, water vapour and liquid water, taken constant and equal to 1005, 1820, and 4180 kJ/kg. The entry conditions of liquid water and water vapour are known and can be measured at the intake; however, the exit humidity of the air and the amount of unevaporated water cannot be measured. This is estimated by measuring the compressor exit temperature and calculating the amount of water that would need to evaporate to cause that decrease in temperature. Taking the thermodynamic model presented in Refs [8,44], the following equation can be derived to calculate the amount of evaporated water; which, by mass conservation, will be equal to the increase in specific humidity of the air.

$$dw = \left(\frac{\ln(PR)}{\ln(TR)} - \frac{\gamma}{\gamma - 1} + \frac{(n_{poly} - \gamma)}{(\gamma - 1)(n_{poly} - 1)} \right) * \frac{R_a}{h_{fg}} (T_2 - T_1) \quad (5)$$

Where PR is the pressure ratio (P_2/P_1), TR the temperature ratio (T_2/T_1), γ , the specific heat ratio, R_a , the gas constant of air, h_{fg} the heat of vaporization of water, and n_{poly} is a constant related to the polytropic compressor efficiency η_{poly} [32],

$$n_{poly} = \frac{\eta_{poly}\gamma}{\eta_{poly}\gamma - \gamma - 1} \quad (6)$$

Equations 5 and 6 are derived from an energy balance across the compressor and removing the adiabatic condition. Instead of assuming an adiabatic process, it is assumed that there is a heat transfer term, which equates to the latent heat of evaporation that is absorbed by the water. The reader is referred to ref. [8,44,45] for further details on the derivations of these equations. An estimation of the unevaporated water is then obtained using Eq. 5. The water vapour and liquid water fractions are then used in Eq.4 to calculate the wet compression work.

Figure 12 shows the same engine parameters as Tab.2 but this time for different water-to-air ratios (0.5 - 2%). The figure also includes the error bands for the cases with the highest amount of experiments (1, 2%), derived from the standard deviation of the samples. The case for 0.5% does not include graphical error bands as the sample size was smaller (3 experiments). As stated above, 7 experiments were done for the largest amount of ingested water (2 %) and 5 experiments were conducted for the case with 1 %. The mean percentage change of each parameter is displayed for extra clarity. All the values presented have been corrected to ISA conditions and were taken at a frequency of 1 Hz. The presented values are representative of over 7,000 data points taken at each operating condition (See Appendix B for more information). The bleed air from the compressor was always kept the same.

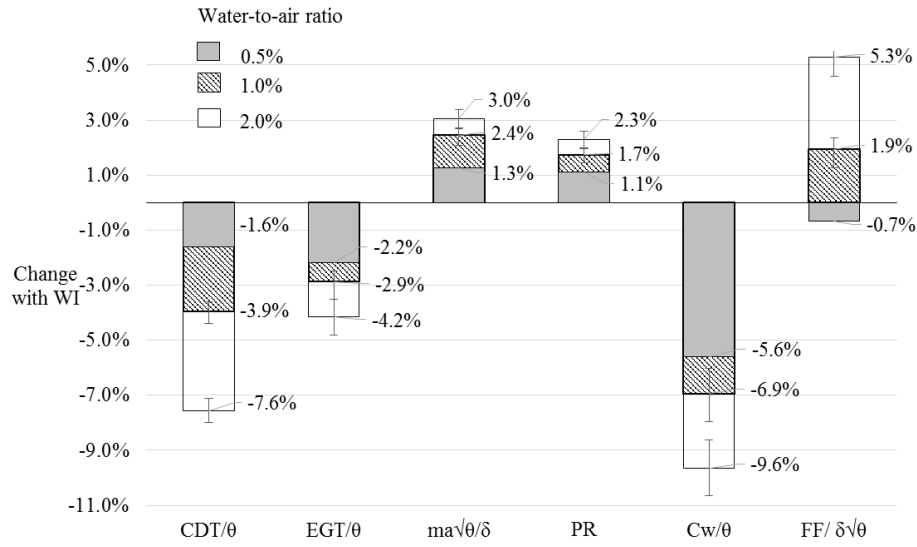


Figure 12 Engine parameter changes with water injection at different water-to-air-ratios (0.5-2%)

As expected, higher water injection ratios cause higher temperature reductions resulting from the increased amount of water in use, hence the corresponding corrected mass flow rise shown in Figure 12. The corrected fuel flow also increases with the amount of injected water, though at a higher magnitude. As such, this increase in the fuel-to-air ratio could bring about a rise in the combustor exit temperature that is not directly measured. However, this is not the case since the evaporation of water is still expected to take place in this combustor due to the relatively low operating temperature and pressure of the compressor. This increase in fuel-to-air ratio observed is consistent with other findings of combustor water injection previously discussed. However, this is not the case for 0.5% injection ratio where the least amount of water is used, suggesting a predominant effect of compressor intercooling (less water reaches the combustion chamber). This is evident by the fact that the compressor specific work reduction is high for the low water-to-air ratios compared to what is achieved when the amount of water is doubled from 0.5% to 1%. The amount of water exiting the compressor can also be estimated using Equ. 5 and the measured CDT. It is important to reiterate that the performance benefits of compressor intercooling are also prevalent at the high injection rates and signified by the drop in CDT and specific work of the compressor in these cases. The compressor work shows large uncertainties compared to the CDT, mass flow and PR. This arises from the fact that the compressor work is dependent on two measurable properties: the temperature and pressure. In addition, the calculation of evaporated water (from Eq.5), needed for estimating the wet compression work adds to the uncertainty.

For the cases of increased corrected fuel flow, more torque is expected to be produced at the turbine. Higher actual turbine work, in turn, increases the compressor power that is indicated by the rise in pressure ratio. Nevertheless, the compressor does less specific

work (in comparison to the increased mass flow) due to the increase in density resulting from intercooling. The standard deviation seen for the EGT was larger than that seen for the CDT, mainly because the EGT was measured at only one position, while the former was measured in two locations and averaged. It is expected that the temperature distribution at the exit of the engine will not be uniform and so an improvement to these conditions would be to measure at circumferential and radial positions across the exit of the engine as recommended in Ref. [20].

The behaviour of the engine is linked to the way in which it is operated. Previous studies [12], considered the modelling of a turbofan engine under compressor water injection. In the analysis, the constraint was the thrust which was kept constant when injecting water. For this operation, the engine rotational speed and compressor specific work would reduce. The thermodynamic efficiency of the engine improves as a result of the reduced required fuel flow for the same useful work output (net thrust). An increase in the fuel-to-air ratio is applicable to both combustor and compressor water injection but with augmented power output or thrust. Studies on the latter show an increase of up to 20% in the useful work [46–48].

4.4 Emissions with water injection

The changes in NO_x and CO emissions as a percentage of the dry (ppmv) value are presented in Figure 13. The figure indicates that as more water is injected, the NO_x emissions reduce further; and this is attributed to more cooling of the engine. The highest reduction of 25% occurred at 2% water-to-air ratio is a case for which more water entered the combustor, as such, the CO emissions increased by about 41%. From the indicated droplet distribution previously discussed, more than 40% of the injected water volume was measured to have droplets between 22 and 35 μm . These droplets are not expected to fully evaporate in the compressor and thus will reach the combustor. The unevaporated water attempts to quench the flame and brings about a reduction in combustion efficiency; a phenomenon experienced when injecting water directly in the combustor [49,50]. The magnitude of these changes decreases with reduced water-to-air ratios. In this study, the TIT is not measured but expected to drop slightly (based on the inference from the decreases in NO_x) and the power output is increased, as signified by the increase in PR and fuel-to-air ratio cases.

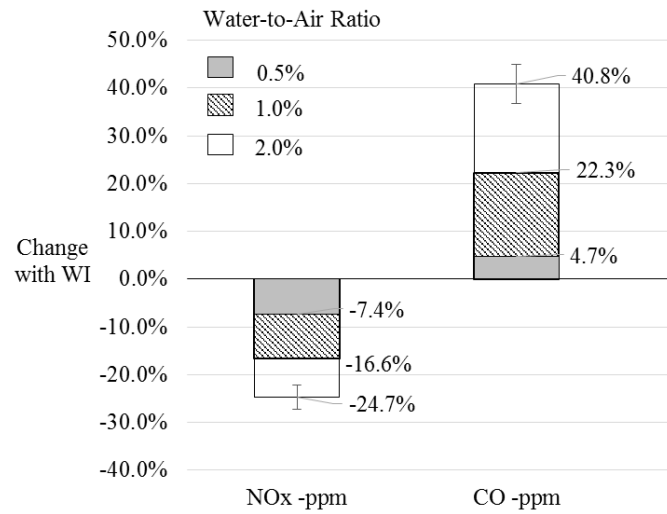


Figure 13 NO_x and CO changes with water injection at 0.5, 1 and 2%

Other studies as discussed in the Introduction have obtained greater reductions in NO_x emissions. This is mainly a result of the operating temperature and pressures of these larger engines. With respect to compressor water injection, the larger engine compressors are more favourable, operating with a CDT that is about twice the value recorded here and with at least 10 times the PR. It is rarely the case that there would be significant unevaporated water reaching the combustors with these same droplet sizes or injection conditions. For the combustor, large civil aircraft reach peak combustor temperatures of about 1,800 K, leading to greater NO_x production. However, these operating temperatures present more beneficial conditions for water injection. A 2-spool turbofan with a take-off PR of 30.5 has a NO_x Emission Index of 33 gNO_x/kg of fuel. During idle, at low power settings, this value drops to 4.5 g/kg due to the low operating temperatures and pressures [51]. The engine considered here has a “dry” emission index of 2.9 g/ kg; as such it already produces considerably less NO_x at baseline than what would be noted on a large engine.

5- Conclusions

This work has examined an impaction pin nozzle spray characteristics at different injection pressure and water temperature, alongside the impacts of injecting generated droplets into the compressor, as well as further ingestion into the combustor to reduce NO_x. The first part of the study shows smaller droplets generated when the higher injection pressure is used. This effect is seen to change axially and transversely, away from the nozzle. The influence of water temperature ranging from 288 K to 325 K is seen to have no influence on the droplet size generated.

For the engine tests, the highest water pressure was selected (138 bar) and the nozzles were installed at the engine's intake. The droplet size at the exit of the injection nozzle was measured and the droplet size at the engine intake was estimated at $37\mu\text{m}$ (D_{v90}) based on correlations. This study shows that injecting 2% of water by mass flow had the following effects on engine performance:

- Reduces the CDT by up to 34K (7%) and EGT by up to 29K (4%).
- Increases pressure ratio and mass flow by up to 2.3 and 3% respectively.
- Increases the fuel-to-air ratio by 2.2% that is associated with the 40% rise in CO.
- NO_x reduces by 25%.

The amount of NO_x reduction at high water-to-air ratios are attributed to a dominant combustor effect, while that of the least amount of water used is mainly based on the compressor effects. In all cases, the compressor specific work and CDT reduces, and the pressure ratio rises, owing to the benefit of compressor water injection on the performance. As shown in analytical studies of compressor water injection, reducing the droplet sizes further will bring about an improvement in the stated parameters.

The present work can serve as a validation case for future numerical simulations on this engine type while serving as evidence of emissions reduction potentials for larger engines. Experimental studies are required, especially in the area of the modern turbofan engines with axial flow compressors, where water injection appears to be more favourable. The small size of the engine investigated causes continuous evaporation from the compressor through to the combustor, that is not likely to occur for larger engines at these water-to-air ratios. The utmost reductions of NO_x for compressor only cooling are expected to be when the same required thrust or power is achieved (rather than augmentation), that will bring about a reduction of the fuel utilised.

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Nomenclature

APU	Auxiliary Power Unit	η_{poly}	Polytropic efficiency
ASME	American Society of Mechanical Engineers	ICAO	International Civil Aviation Organization
CC	Combustion Chamber	ISA	International Standard Atmosphere
CDT	Compressor Discharge Temperature	K	Nozzle characteristic constant
CO	Carbon Monoxide	μ	correction factor- mass flow
CO ₂	Carbon Dioxide	m_a	Air Mass Flow
C _p	Specific heat (J/ kg K)	m_w	water mass flow
D	Distance from the nozzle	NO _x	Nitrogen Oxides
δ	correction factor- distance	η_{poly}	polytropic coefficient
δ	Pressure Correction factor P/Pisa	π	correction factor- pressure
D32/ SMD	Sauter Mean Diameter	P	Pressure
D _v 10	Droplet diameter: 10% of the volume	ppm	Parts Per Million (Volume)
<u>D_v</u> 50	Droplet diameter: 50% of the volume	PR	Pressure Ratio
D _v 90	Droplet diameter: 90% of the volume	P _w	Water Pressure
EGT	Exit Gas Temperature	θ	Temperature correction factor T/T _{isa}
EI	Emission Index	Ra	Specific gas constant of air 287 J/kg K
f	injection ratio, %	RPM	Revolutions Per Minute
FF	Fuel Flow	SD	Standard Deviation
FS	Flat Spray	T	Temperature
FTIR	Fourier Transform Infrared	TIT	Turbine Inlet Temperature
γ	Air specific heat ratio, 1.4	TR	Temperature Ratio
h	Specific enthalpy (J/kg)	Va	Air Velocity
HC	Hydro Carbons	WAR	Water-To-Air Ratio
<u>h_{fg}</u>	Heat of vaporization of water 2500 kJ/kg	ω	correction factor- air velocity
HC	Hollow Cone	w	specific humidity
IP	Injection Pin	w _c	Compressor Specific Work

References

1. Future AS. ICAO Environmental Report 2016. 2016;
2. EEA (European Environment Agency). European Aviation Environmental Report 2016. 2016. Available at: DOI:10.2822/385503
3. Block N. DA., Igie U. Case For Exploring Compressor Water Injection For Airport Emission Reduction GT2017-64780. In: ASME (ed.) Asme turbo expo: Power for land, sea and air. Charlotte: American Society of Mechanical Engineers (ASME); 2017. p. TBC.
4. Mishra A. Aviation Environment Circular 1 of 2013. General of Civil Aviation. New Delhi; 2010.
5. Deonandan I., Balakrishnan H. Evaluation of Strategies for Reducing Taxi-out Emissions at Airports. 9th AIAA Aviation Technology, Intergration and Operations (ATIO) conference. 2010. pp. 1–14. Available at: DOI:10.2514/6.2010-9370
6. Liu Y., Sun X., Sethi V., Nalianda D., Li Y., Wang L. Review of modern low emissions combustion technologies for aero gas turbine engines Committee on Aircraft Engine Emissions Committee on Aviation Environmental Protection Committee on Aircraft Noise. Progress in Aerospace Sciences. Elsevier Ltd; 2017; 94(August): 12–45. Available at: DOI:10.1016/j.paerosci.2017.08.001
7. Grönstedt T., Rolt A., Tantot N., Xisto C., Donnerhack S., Schmitz O., et al. Ultra Low Emission Technology Innovations for Mid-Century Aircraft Turbine Engines. ASME Turbo Expo: Turbomachinery Technical Conference and Exposition. 2016. pp. 1–13.
8. Block Novelo DA., Igie U. Aero engine compressor cooling by water injection - Part 1: Evaporative Compressor Model. Energy. 2018; 160: 1224–1235. Available at: DOI:10.1016/j.energy.2018.05.171
9. Sun L., Zheng Q., Li Y., Luo M., Wang J., Bhargava RK. Numerical Through Flow Simulation of a Gas Turbine Engine With Wet Compression. Asme turbo expo: Power for land, sea and air. Copenhagen; 2012. pp. 1–13.
10. Sun L., Sun T., Wang Y., Yang W. Numerical Simulation of Pollutant Emission of A Turbojet Engine with Water Injection. ASME Turbo Expo 2016: Turbomachinery Technical Conference and Exposition GT2016. Seoul; 2016. pp. 1–9.
11. Daggett DL., Ortanderl S., Eames D., Berton JJ., Snyder CA. Revisiting Water Injection for Commercial Aircraft. World Aviation and Exposition. Reno, USA; 2004.
12. Block Novelo DA., Igie U. Aero engine compressor cooling by water injection - Part 2: Performance and emission reductions. Energy. 2018; 160(x): 1236–1243. Available at: DOI:10.1016/j.energy.2018.05.171
13. Utamura M., Takehara I., Horii N., Kuwahara T. A New Gas Turbine Cycle for

- Economical Power Boosting. The American Society of Mechanical Engineers. 1997; 97-AA-142: 1–10.
14. Utamura M., Takehara I., Karasawa H. MAT, a novel, open cycle gas turbine for power augmentation. *Energy Conversion and Management*. 1998; 39(16): 1631–1642. Available at: DOI:10.1016/S0196-8904(98)00088-0
 15. Jolly S. Wet compression - a powerful means of enhancing combustion turbine capacity. Power-Gen International. Orlando, Florida; 2002.
 16. Roumeliotis I., Mathioudakis K. Water Injection on Compressor Stage Operation. *Transactions of ASME*. 2007; 129(July): 778–784. Available at: DOI:10.1115/1.2718223
 17. Schnitzler JP., von Deschwanen I., Clauss S., Berna F., Dohmen HJ., Werner K. Experimental Determination of a Four Stage Axial Compressor Map Operating in Wet compression. *ASME Turbo Expo 2014: Turbine Technical Conference and Exposition*. Dusseldorf; 2014. pp. 1–10.
 18. Munari E., D’Elia G., Morini M., Pinelli M., Spina PR. Stall and Surge in Wet Compression: Test Rig Development and Experimental Results. *Journal of Engineering for Gas Turbines and Power*. 2019; 141(July): 1–12. Available at: DOI:10.1115/1.4042474
 19. Bahr DW., Lyon TF. NO_x Abatement In Aircraft-Derivative Turbine Engines. The American Society of Mechanical Engineers. 1984; 84-GT-103.
 20. Walsh PP., Fletcher P. *Gas Turbine Performance*. 2nd edn. Oxford: Blackwell Science; 2004. 646 p.
 21. Shahpouri S., Houshfar E. Nitrogen oxides reduction and performance enhancement of combustor with direct water injection and humidification of inlet air. *Clean Technologies and Environmental Policy*. Springer Berlin Heidelberg; 2019; (0123456789). Available at: DOI:10.1007/s10098-019-01666-4
 22. Daggett DL., Fucke L., Hendricks RC., Eames DJH. Water Injection on Commercial Aircraft to Reduce Airport Nitrogen Oxides. *Nasa/Tm—2010-213179*. 2010; (March).
 23. C. W. Control of NO_x Emissions from Industrial Gas Turbine Combustion Systems. *A&WMA Annual Meeting Vol.5*. Anaheim, California; 1989.
 24. William SB., Henderson RE. Aircraft Exhaust Pollution and its effect on the U.S. Air Force AD-783 828. Ohio, Wright Patterson Air Force Base; 1974.
 25. Bhargava RK., Meher-Homji CB., Chaker MA., Bianchi M., Melino F., Peretto A., et al. Gas Turbine Fogging Technology: A State-of-the-Art Review—Part II: Overspray Fogging—Analytical and Experimental Aspects. *Journal of Engineering for Gas Turbines and Power*. 2007; 129(2): 454. Available at: DOI:10.1115/1.2364004
 26. Chaker M., Meher-Homji CB. Gas Turbine Power Augmentation: Parametric

- Study Relating to Fog Droplet Size and Its Influence on Evaporative Efficiency. *Journal of Engineering for Gas Turbines and Power*. 2011; 133(9): 092001. Available at: DOI:10.1115/1.4002883
27. Chaker M., Mee T. Design Consideration of Fogging and Wet Compression Systems as Function of Gas Turbine Inlet Duct Configurations. ASME Turbo Expo: Turbine technical conference and exposition GT2015. 2018. pp. 1–14.
 28. Chaker M a. Key Parameters for the Performance of Impaction-Pin Nozzles Used in Inlet Fogging of Gas Turbine Engines. *Journal of Engineering for Gas Turbines and Power*. 2007; 129(2): 473. Available at: DOI:10.1115/1.2364006
 29. Savic S., Mitsis G., Haertel C., Khaidarov S., Pfeiffer P. Spray Interaction and Droplet Coalescence in Turbulent Air-Flow. Experimental Study With Application To Gas Turbine High Fogging. 2002; (September): 40–45.
 30. Chaker M a. Key Parameters for the Performance of Impaction-Pin Nozzles Used in Inlet Fogging of Gas Turbine Engines. *Journal of Engineering for Gas Turbines and Power*. 2007; 129(2): 473. Available at: DOI:10.1115/1.2364006
 31. Malvern Instruments Ltd. man0368 Issue 3.0. Spraytec User Manual. Worcestershire; 2007.
 32. ASME. Gas Turbine Inlet Air-Conditioning Equipment- Appendix A Method of Testing Atomizing Nozzles PTC 51 - 2011. 1st edn. 2011. 132 p.
 33. Chaker M., Meher-Homji CB., Mee T. Inlet Fogging of Gas Turbine Engines—Part II: Fog Droplet Sizing Analysis, Nozzle Types, Measurement, and Testing. *Journal of Engineering for Gas Turbines and Power*. 2004; 126(3): 559. Available at: DOI:10.1115/1.1712982
 34. Chaker M., Meher-homji CB., MEE TI. Inlet Fogging of Gas Turbine Engines-Experimental and Analytical Investigations on Impaction Pin Fog Nozzle Behaviour GT-38801. ASME Turbo Expo 2003: Power for Land Sea and Air. Atlanta; 2003. pp. 1–17.
 35. Bhargava RK., Meher-Homji CB., Chaker M a., Bianchi M., Melino F., Peretto A., et al. Gas Turbine Fogging Technology : A State-of-the-Art Review — Part II : Overspray Fogging — Analytical. *Journal of Engineering for Gas Turbines and Power*. 2007; 129(April 2007). Available at: DOI:10.1115/1.2364004
 36. Chaker M., Meher-Homji CB. Gas Turbine Power Augmentation: Parametric Study Relating to Fog Droplet Size and Its Influence on Evaporative Efficiency. *Journal of Engineering for Gas Turbines and Power*. 2011; 133(9): 092001. Available at: DOI:10.1115/1.4002883
 37. Chaker M., Meher-Homji CB., Mee T. Inlet Fogging of Gas Turbine Engines—Part II: Fog Droplet Sizing Analysis, Nozzle Types, Measurement, and Testing. *Journal of Engineering for Gas Turbines and Power*. 2004; 126(3): 559. Available at: DOI:10.1115/1.1712982
 38. Daly M. Jane's Aero-engines. 2nd edn. IHS (ed.) Janes Information Group; 2015.

449 p.

39. Volponi AJ. Gas Turbine Parameter Corrections. *Journal of Engineering for Gas Turbines and Power*. 1999; 121(October 1999): 613–621.
40. Turbomecha. Turbomeca Artouste 520 Airborne Auxiliary Power Trident Installation Manual. 1971.
41. Igie U., Diez-Gonzalez P., Giraud A., Minervino O. Evaluating Gas Turbine Performance Using Machine-Generated Data: Quantifying Degradation and Impacts of Compressor Washing. *Journal of Engineering for Gas Turbines and Power*. 2016; 138(12): 122601. Available at: DOI:10.1115/1.4033748
42. ICAO-International Civil Aviation Organisation. Environmental Protection, Annex 16, Volume II Aircraft Engine Emissions. Chicago; 2008.
43. Spalding DB. *Combustion and Mass Transfer*. 1st edn. London: Pergamon Press; 1979. 406 p.
44. Zheng Q., Sun Y., Li S., Wang Y. Thermodynamic Analyses of Wet Compression Process in the Compressor of Gas Turbine. *Journal of Turbomachinery*. 2003; 125(3): 489. Available at: DOI:10.1115/1.1575254
45. Hill PG. Aerodynamic and Thermodynamic Effects of Coolant Injection on Axial Compressors. *The Aeronautical Quarterly*. 1963; November: 331–348.
46. Bhargava R., Meher-Homji CB. Parametric Analysis of Existing Gas Turbines With Inlet Evaporative and Overspray Fogging. Volume 4: Turbo Expo 2002, Parts A and B. 2002; 4 A(January 2005): 387–401. Available at: DOI:10.1115/GT2002-30560
47. Wilcox EC., Trout AM. Analysis of Thrust Augmentation of Turbojet Engines by Water Injection at Compressor Inlet Including Charts for calculation Compression Process with Water Injection. 1951.
48. Sanaye S., Tahani M. Analysis of gas turbine operating parameters with inlet fogging and wet compression processes. *Applied Thermal Engineering*. Elsevier Ltd; 2010; 30(2–3): 234–244. Available at: DOI:10.1016/j.applthermaleng.2009.08.011
49. Roumeliotis I., Mathioudakis K. Evaluation of water injection effect on compressor and engine performance and operability. 2010; 87: 1207–1216. Available at: DOI:10.1016/j.apenergy.2009.04.039
50. Lefebvre AH., Dilip RB. *Gas Turbine Combustion Alternative Fuels and Emissions*. 3rd edn. New York: CRC Press; 2010. 560 p.
51. ICAO. ICAO Engine Exhaust Emissions Data Bank. 2013. Available at: <https://www.easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank#6>

Appendix A- Nozzle Selection

Figure A1 shows the behaviour of the four types of nozzles investigated here when subjected to increasing pressure. The Flat Spray (FS) nozzles are rated at low pressures and can produce droplets in the range of 100 – 450 micron at the highest tested pressure of 90 bar. The hollow cone nozzles (HC), despite having different spraying angles, all had very similar droplet diameters throughout the pressure range investigated. The droplet sizes were also too large for the required application. The Impaction pin (IP) and Swirl Jet Nozzles (SJ) produced the smallest diameters of all, and operate at higher pressure ranges. An IP nozzle was selected over the SJ as they are capable of delivering the higher flow-rate required to meet the targeted 2% water-to-air ratio.

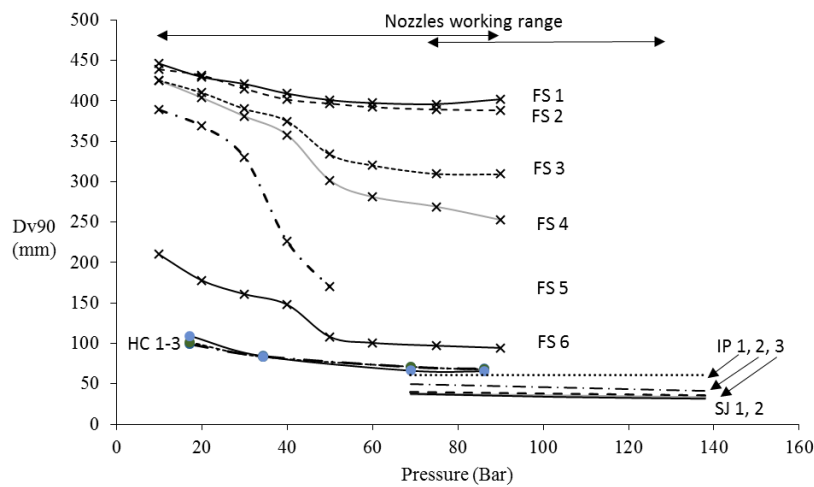


Figure A 1 Behaviour of droplet size (Dv90) for 11 different nozzles at increasing pressure.

Appendix B- Statistical significance of the data

Droplet measurement:

The values reported on the main text for droplet size are time-averages of the readings taken from the laser. The laser software has a function that allows the user to select a time range, in our case being 1- 2 minutes (60- 120 readings), and to get a time-averaged size of the droplet distribution for that range. Figure B1 shows the droplet diameter with time for the case when the water was applied to moving flow (engine intake). It can be seen that despite the fact that the readings were taken for 2 minutes, the droplet size values are quite stable. This was the case for most of the reported values on the main text.

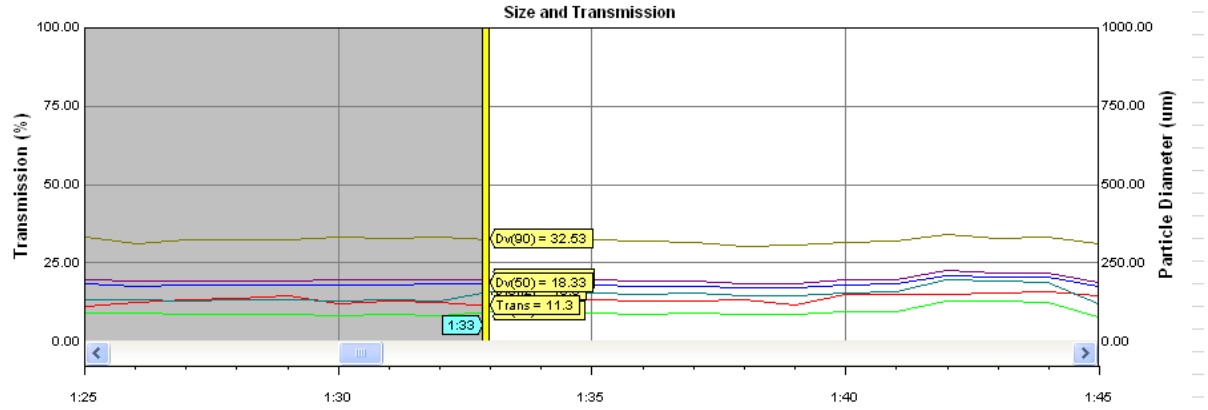


Figure B 1 Droplet Size Distribution with time

Engine Performance Monitoring

The values presented on Figs 10, 11 and Tab.2 are the result of time-averaging each performance parameter, and comparing it to its corresponding dry case. For example, the “dry” CDT was monitored for 8 minutes, and about 480 readings were taken. Water was then injected and the CDT was monitored for another 8 minutes. The average and standard deviation of each sample, for each performance parameter were recorded. Then, a normal probability distribution curve was fitted to the results following Eq. B1. Where σ is the standard deviation, x is each individual temperature (or pressure) reading, and μ is the mean of all the measurements.

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (B1)$$

The probabilistic distribution for the CDT when water was injected at a ratio of 2% is shown in Fig, B2- Left. In this case, the mean of the 480 readings was 436.11 K and the Standard deviation 0.467 K (0.11%). For this case, and all the others observed, even if a confidence level of 2 standard deviations (2σ) is taken (95.4% confidence), the mean won't change significantly since the SD is so low.

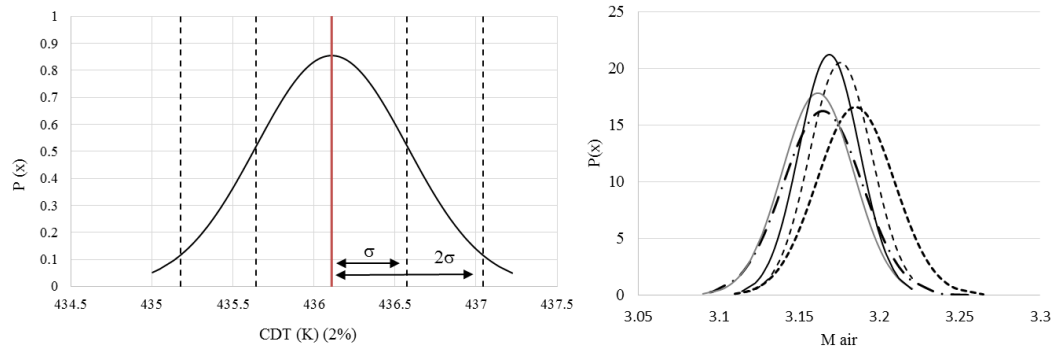


Figure B 2 Normal distribution of the means of CDT (2%) (Left, and Air mass flow (dry)(Right)

Figure B2-Right shows a similar distribution but this time for the air mass flow (dry) and comparing 5 experiments. Each Gaussian curve represents one case. It can be noted that the mean values of each curve are very close together. The distance between these means can be evaluated by the Standard Deviation between the experiments. A similar SD is presented in Tab.2 comparing the changes in performance with water injection for different experiments, against their corresponding dry value. Figure B2- Left represents the case for 2%, and it can be plotted alongside the cases for 1%, 0.5% and dry as seen in Figure B3. The temperature is seen to reduce with increasing injection ratio, but also it is also perceivable how close the distributions are from the mean. This all is an indicator that the averaged values used for the analysis are representative of the conditions of the gas inside the engine, and the experiments have good repeatability.

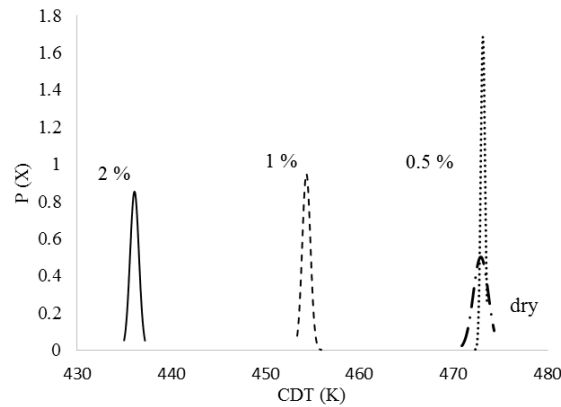


Figure B 3 Normal distribution of CDT for the case of dry, and 0.5-2% injection ratio

Additional Information for Chapter VII- Nozzle Analysis

Prior to the experimental results presented in Chapter VII, 14 different nozzles were tested, and the nozzle type with the best droplet diameter/flow configuration was chosen for further testing. For the nozzle selection, all the samples were measured 75 mm away from the nozzle exit, in agreement with the ASME standard for inlet fogging nozzles. The testing configuration is depicted in Fig. AI 1. Further details regarding the experimental set-up and individual nozzle results can be found in Ref.[1]. The keen reader is directed to this reference, which is a thesis developed as part of this research and contains detailed descriptions of the equipment, methods, and nozzle testing results.

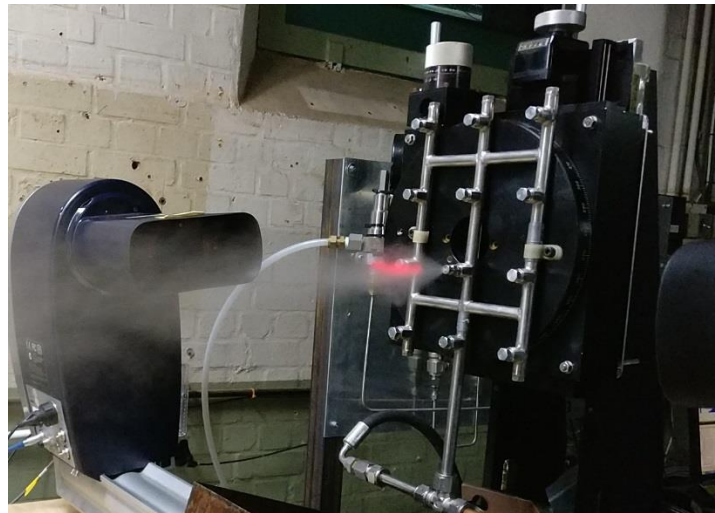


Figure AI 1 Droplet Measurement Set-Up

The measurements were done always at three positions across the plume, as shown in Fig. AI 2. The laser output gives the droplet size distribution, along with the concentration value (C_v), which is the number of particles considered for that distribution. By multiplying each droplet diameter with the corresponding C_v , and dividing by the total number of particles considered during sampling, a weighted average of the plume can be obtained (Eq. 1). The top, middle, and bottom positions were always the same for each type of nozzles tested, this was controlled by means of the daedal positioning system. Since each nozzle has a different spraying angle, the relative “top” and “middle” points were adjusted depending on the nozzle type.

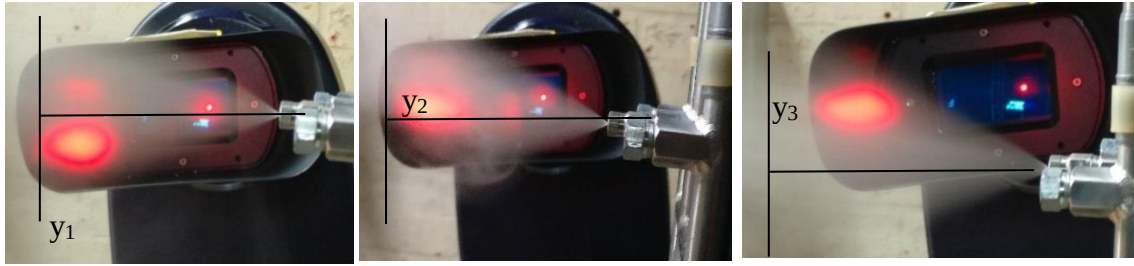


Figure AI 2 Droplet size measurements taken across the plume.

$$D_{avg} = \frac{[Dy_1 * Cv_{y1} + Dy_2 * Cv_{y2} + Dy_3 * Cv_{y3} + \dots + Dy_n]}{[Cv_{y1} + Cv_{y2} + Cv_{y3} + \dots + Cv_{yn}]} \quad (1)$$

Each nozzle was tested at its nominal working pressure, this was done to ensure that the nozzle was working in optimum conditions and that the integrity of the element was not jeopardized. In addition to taking measurements at the top, centre, and bottom, one extra measurement was taken of the plume core only as explained earlier in [Chapter VII](#). This was achieved by setting the laser at the middle position and by shading the sides of the plume. This procedure was only applied to conically shaped sprays and was not necessary for flat-fan nozzles.

Table AI 1 Nozzle characteristics from the manufacturer. Dv 90 was measured with a laser

Nozzle ID	Nozzle Type	Orifice Diam (mm)	Spraying Angle (degrees)	Nominal Flow (LPM)	Dv 90 @ P _{max}
FS 1	Flat Spray	1.4	50	5.1 @ 20 bar	402
FS 2	Flat Spray	1.1	40	3.1 @ 20 bar	388
FS 3	Flat Spray	0.66	25	1.0 @ 20 bar	309
FS 4	Flat Spray	0.91	65	2.0 @ 20 bar	252
FS 5	Flat Spray	0.38	65	0.3 @ 20 bar	170
FS 6	Flat Spray	0.46	95	0.5 @ 20 bar	94
HC1	Hollow Cone	0.74	70	1.3 @ 20 bar	65
HC2	Hollow Cone	0.64	80	1.2 @ 20 bar	61
HC3	Hollow Cone	-	80	1.4 @ 20 bar	60
IP 1	Impaction Pin	0.20	-	0.3 @ 68 bar	60
IP 2	Impaction Pin	0.13	-	0.1 @ 68 bar	41
IP 3	Impaction Pin	0.15	-	0.2 @ 68 bar	37
SJ 1	Swirl Jet	0.2	-	0.05 @ 68 bar	35
SJ 2	Swirl Jet	0.1	-	0.02 @ 68 bar	33

Four type of nozzles were tested: Hollow cone (HC), Flat Spray (FS), Swirl Jet (SJ), and Impaction Pin (IP). Within each type of nozzle, different configurations like spray angle or orifice diameter were tested, to make a total of 14 different nozzles. Table AI 1, summarizes the characteristics of each nozzle, as given by the manufacturer. The column corresponding to the droplet diameter (D_v 90) gives the values of the measured diameter

at the highest operating pressure for each nozzle. These measurements were taken using the Laser equipment.

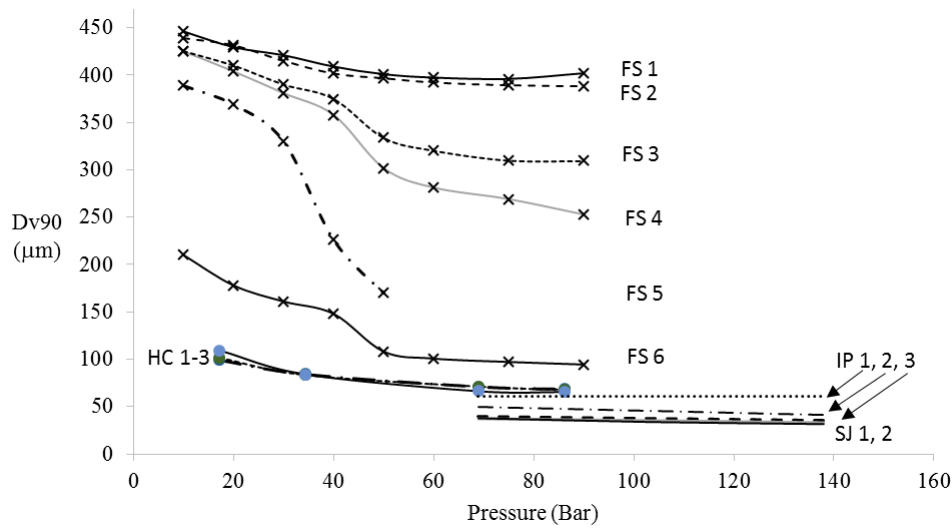


Figure AI 3 Nozzles behaviour with increasing pressure

The figure shows the compromise between droplet size and flows (in Litres per minute, LPM). Nozzles with a greater orifice, produce higher flows but considerably larger droplet diameters. Since smaller droplets are required for this application, all the Flat Spray and Hollow Cone Nozzles were neglected. The nozzle that promises the smaller droplet diameter is the Swirl Jet nozzle with an orifice diameter of 0.1 mm. However, this nozzle can only produce 0.02 LPM. For the engine testing, a maximum flow of 3.6 LPM is required, hence 18 nozzles would be required to match the desired water quantity. Since the inlet of the engine is less than 300 mm in diameter, it is not practical to install 18 nozzles in such a narrow space; the vicinity of the nozzles would inevitably lead to high droplet coalescence which could considerably increase the droplet diameter distribution. For this reason, an impaction pin nozzle, with an orifice diameter of 0.15 mm was chosen. This nozzle (IP3) is a good compromise between small droplet diameters and water flow. The nozzle manifold used in the engine has 12 nozzles with enough spacing between them to try to minimize droplet merge. Figure AI 3 shows the behaviour of the four groups of nozzles when subjected to increasing pressure. All the Flat Spray nozzles are rated at low pressures and can produce droplets in the range of 100 – 450 micron at the highest tested pressure of 90 bar. These droplets are all larger than what is needed for the wet compression application. It is interesting to see that the higher pressure has an effect of decreasing the droplet diameter, but only up to a pressure of about 60 bar. After that the reduction is negligible. The hollow cone nozzles (HC), despite having different spraying angles, all had very similar droplet diameters throughout the pressure range investigated, however, the droplet sizes were also too large for the required application. Finally, the

impaction pin (IP) and Swirl Jet Nozzles (SJ), produced the smallest diameters of all, and operate at higher pressure ranges



Figure AI 4 Impaction pin (left) and Swirl Jet (Right) nozzles plume

Figure AI 4 shows the difference between the plume of an impaction pin nozzle and that of a swirl jet nozzle. It is visible how the impaction pin nozzle can deliver much higher flow rates, but at the expense of greater droplet diameters. Figure AI 5 from left to right depicts the hollow cone and flat spray (65 and 25 degrees) nozzles. The shape and density of the different plumes can be perceived with the naked eye.



Figure AI 5 Hollow cone (Left), Flat Spray 65° angle (centre) and Flat Spray 25° angle (right) plumes

An important characteristic noticed when testing flat spray nozzles at increasing pressure, was that the droplet size distribution became wider (further away from the mean), as the pressure was increasing. Figure AI 6, shows how for 10 bar of pressure, the droplet diameters have the following distribution: 10% of the volume is distributed in droplets of 78 μm or smaller, 50% of the volume in droplets smaller than 213 μm (D_{v50}), and 90% of 425 μm or smaller. For this case, the distribution curve is wide; the smallest size is 78, and the larger is 425 (5.4 times larger). As the pressure increases to 90 bar, the smallest

size (Dv10) is 22 μm , much smaller than at 10 bar, and the largest size also reduces, but not as much, and becomes 303 μm . In this case, the smallest droplet is now 13 times smaller than the larger one, meaning the distribution is becoming less and less uniform. The droplet size distribution for these types of nozzles is much wider compared to impaction pin nozzles. For these type of nozzles, the smallest size measured (Dv10) was seen to be 2 to 3 times smaller than the largest size (Dv 90), and this proportion was respected across the investigated pressures.

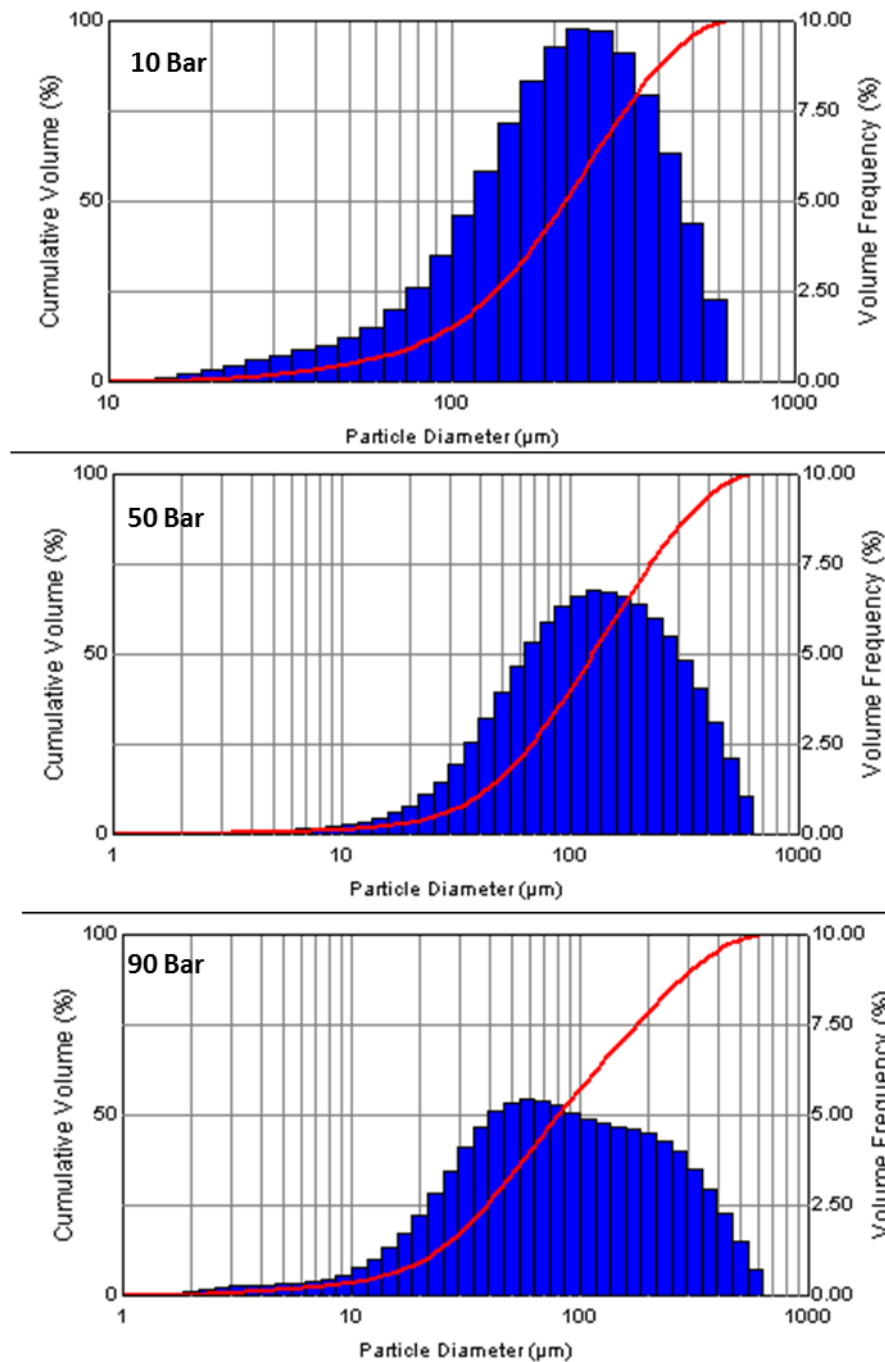


Figure AI 6 Droplet size distribution with increasing pressure for Flat Spray Nozzles

References to the Additional Information Section:

- [1] Prakash, V., 2018, “Experimental Investigation of Compressor Water Injection in Gas Turbine Engine to Reduce NO_x Emissions,” Cranfield University.

VIII. Conclusions and Future Work

“Never before have we had such an awareness of what we are doing to the planet and never before had we had the power to do something about that. We have a responsibility to care for our planet. The future of humanity and indeed all life on earth now depends on us”.

Sir David Attenborough

“Our intelligence and our technology have given us the power to affect the climate. How will we use this power?”

Carl Sagan

1- Conclusions

Compressor water injection was considered as a potential solution to reduce airport NO_x emissions. The high enthalpy of vaporization of water, compared to other substances, makes it a highly efficient intercooler that reduces the cycle operating temperature and NO_x emissions in up to 10% and 50% respectively. This approach was considered here to be applied only during take-off and climb, up to an altitude of 3,000 ft. or 914 m. To account for the effects of water injection, an analytical evaporative tool was developed, and used in conjunction with two in-house performance simulation tools, *Hermes*, and *Turbomatch*. The trends observed with these numerical tools were compared against an experiment performed on a single-shaft gas turbine. Similar trends were observed with the experimental engine, as those calculated on the simulated engines. In the simulations, smaller water droplets were seen to be more beneficial for compressor injection, as they follow the flow path thereby reducing the possibility of blade impingement or damage. Distributing the water mass in a larger number of droplets, by means of reduced droplet diameter, also increases the intercooling efficiency ensuring complete evaporation within the compressor. If water is applied after the low-pressure compressor (commonly referred to as the “fan”), the droplets will be injected into a hot and dry medium. These conditions favour evaporation and extend the application of water injection into low ambient temperatures and/or high ambient humidity. This study thus suggests that water injection can be applied over a wider environmental range than previously thought.

The intercooling effect inside the compressor was shown to lower the specific compressor work, thereby reducing the amount of specific energy that the turbine needs to deliver to the compressor. This resulted in more energy available at the exit of the turbine for the same throttle setting. In aero-engines, this energy is directly transferred into augmented thrust. If the throttle setting is lowered to restore the “dry” thrust, the reduced compressor work will result in a fuel saving while the water is applied. Depending on the engine architecture, the fuel savings seen on an uninstalled-static engine were between 5.3 and 7.8 %. The resulting turbine temperature reductions (167-247 K) require special attention, as they can lead to an increase in the hot-section life of the engine with associated lowered maintenance costs. The three-spool engine was seen to be more beneficial for water injection compared to the two-spool. The three-spool configuration has an intermediate pressure compressor, which operates at higher pressures/temperatures and is physically longer than a booster compressor, therefore enhancing the evaporation process.

The extra weight of including this system on board of a narrow and wide body aircraft was estimated to be 642 and 1004 kg respectively, including the water. The water weight (501 and 814 kg) is expected to be consumed during the take-off and early climb segments. The fuel penalties associated with the extra weight were compared against the

fuel benefits obtained from intercooling the compressor for both aircraft considering different mission lengths. It was noted that for the narrow-body aircraft, there were no fuel penalties in missions shorter than 1,250 km. For the longest mission considered, of 4,054 km, there was a negligible fuel penalty of 0.04%. For the wide-body aircraft, there were no significant fuel penalties, even for the longest simulated mission of 11,350 km. In all the cases analysed a reduction in Landing and Take-Off (LTO) emissions of 42-43% was noted. The analytical evaporative model, which was the base for subsequent simulations, was based on the thermodynamics of isolated water droplets. The simulations did not consider droplet brake-up, merge, or condensation. It was also assumed a uniform distribution of spherical droplets of the same initial size. To extend the analysis to a more realistic case, an experiment was done by using commercially available fogging nozzles and a single-shaft gas turbine.

The experimental study showed that water sprays have a distribution of droplets of different sizes. It is practically impossible to have a single droplet diameter size in a spray plume as was assumed in the analytical studies. Prior to injecting water into the engine, multiple nozzles were evaluated and a nozzle that presented a good compromise between droplet size and flow delivery was chosen. The spray was introduced into the intake of a single-shaft gas turbine (at 2% water-to-air ratio), producing reductions in compressor discharge temperature of 34 K (7.4%), which translated into NO_x emissions reductions of up to 25%. The reductions were lower than those predicted with analytical methods due to the larger droplet sizes present in the spraying plume. Also the combustor inlet and outlet temperature of the experimental engine were 448 K (measured) and 998 K (estimated), respectively. These combustor temperatures are much lower compared to what is found on an aero-engine, where the turbine inlet (combustor outlet) temperatures can reach 1800 K. Thermal NO_x emissions, for example are expected to occur at temperatures above 1800 K, and although the averaged TIT of an aero engine might be below that, it is the hot “pockets” in the combustion chamber that are of concern regarding thermal NO_x formation. According to Lefebvre, in the case of a modern aero-engine, it is expected that thermal NO_x are responsible for 60% of the total NO_x formation, while prompt NO_x are around 30% and NO_2 represent 10%. In combustors of flame temperature of 1500 K, only 5% of the NO_x are thermal, and 65% are prompt (but still formed from endothermic reactions). This helps to understand why a higher reduction in NO_x emissions would be expected if water injection was applied on high-pressure ratio compressors.

Although all the analytical and numerical work is done on multi-shaft engines, the experiment was done on a single-shaft stationary gas turbine. The behaviour of multi-

shaft, high-pressure-ratio engines is expected to differ from that observed with the experimental engine.

Current available nozzle technology can only generate droplets of 10 or 14 μm , and these only represent 10% of the volume of the spray. In the analytical predictions, monodispersed droplets of 5 or 10 μm were considered which are challenging to obtain with standard fogging methods. It was stated by simulating isolated droplets, that if the droplets were 20 μm in size or larger the effects on compressor temperature would be negligible. The sprays used for the experimental testing of the engine had droplets of up to 30 – 40 μm , and the effects on improving engine performance were still considerable. The final “cooling” benefits, seemed to be less dependent droplet size than initially thought, but this is an effect of two very different mechanisms. If droplets in a range of 2- 10 μm are used, they will be likely to fully evaporate inside the compressor without penetrating the blade’s boundary layer, and follow the flow path. Although the evaporation profile will be distinctively different between the sizes, results showed that a fast initial cooling (from smaller droplets) can be compensated by a prolonged intercooling (from larger droplets), giving as a result very close temperature reductions. If larger droplets are used (20- 40 μm), these droplets would most likely hit the blades and be centrifuged outwards. This will cause a film of water to be formed on the blades and casing of the compressor which would also evaporate and contribute to the overall cooling of the engine. Although this second approach would not be practical due to the loss in aerodynamic efficiency and the risk of blade damage, the cooling to the engine would still be considerable. It is likely that a spray which has a wide range of droplet sizes, when applied to an engine like the experimental one presented here would give as a result a combination of the effects outlined before. The search for nozzles that can generate smaller droplets are then paramount not to ensure a large temperature drop, but to protect the engine components against erosion or corrosion from the water droplets.

This study demonstrates that atomizing fine water droplets into the compressor of a gas turbine has the potential of reducing NO_x emissions in up to half. It is shown that if the droplets are small enough, the performance of the engine is not impaired by this and a benefit in fuel flow and turbine inlet temperature is perceived. It was also shown that the extra weight is not a constraint as previously thought and that the implementation of this system on an engine requires thorough investigation on droplet generation, integration, and reliability. This approach does not compete against other alternatives, as it can be used in conjunction with novel engine components or propulsion architectures. Given the benefits that this technology can have in terms of life extension and environmental footprint, it seems like a feasible alternative to consider for future engine concepts, or even as a retrofit in existing engines.

2- Outlook and Future Work

Water Injection can enable future possibilities for new engine architectures such as:

- The increased mass flow and thrust saw while water is applied could lead to a reduced core size engine. This engine could benefit from a higher bypass ratio, or if the bypass ratio is unchanged the whole power plant could be reduced in size. The thrust at take-off would still be the nominal take-off but the weight and drag of the system would be reduced.
- Water Injection, at a lower rate, could be used for the entire mission duration. The aircraft could be equipped to carry fuel and water, or alternatively, the system could be coupled with contrail avoidance systems which condensate the water vapour at the exit of the engine. This water could then be treated and reintroduced into the engine for intercooling.
- Water Injection could also be used in incumbent engine-aircraft architectures such as hybrid propulsion. The fogging spray could still be applied to the gas generator producing the same benefits in terms of performance and emissions than what has been predicted for an aero-engine. This could potentially also reduce the size of the power-plant and the inlet duct.

None of this possibilities are considered in the work presented here, but could be a matter for future studies.

For the technology to reach more mature stages, at least the following studies need to be completed:

- The aerodynamic behaviour of the compressor when atomized water is introduced needs further consideration. Experimental and computational analysis done in the past give some insight as to the performance effects that water injection can have on multi-stage compressors, but more work is required in this field.
- Experimental work on gas turbines with multi-stage axial flow compressors needs to be done. The study presented here was performed on a single-shaft gas turbine with a centrifugal compressor, and water was injected at the intake of the engine. The case with the highest promise is that of an axial flow compressor, where water is injected after the fan compressor. Experimentation on this location is required to quantify the performance and emissions changes of a water injected turbofan.
- Experimental work on fogging nozzles is also required to be able to produce the correct droplet size and distribution that can achieve fast evaporation without damaging the blades of the engine.

- A study about the potentials that water injection has on hot-section life extension needs to be done. A reduction of turbine inlet temperature of 100-200 K can have considerable implications on the life-limiting parts of the engine, and thus on the maintenance costs.
- An economic evaluation of compressor water injection needs to be done. The benefits in terms of maintenance savings, fuel, and taxation, need to be compared to the capital cost, certification, and installation of the system.
- A study about the integration of the nozzles into the engine is a paramount step towards the implementation of this system. The location of the water tanks, pipes, valves and pumps is also a matter for further study.

Thesis Appendix: Additional Information

Input Files for *Turbomatch* and *Hermes*.

Turbomatch file: 2- spool Engine

```
!Engine: CFM56-5B1/P (2-spool with booster)
!To fit Airbus A320
!Model Name:

|
!Design point: Cruise (10,668m, M=0.8, ISA) (Data from Janes)
!Thrust: 22.33 kN
!SFC: 16.98 mg/Ns

!Top of Climb Data:
!Thrust:25.04 kN
!OPR: 32.6

!Take-off Data:
!Thrust: 120.1 kN
!Mass Flow: 408.2 kg/s
!BPR 5.7

!Other data
!Red line EGT: 950C
!Fan RPM: 5,200
!Core RPM: 15,183
```

```
////
OD SI KE VA FP
-1
-1
INTAKE S1,2 D1-6 R300
COMPRES2,3 D7-18 R305 V7 V8
PREMAS S3,30,4 D19-22 V19
DUCTER S30,31 D23-27 R310
NOZCON S31,32,1 D143,144 R351
COMPRES4,5 D33-44 R320 V33
PREMAS S5,40,6 D77-80
COMPRES6,7 D53-64 R335 V53 V54
PREMAS S7,44,8 D97-100
PREMAS S8,45,9 D101-104
BURNER S9,10 D105-112 R350
MIXEES S10,44,11
TURBIN S11,12 D113-127 V114
TURBIN S12,13 D128-142 V129
NOZCON S13,14,1 D145,146 R355
PERFOR S1,0,0 D147-150,355,300,350,351,0,0,0,0,0
CODEND
```

```

BRICK DATA////
1 10668      ! INTAKE: Altitude
2 0.0        ! Deviation from ISA temperature|
3 0.8        ! Mach number
4 0.99       ! Pressure recovery
5 0          ! Deviation from ISA pressure [atm]
6 0          ! Relative humidity [%]

7 0.85       ! FAN - COMPRESSOR: Z = (R-R[choke])/(R[surge]-R[choke]) (if =
8 1          ! DP Relative rotational speed PCN
9 1.643      ! DP Pressure ratio 1.65
10 0.90      ! DP isentropic efficiency
11 0         ! Error selection
12 1         ! Compressor Map Number
13 1         ! Shaft number
14 1         ! Scaling Factor of Pressure Ratio - Degradation factor
15 1         ! Scaling Factor of Non-D Mass Flow - Degradation factor
16 1         ! Scaling Factor of Isentropic Efficiency - Degradation fact
17 -1        ! Effective component volume [m^3]
18 0         ! Stator angle (VSV) relative to DP

19 0.847     ! BYPASS - PREMAS: LAMDA W BYPASS (wout/win) BPR = 5.7 T-O
20 0         ! DELTA W
21 1         ! LAMBDA P
22 0         ! DELTA P

23 0         ! BYPASS DUCT - DUCTER: Air duct
24 0.01      ! Total pressure loss: DELTA(P)/Pin (Pressure loss = 1%)
25 0         ! Combustion efficiency
26 100000    ! Limiting value of Fuel Flow (=100000 if not needed)
27 -1        ! Effective component volume [m^3]

33 0.85      ! COMPRESSOR-BOOSTER: Z = (R-R[choke])/(R[surge]-R[choke]) (if
34 1         ! DP Relative rotational speed PCN
35 2.80      ! DP Pressure ratio (2.8225)
36 0.88      ! DP isentropic efficiency
37 1         ! Error selection
38 2         ! Compressor Map Number
39 1         ! Shaft number
40 1         ! Scaling Factor of Pressure Ratio - Degradation factor
41 1         ! Scaling Factor of Non-D Mass Flow - Degradation factor

```

```

42 1          ! Scaling Factor of Isentropic Efficiency - Degradation fact
43 -1         ! Effective component volume [m^3]
44 0          ! Stator angle (VSV) relative to DP

77 0.00       ! BOOSTER HANDLING BLEED - PREMAS
78 0          ! DELTA W
79 1          ! LAMBDA P
80 0          ! DELTA P

53 0.85       ! HP COMPRESSOR: Z = (R-R[choke])/(R[surge]-R[choke]) (if ==-1.
54 1          ! DP Relative rotational speed PCN
55 6.86       ! DP Pressure ratio 7
56 0.88       ! DP isentropic efficiency
57 1          ! Error selection
58 5          ! Compressor Map Number
59 2          ! Shaft number
60 1          ! Scaling Factor of Pressure Ratio - Degradation factor
61 1          ! Scaling Factor of Non-D Mass Flow - Degradation factor
62 1          ! Scaling Factor of Isentropic Efficiency - Degradation fact
63 -1         ! Effective component volume [m^3]
64 0          ! Stator angle (VSV) relative to DP

97 0.13       ! HPT COOLING - PREMAS: LAMDA W
98 0          ! DELTA W
99 1          ! LAMBDA P
100 0         ! DELTA P

101 0.1       ! CUSTOMER BLEED (Cabin pressurisation) - PREMAS: LAMDA W
102 0         ! DELTA W
103 1         ! LAMBDA P
104 0         ! DELTA P

105 0.05      ! COMBUSTOR: Pressure loss (=Total pressure loss/Inlet total pr
106 0.999     ! Combustion efficiency
107 -1        ! Fuel flow (If -1. is given the TET must be determined in t
108 0         ! (>0) water flow [kg s-1 or lb s-1] or (<0) water to air ra
109 288       ! Temperature of water stream [K]
110 0         ! Phase of water (0=liquid, 1=vapour)
111 1         ! Scaling factor of ETAb (combustion efficiency) - Degradati
112 -1        ! Effective component volume [m^3]

113 0         ! HP TURBINE: Auxiliary or power output [w]
114 -1        ! DP Relative non-dimensional massflow w/wmax (if = -1, valu
115 -1        ! DP Relative non-rimensional speed CN (if = -1, value 0.6 i
116 0.93095   ! DP isentropic efficiency
117 -1        ! DP Relative non-dimensional speed PCN (= -1 for compressor
118 2         ! Shaft Number (for power turbine, the value "0." is used)
119 5         ! Turbine map number
120 -1        ! Power law index "n" (POWER = PCN^n) If = -1, power is assu
121 1         ! Scaling factor of TF (non-D inlet mass flow) - Degradation
122 1         ! Scaling factor of DH (enthalpy change) - Degradation facto
123 1         ! Scaling factor of ETAC is (Turbine isentropic efficiency)
124 200       ! DP Rotor rotational speed [RPS]
125 30        ! Rotor moment of inertia [kg.m^2]
126 -1        ! Effective component volume [m^3]
127 0         ! NGV angle, relative to D.P.

128 0         ! LP TURBINE: Auxiliary or power output [w]
129 -1        ! DP Relative non-dimensional massflow w/wmax (if = -1, valu
130 -1        ! DP Relative non-rimensional speed CN (if = -1, value 0.6 i
131 0.93095   ! DP isentropic efficiency
132 -1        ! DP Relative non-dimensional speed PCN (= -1 for compressor
133 1         ! Shaft Number (for power turbine, the value "0." is used)
134 5         ! Turbine map number
135 -1        ! Power law index "n" (POWER = PCN^n) If = -1, power is assu
136 1         ! Scaling factor of TF (non-D inlet mass flow) - Degradation
137 1         ! Scaling factor of DH (enthalpy change) - Degradation facto

```

```

138 1          ! Scaling factor of ETAC is (Turbine isentropic efficiency)
139 200        ! DP Rotor rotational speed [RPS]
140 150        ! Rotor moment of inertia [kg.m^2]
141 0.15       ! Effective component volume [m^3]
142 0          ! NGV angle, relative to D.P.

143 -1        ! BYPASS NOZZLE: Switch set (= "1" if exit area "floats"
!          = "-1" if exit area is fixed)
144 -1        ! Scaling factor

145 -1        ! CONVERGENT NOZZLE: Switch set (= "1" if exit area "floats"
!          = "-1" if exit area is fixed)
146 -1        ! Scaling factor

147 -1        ! ENGINE RESULTS - PERFOR: Power output - Power or Power turbin
148 -1        ! Propeller efficiency (= -1 for turbojet/turbofan)
149 0         ! Scaling index ("1" = scaling needed, "0" = no scaling)
150 0         ! Required DP net thrust(Turbojet,turbofan) or shaft power (
! = 0 if Scaling index = 0

-1
1 2 172      ! Mass flow (kg/s)
10 6 1439.9  ! TET (K)
-1

-1
10 6 1527.5  !TET TOC
-1

1 0
3 0
-1
10 6 1651.3  !TET T-O
-1

-1
10 6 1543.4  !TET-Climb
-1

-1
10 6 1146.8  !TET- Approach

-1          ..
-1
10 6 877     !TET Idle
-1

-3

```

Turbomatch file: 3- spool Engine

```

////
OD SI KE VA FP
-1
-1
INTAKE S1,2 D1-6 R100
COMPRES S2,3 D7-18 R110 V7 V8
PREMAS S3,4,15 D19-22 R120 V19
DUCTER S15,16 D23-27 R130
NOZCON S16,17,1 D28,29 R140 V30 V31
COMPRES S4,5 D30-41 R150 V42 V43
COMPRES S5,6 D42-53 R160
PREMAS S6,7,18 D54-57 R170
DUCTER S18,19 D58-62
BURNER S7,8 D63-70
PREMAS S19,20,21 D71-74
MIXEES S8,20,9 D75-89 V76
TURBIN S9,10 D90-104 V91
MIXEES S10,21,11 D105-119 V106
TURBIN S11,12 D120,121 R180
TURBIN S12,13 D122-125,180,100,170,130,0,0,0,0
NOZCON S13,14,1
PERFOR S1,0,0
CODEND
////
! INTAKE - Aeroplane Inlet
1 10668.0 ! ALTITUDE
2 0. ! ISA Temperature DEVIATION
3 0.85 ! MACH NO.
4 0.99 ! PRESSURE RECOVERY
5 0. ! Deviation from ISA Pressure[atm]
6 0. ! Relative Humidity [%]
! COMPRES - Fan
7 0.85 ! SURGE MARGIN
8 1. ! ROTATIONAL SPEED,N1
9 1.65 ! FAN PRESSURE RATIO 1.6
10 0.92 ! EFFICIENCY
11 0. ! ERROR SELECTOR
12 2. ! MAP NUMBER
13 1. ! Shaft Number
14 1. ! Scaling Factor of Pressure Ratio
15 1. ! Scaling Factor of Non-D Mass Flow
16 1. ! Scaling Factor of Isentropic Efficiency
17 1. ! Effective Component Volume[m^3](value is ignored if Steady-State)
18 0. ! Stator Angle(vsv)Relative to DP
! PREMAS - Bypass - Main
19 0.08547 ! LAMDA BPR at Cruise=10.7
20 0. ! MASS FLOW LOSS
21 1. ! PRESSURE FACTOR
22 0. ! PRESSURE LOSS
! Bypass duct
23 0. ! REHEAT SELECTOR
24 0.01 ! PRESSURE LOSS 1%
25 0. ! REHEAT COMB.EFFICIENCY
26 0. ! MAX REHEAT FUEL FLOW
27 -1. ! Effective Component volume[m^3]
!Bypass Convergent Nozzle
28 -1. ! Fan Exhaust Nozzle: Fixed Area
29 1. ! Scaling Factor
! IP COMPRESSOR
30 0.85 ! SURGE MARGIN
31 1. ! ROTATIONAL SPEED
32 5.5 ! PRESSURE RATIO 5.59
33 0.9 ! EFFICIENCY
34 1. ! ERROR SELECTOR
35 5. ! MAP NUMBER
36 2. ! Shaft Number

```

```

37 1.      ! Scaling Factor of Pressure Ratio
38 1.      ! Scaling Factor of Non-D Mass Flow
39 1.      ! Scaling Factor of Isentropic Efficiency
40 1.      ! Effective Component Volume[m^3]
41 0.      ! Stator Angle(vsv)Relative to DP
! HP COMPRESSOR
42 0.85    ! SURGE MARGIN
43 1.      ! ROTATIONAL SPEED
44 5.52    ! PRESSURE RATIO 5.59
45 0.9     ! EFFICIENCY
46 1.      ! ERROR SELECTOR
47 5.      ! MAP NUMBER
48 3.      ! Shaft Number
49 1.      ! Scaling Factor of Pressure Ratio
50 1.      ! Scaling Factor of Non-D Mass Flow
51 1.      ! Scaling Factor of Isentropic Efficiency
52 1.      ! Effective Component Volume[m^3]
53 0.      ! Stator Angle(vsv)Relative to DP
! HPT Turbine COOLING BYPASS
54 0.82    ! COOLING AIR 18% Core Engine Flow
55 0.      ! MASS FLOW LOSS
56 1.      ! PRESSURE FACTOR
57 0.      ! PRESSURE LOSS
! Cooling Duct
58 0.      ! REHEAT SELECTOR
59 0.01    ! PRESSURE LOSS 1%
60 0.      ! REHEAT COMB.EFFICIENCY
61 0.      ! MAX REHEAT FUEL FLOW
62 -1.     ! Effective Component Volume[m^3]
! BURNER
63 0.05    ! PRESSURE LOSS
64 0.9999  ! COMBUSTION EFFICIENCY
65 -1.     ! FUEL FLOW
66 0.      ! (>0)water Flow[kg s-1 or lb s-1] or (<0) water to Air Ratio
67 288.    ! Temperature of water Stream[K]
68 0.      ! Phase of water(0=Liquid, 1=Vapour)
69 1.      ! Scaling Factor of ETAb(combustion efficiency)
70 1.      ! Effective component volume[m^3]
! HPNGV cooling air
71 0.5833  ! 10.5%/18% 8% for HPNGV 2.5% for Front Half of HProtor
72 0.      ! LOSS
73 1.      ! PRESSURE FACTOR
74 0.      ! PRESSURE LOSS
! TURBINE-HP
75 500000  ! AUX.WORK 500 KW
76 0.8     ! REL NON-D MASS FLOW
77 0.6     ! REL NON-D SPEED
78 0.90    ! EFFICIENCY
79 -1.     ! REL ROT.SPEED(COMP TURB=-1)
80 3.      ! COMP NO. FROM LOW END
81 5.      ! TURBINE MAP
82 -1.     ! POWER LAW
83 1.      ! Scaling Factor of TF(non-D inlet mass flow)
84 1.      ! Scaling factor of DH(enthalpy change)
85 1.      ! Scaling factor of ETAc is (Turbine isentropic efficiency)
86 200.    ! Rotor Rotational Speed[RPS]RPM=12000
87 60.     ! Rotor Moment of Inertia[kg.m^2]
88 1.      ! Effective Component Volume[m^3]
89 0.      ! NGV Angle, Relative to D.P.
! TURBINE-IP
90 0.      ! AUX.WORK
91 0.8     ! REL NON-D MASS FLOW
92 0.6     ! REL NON-D SPEED
93 0.91    ! EFFICIENCY
94 -1.     ! REL ROT.SPEED
95 2.      ! COMP NO. FROM LOW END

```

```

96 5.          ! TURBINE MAP
97 -1.         ! POWER LAW
98 1.          ! Scaling Factor of TF(non-D inlet mass flow)
99 1.          ! Scaling Factor of DH(enthalpy change)
100 1.         ! Scaling Factor of ETAC is (Turbine isentropic efficiency)
101 142.       ! Rotor Rotational Speed[RPS]RPM=8500
102 70.        ! Rotor Moment of Inertia[kg.m^2]
103 1.         ! Effective Component Volume[m^3]
104 0.         ! NGV Angle, Relative to D.P.
! TURBINE-LP
105 0.         ! AUX.WORK
106 0.8        ! REL NON-D MASS FLOW
107 0.6        ! REL NON-D SPEED
108 0.93       ! EFFICIENCY
109 -1.        ! REL ROT.SPEED
110 1.         ! COMP NO. FROM LOW END
111 5.         ! TURBINE MAP
112 -1.        ! POWER LAW
113 1.         ! Scaling Factor of TF(non-D inlet mass flow)
114 1.         ! Scaling Factor of DH(enthalpy change)
115 1.         ! Scaling Factor of ETAC is (Turbine isentropic efficiency)
116 50.        ! Rotor Rotational Speed[RPS]RPM=3000
117 75.        ! Rotor Moment of Inertia[kg.m^2]
118 1.         ! Effective Component Volume[m^3]
119 0.         ! NGV Angle,Relative to D.P.
! Core CONVERGENT NOZZLE
120 -1.       ! SWITCHCH, AREA FIXED
121 1.        ! Scaling Factor
! PERFORMANCE
122 -1.       ! POWER (-1=TURBOJET/FAN)
123 -1.       ! PROPELLER EFFICIENCY("")
124 0.        ! SCALING INDEX
125 0.        ! REQ'D D.P. THRUST

! -----
! Design Point: Cruise (1)

-1
1 2 540.0      ! INLET MASS FLOW(kg/s) orig: 552
8 6 1710.0     ! TET(K) orig: 1734
-1

! Off-Design Point: Top of Climb (2) Th 70.523 Kn, PR 52

-1
8 6 1741.0
-1

! Off-Design Point: Takeoff (3) Th 323.7 kN PR42.53 BPR 9.39

1 0.0
3 0.0
-1
8 6 1810.0
-1

! *****LTO cycle calculations for NOx simulations at 7%,30%, 85% and 100% thrust ( *****
! Climb (85%) = 275.0286 kN (16)

2 0 ! ISA Temperature
-1
8 6 1709.9

-1

! Approach (30%) 97.0689 kN (17)
-1
8 6 1299.85
-1

! Idle (7%) 22.65 kN (18)
-1
8 6 1098.3
-1

-3

```

Hermes File: Narrow Body Aircraft

```

!Input file for the geometric, mission and engine specifications of the aircraft Aircraft AirbusA320; Engine: CMF 56-5b *
ENGINE_SPEC:CFM56-5B1
!GEOMETRIC DETAILS
! Wing Geometry
122.4 ! AcWingAInit - wing area
9.50 ! AcWingAspr - Aspect ratio
0.10 ! AcWingCThr - Thickness chord ratio
25.00 ! AcWingSwpa - Sweep angle (in degrees)
0.2 ! AcWingTpr - Taper ratio
0.15 ! AcWingRtThir - Root thickness ratio
0.095 ! AcWingOtThir - Outer thickness ratio
! Tailplane Geometry
31.0 ! ActailAInit - Tailplane area
5.0 ! ActailAspr - Aspect ratio
0.112 ! ActailCThr - Thickness chord ratio
40. ! ActailSwpa - Sweep angle (in degrees)
0.3 ! ActailTpr - Taper ratio
0.1 ! ActailRtThir - Root thickness ratio
0.095 ! ActailOtThir - Outer thickness ratio
! Fin Geometry
22.5 ! AcFinA - Fin area
5.87 ! AcFinSpan - Span
0.100 ! AcFinCThr - Thickness chord ratio
46. ! AcFinSwpa - Sweep angle (in degrees)
0.375 ! AcFinTpr - Taper ratio
0.095 ! AcFinRtThir - Root thickness ratio
0.095 ! AcFinOtThir - Outer thickness ratio
! Fuselage Geometry
4.045 ! AcFusDia - Diameter
37.57 ! AcFusLen - Length
! Landing Gear Characteristics
2 ! ACLGTyp1 - Landing gear type ***=default, 1=Bogie, 2=Small twin wheel***
1 ! ACLGTyp2= 0,1,2
1 ! ACLGTyp3= 0,1,2
-1 ! ACLGTyp4= 0,1,2,-1 *** -1-if the aircraft only has 3 LG -1 has to be declared
-1 ! ACLGTyp5= 0,1,2,-1 *** for the last 2 values
2 ! ACLGDep1 - Number of segments with LG down for descent
! High lift systems
1 ! ACFlapSegTo - Number of Segments with flaps deployed during TO
3 ! ACFlapSegApp - Number of Segments with flaps deployed for approach
2 ! ACFlapSegLand - Number of Segments with flaps deployed during Landing
1.10 ! ACExtSrTo - wing area extension ratio TO
1.15 ! ACExtSrApp - wing area extension ratio approach
1.20 ! ACExtSrLand - wing area extension ratio Landing
10.0 ! ACFlapAngleTo - Flap Angle TO IN DEGREES
20.0 ! ACFlapAngleApp - Flap Angle Approach
35.0 ! ACFlapAngleLand - Flap Angle Land
1 ! ACFlapSlots - Number of Flap Slots (1-3)
! Engine Geometry
2.1 ! EngNacDiaInit - Diameter
4.96 ! EngNacLenInit - Length
!MISSION/WEIGHT SPECIFICATION DATA
37230. ! ACaFrWtInit - Airframe weight 42200 WITH ENGINES, THIS IS AIRFRAME ONLY
2 ! ACEngNb - Number of Engines
2550 ! EngWtInit - Engine weight, (kg/engine)(2500 Dry engine)
20400 ! ACPlDwt - Payload weight, (kg) (20400)
14270 ! ACFuelWtInit - Fuel weight, (kg) (24240 -2017 version)
20400 ! ACPlDwtmax - Maximum payload weight, kg
18729 ! ACFuelWtmax - Maximum fuel weight, kg (18729 STANDARD VERSION (2017), 21005 WITH ADDITIONAL CENTRAL TANK, AIRPOT MAINTENANCE MANUAL)
66000. ! ACLandWtmax - Maximum landing weight, kg
78000. ! ACTotWtmax - Maximum take-off weight, kg
0.1 ! DVFuelRatio - Diversion fuel weight to total fuel weight (%)
0.1 ! ACFuelContpc - Relative contingency fuel to remain after landing (%)
1249 ! ACrng - Range to be Flown (km) ! Mission (2)
200. ! ACrngdv - Diversion range to be flown (km)
2 ! ACmiStype - Mission to be flown (1-fixed fuel get range) or (2-fixed range for given Pload get fuel) *****Mission type 1 for
1 ! DVMission - specify if diversion mission is to be run (1- NO diversion mission) or (2- YES to diversion mission)

!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
!CRUISE MAIN/DIVERSION AND HOLDING DATA
1 ! number of cruise altitudes and Mach numbers
1 ! number of cruise Temperature Deviations from ISA day (the trip is splitted equally into this number of parts. Every part has the respecti
1 ! number of diversion cruise altitudes
0.1 ! Cruise small segment time interval in (min). This value affects the accuracy of the calculations, so keep it small.
10886. ! Cruise altitudes in [m] (WARNING: THE ALTITUDES CANNOT BE THE SAME!!!!!!!!!!!!!!)
0.78 ! Cruise Mach numbers, the same number with cruise altitudes
0 ! Cruise ambient temperature deviation from ISA, in [K]
6096. ! Diversion cruise altitudes (m)
0.65 ! Diversion cruise Mach numbers,
0 ! Diversion cruise ambient temperature deviation from ISA, in [K]
200.0 ! Holding altitude (m) (1500 ft)
30. ! Hold time in (min)
!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

!CLIMB DATA
128 ! Climb segments Number
! Altitudes(m) | DTisa(k) | EAS(knots) | Power(0.-1.)
460.0 0 154 1
487.68 0 149 1
670.56 0 166 1
762.0 0 180 1
944.88 0 199 1
1097.28 0 219 1
1249.68 0 241 1
1402.08 0 262 1
1554.48 0 261 1
1676.4 0 259 1
1798.32 0 257 1
1920.24 0 260 1
2011.68 0 260 1
2103.12 0 261 1
2134.3 0 260 1

```

2134.3	0	260	1				
2225.04	0	267	1				
2286.0	0	275	1				
2438.4	0	274	1	11894.3	0	436	1
2499.36	0	273	1	11894.4	0	437	1
2712.72	0	279	1	11894.5	0	437	1
2895.6	0	283	1	11894.6	0	437	1
3322.32	0	315	1				
3627.12	0	343	1				
4023.36	0	349	1				
4480.56	0	361	1				
4846.32	0	368	1				
5273.04	0	372	1				
5547.36	0	379	1				
5882.64	0	392	1				
6187.44	0	398	1				
6339.84	0	402	1				
6400.8	0	401	1				
6400.9	0	400	1				
6492.24	0	400	1				
6644.64	0	403	1				
6766.56	0	405	1				
6888.48	0	408	1				
6979.92	0	409	1				
7132.32	0	413	1				
7254.24	0	414	1				
7528.56	0	417	1				
7802.88	0	427	1				
8321.04	0	439	1				
8747.76	0	439	1				
9174.48	0	450	1				
9570.72	0	460	1				
10058.4	0	461	1				
10454.6	0	458	1				
10759.4	0	455	1				
10881.3	0	453	1				
11277.6	0	450	1				
11582.4	0	445	1				
11856.7	0	445	1				
11887.2	0	444	1				
11887.3	0	440	1				
11887.4	0	438	1				
11887.5	0	438	1				
11887.6	0	438	1				
11887.7	0	438	1				
11887.8	0	437	1				
11887.9	0	438	1				
11888.0	0	438	1				
11888.1	0	438	1				
11888.2	0	437	1				
11888.3	0	437	1				
11888.4	0	437	1				
11888.5	0	436	1				
11888.6	0	436	1				
11888.7	0	434	1				
11888.8	0	434	1				
11888.9	0	434	1				
11889.0	0	438	1				
11889.1	0	439	1				
11889.2	0	440	1				
11889.3	0	439	1				
11889.4	0	438	1				
11889.5	0	437	1				
11889.6	0	438	1				
11889.7	0	437	1				
11889.8	0	436	1				
11889.9	0	435	1				
11890.0	0	437	1				
11890.1	0	438	1				
11890.2	0	438	1				
11890.3	0	440	1				
11890.4	0	440	1				
11890.5	0	439	1				
11890.6	0	440	1				
11890.7	0	441	1				
11890.8	0	441	1				
11890.9	0	442	1				
11891.0	0	443	1				
11891.1	0	444	1				
11891.2	0	436	1				
11891.3	0	427	1				
11891.4	0	429	1				
11891.5	0	428	1				
11891.6	0	428	1				
11891.7	0	429	1				
11891.8	0	430	1				
11891.9	0	430	1				
11892.0	0	432	1				
11892.1	0	434	1				
11892.2	0	437	1				
11892.3	0	436	1				
11892.4	0	435	1				
11892.5	0	434	1				
11892.6	0	432	1				
11892.7	0	432	1				
11892.8	0	436	1				
11892.9	0	437	1				
11893.0	0	437	1				
11893.1	0	437	1				
11893.2	0	437	1				
11893.3	0	437	1				
11893.4	0	437	1				
11893.5	0	437	1				
11893.6	0	437	1				
11893.7	0	436	1				
11893.8	0	436	1				
11893.9	0	436	1				
11894.0	0	436	1				
11894.1	0	435	1				
11894.2	0	436	1				
11894.3	0	436	1				

Hermes File: Wide Body Aircraft

```
!Input file for the geometric, mission and engine specifications of the aircraft Aircraft B787-9 Data from: Easa TypeCertificate, Janes all the world airc
ENGINE_SPEC:Trent1000
!GEOMETRIC DETAILS
! Wing Geometry
360.0 ! AcWingAinit - wing area (wikipedia, jenkinson 360)
10.0 ! AcWingASpr - Aspect ratio (span^2/Area)
0.12 ! AcWingCTHr - Thickness chord ratio (CAD Drawing boeing.com Scale 1:200 model)
34.0 ! AcWingSwpa - Sweep angle (in degrees) (CAD Drawing Boeing.com)
0.10 ! AcWingTpr - Taper ratio (CAD Drawing boeing.com Scale 1:200 model)
0.10 ! AcWingRtThir - Root thickness ratio (CAD Drawing boeing.com Scale 1:200 model)
0.09 ! AcWingOtThir - outer thickness ratio (CAD Drawing boeing.com Scale 1:200 model)
! Tailplane Geometry
78.48 ! ActailAinit - Tailplane area X -horizontal (Span^2/AR) Span:Janes.
5.0 ! ActailASpr - Aspect ratio (Assumed Same as 777)
0.14 ! ActailCTHr - Thickness chord ratio (CAD Drawing boeing.com Scale 1:200 model)
40. ! ActailSwpa - Sweep angle (in degrees) (CAD Drawing boeing.com Scale 1:200 model)
0.34 ! ActailTpr - Taper ratio (CAD Drawing boeing.com Scale 1:200 model)
0.125 ! ActailRtThir - Root thickness ratio (CAD Drawing boeing.com Scale 1:200 model)
0.17 ! ActailOtThir - outer thickness ratio (CAD Drawing boeing.com Scale 1:200 model)
! Fin Geometry
53.23 ! AcFinA - Fin area X-vertical with AR of 1.5 and measured span. (1.5 common AR for Fin, A320, B777)
9.01 ! AcFinSpan - Span (CAD Drawing boeing.com Scale 1:200 model)
0.1 ! AcFinCTHr - Thickness chord ratio (CAD Drawing boeing.com Scale 1:200 model - taken at 1/4s)
46. ! AcFinSwpa - Sweep angle (in degrees) (CAD Drawing boeing.com Scale 1:200 model)
0.37 ! AcFinTpr - Taper ratio (CAD Drawing boeing.com Scale 1:200 model)
0.1 ! AcFinRtThir - Root thickness ratio (CAD Drawing boeing.com Scale 1:200 model)
0.14 ! AcFinOtThir - outer thickness ratio (CAD Drawing boeing.com Scale 1:200 model)
! Fuselage Geometry
5.77 ! AcFusDia - Diameter (Boeing Airport planning document, EASA type certificate)
62.03 ! AcFusLen - Length C (787-9 Janes, EASA type certificate)
! Landing gear characteristics
2 ! AcLGTyp1 - Landing gear type ***0=default, 1=Bogie, 2=Small twin wheel*** C
1 ! AcLGTyp2 = 0,1,2
1 ! AcLGTyp3 = 0,1,2
-1 ! AcLGTyp4 = 0,1,2,-1 *** -1=if the aircraft only has 3 LG -1 has to be declared
-1 ! AcLGTyp5 = 0,1,2,-1 *** for the last 2 values
2 ! AcLGDepl - Number of segments with LG down for descent
! High lift systems
1 ! AcFlapSegTo - Number of Segments with flaps deployed during TO
3 ! AcFlapSegApp - Number of Segments with flaps deployed for approach
2 ! AcFlapSegLand - Number of Segments with flaps deployed during Landing
1.10 ! AcExtSTo - wing area extension ratio TO
1.15 ! AcExtSApp - wing area extension ratio approach
1.27 ! AcExtSLand - wing area extension ratio Landing (Totalarea+slats+flaps/totalarea)
10.0 ! AcFlapAngleTo - Flap Angle TO IN DEGREES C
20.0 ! AcFlapAngleApp - Flap Angle Approach C
35.0 ! AcFlapAngleLand - Flap Angle Land C
2 ! AcFlapSlots - Number of Flap Slots (1-3)
! Engine Geometry
3.798 ! EngNacDiaInit - Diameter - Easa Type Certificate, engine
4.771 ! EngNacLenInit - Length C - EASA type certificate, engine
!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
!MISSION/WEIGHT SPECIFICATION DATA
116784 ! AcAfrwtInit - Airframe weight ~(NO ENGINES!!) (From Airport Manual, deducted from Payload range diagram) 128850
2 ! AcEngNb - Number of Engines X
6033 ! EngwtInit - engine weight, (kg/engine) (From Easa type certificate of the engine)
52587 ! AcPlDwt - Payload weight, (kg) X XXXXXXXXXXXXXXXXXXXX
101457 ! AcFuelwtInit - Fuel weight, (Kg) XXXXXXXXXXXXXXXXXXXX
52587 ! AcPlDwtmax - Maximum payload weight, kg (From Airport Manual, deducted from Payload range diagram)
101457 ! AcFuelwtmax - Maximum fuel weight, kg (From Airport Manual, Janes)
192777 ! AcLandwtmax - Maximum landing weight, kg C(From Airport Manual, Janes))
254011 ! AcTowtmax - Maximum take-off weight, kg
0.01 ! DVfuelRatio - Diversion fuel weight to total fuel weight (%) (Jenkinson page 225)
0.05 ! AcFuelContpc - Relative contingency fuel to remain after landing (%)
4054 ! AcRng - Range to be flown (km) *****
200. ! AcRngdv - Diversion Range to be flown (km)*****
2 ! AcMISType - Mission to be flown (1-fixed fuel get range) or (2-fixed range for given Pload get fuel)*****
1 ! DVMission - specify if diversion mission is to be run (1- NO diversion mission) or (2- YES to diversion mission ONLY FOR MISSION TYPE 2)

!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
!CRUISE MAIN/DIVERSION AND HOLDING DATA
2 ! number of cruise altitudes and Mach numbers
1 ! number of cruise Temperature Deviations from ISA day (the trip is splitted equally into this number of parts. Every part has the respective D
1 ! number of diversion cruise altitudes
0.1 ! Cruise small segment time interval in (min). This value affects the accuracy of the calculations, so keep it small.
10668.11278. ! Cruise altitudes in [m] (WARNING: THE ALTITUDES CANNOT BE THE SAME!!!!!!)
0.85,0.85 ! Cruise Mach numbers, the same number with cruise altitudes
0. ! Cruise ambient temperature deviation from ISA, in [K]
6096. ! Diversion cruise altitudes (m)
0.65 ! Diversion cruise Mach numbers,
0. ! Diversion cruise ambient temperature deviation from ISA, in [K]
200.0 ! Holding altitude (m) (1500 ft)
30. ! Hold Time in (min)
!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
!CLIMB DATA
33 ! Climb segments Number
! Altitudes(m) | DTisa(K) | EAS(knots) | Power(0.-1.)
460 0 145 1
548.64 0 151 1
640.08 0 171 1
792.48 0 201 1
1036.32 0 212 1
1219.2 0 238 1
1676.4 0 281 1
1859.28 0 289 1
2103.12 0 297 1
2346.96 0 303 1
2560.32 0 303 1
2865.12 0 304 1
3535.68 0 300 1
3657.6 0 317 1
3779.52 0 327 1
4084.32 0 404 1
4815.84 0 416 1
5516.88 0 423 1
6156.96 0 439 1
6644.64 0 457 1
7162.8 0 468 1
7589.52 0 479 1
7802.88 0 485 1
7924.8 0 488 1
8077.2 0 488 1
8351.52 0 494 1
8717.28 0 505 1
9083.04 0 508 1
9540.24 0 504 1
9997.44 0 495 1
10088.8 0 494 1
10393.6 0 490 1
10669.0 0 484 1
!XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
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!MATCHCALLS SPECIFICATIONS (*****HERMES DOES NOT READ THIS PART*****)
!-----
!Number of points in the Engine Design Point input file to be skipped
!before the mission profile starts (including the design point)
1
!-----
!Burner exit station number c
8
!-----
!ENGINE TET RANGE FOR EACH PHASE
30          ! TET number for Take Off
15          ! TET number for Climb
30          ! TET number for Main and Diversion Cruise
15          ! TET number for Flight Idle(Descent) and Ground Idle
5           ! TET number for Approach
10.         ! TET step change in [K] for Take off
5.          ! TET step change in [K] for Climb
10.         ! TET step change in [K] for Main and Diversion Cruise
5.          ! TET step change in [K] for Flight Idle(Descent) and Ground Idle
5.          ! TET step change in [K] for Approach
1830.       ! Max TET in [K] for Take off C (1908)
1751.       ! Max TET in [K] for Climb C (1890)
1780.       ! Max TET in [K] for Main Mission Cruise C (1750)
1358.       ! Max TET in [K] for Flight Idle(Descent) and Ground Idle (IDLE 118, Approach 1318)
1558.       ! Max TET in [K] for Approach 1518
!-----
!ADDITIONAL ENGINE PERFORMANCE STATION VECTOR DATA (STATION, ITEM)
9           ! Number of additional engine performance station vector data
!Station | Item
1 6
4 6
5 6
6 6
8 6
1 4
4 4
5 4
6 4
!-----
!ADDITIONAL ENGINE PERFORMANCE BRICK DATA (DESCRIPTION, BRICK NO, ITEM)
1           ! Number of additional engine performance brick data
!Description | BrickNo | Item (WARNING: The BrickNo is defined according to the tabular output file of turbomatch)
HPC_PCN 12 2
!-----
!ADDITIONAL OFF DESIGN ENGINE CONFIGURATIONS (LIKE BLEEDS etc.)
!Specify additional off design specification for each flight phase (e.g. for brick data 26 "26 0.95")
2           ! Number of additional off design specifications for each flight phase
!You have to specify the same number of additional specs for all the phases, i.e. if you specify something you have to do it for every flight phase
!-----
!TAKE OFF SPECIFICATIONS
!-----
82 1200. 0. 0. ! BDnum TET ValueBelowTET ValueAboveTET
102 1200. 0. 0. ! BDnum TET ValueBelowTET ValueAboveTET
!-----
!CLIMB SPECIFICATIONS
!-----
82 1200. 0. 0. ! BDnum TET ValueBelowTET ValueAboveTET
102 1200. 0. 0. ! BDnum TET ValueBelowTET ValueAboveTET
!-----
!CRUISE SPECIFICATIONS
!-----
82 1200. 0. 0. ! BDnum TET ValueBelowTET ValueAboveTET
102 1200. 0. 0. ! BDnum TET ValueBelowTET ValueAboveTET
!-----
!FLIGHT/GROUND IDLE SPECIFICATIONS
!-----
82 1200. 0. 0. ! BDnum TET ValueBelowTET ValueAboveTET
102 1200. 0. 0. ! BDnum TET ValueBelowTET ValueAboveTET
!-----
!APPROACH SPECIFICATIONS
!-----
82 1200. 0. 0. ! BDnum TET ValueBelowTET ValueAboveTET
102 1200. 0. 0. ! BDnum TET ValueBelowTET ValueAboveTET
!-----
!INPUT AND OUTPUT FILE PATHS
!Engine Design Point Specification file (input to Hermes)
Trent1000-2.dat

```