

CRANFIELD UNIVERSITY

ONGOEBI MAUREEN ORUBIDE ETEBU

**BLENDING AND SPRAY ATOMIZATION MODELLING FOR
GASOLINE-ETHANOL FUELS**

**SCHOOL OF ENERGY, ENVIRONMENT AND AGROFOOD
RENEWABLE ENERGY ENGINEERING CENTRE**

PhD

Academic Year: 2015-2017

Supervisor: Dr. Ilai Sher

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for the degree of PhD**

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ABSTRACT

To achieve the ever stringent Is of low emission and to further improve the fuel economy, a much greater control of atomization and spray processes is required in the atomizer design of spray systems. In order to achieve this I, modeling of atomization characteristics of gasoline-ethanol fuel blends, fuel breakup models and correlations between flow patterns and droplet characteristics were adopted using OpenFOAM Computational Fluid Dynamics (CFD) model for direct gasoline injector using a simple mesh structure at constant volume. The Rosin Rammler distribution model was used to generate the number of spray particles injected into the cylinder. The spray modeling and atomization involved blob sheet model and KH-RT model while the numerical technique for simulating atomization process by CFD included the use of governing equations such as Eulerian for gas phase, lagrangian for disperse phase and turbulence modeling. The evaluation of the effect of fuel blends, injection pressure, and ambient gas pressure and spray cone angle on the axial spray tip penetration, spray width, and overall Sauter Mean Diameter (SMD) were carried out. The SMD was discovered to be affected by varying the degree of injection cone angle. The spray tip penetration lengths were larger for higher injection cone angles while higher penetration lengths were obtained at higher injection pressures. One salient conclusion drawn from the modeling is that as the number of particle increased, the density of clusters became smaller.

Keywords: SMD, Cone angle, gasohol, fuel-bled, atomization, spray.

DECLARATION

I, ETEBU, Ongoebi Maureen Orubide (Student ID 214772) declare that this thesis represents my original work and has not been previously submitted elsewhere or in this University for the award of a degree of Doctor of Philosophy in Mechanical Engineering.

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The immense support I received from my husband and children deserves mention. I thank them for everything, particularly for their moral support and prayers.

Finally, I give my gratitude to my heavenly Father for giving me the opportunity and resources to undertake this programme. Lord thank you very much.

DEDICATION

This thesis is dedication to NANAOWEI

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NOMENCLATURE

CFD	Computation Fluid Dynamics
DDM	Discrete Droplet Method
DNS	Direct Numerical Simulation
E100	Ethanol fuel
E15	15-85 % Ethanol-Gasoline blended fuel
E50	50-50 % Ethanol-Gasoline blended fuel
E85	85-15 % Ethanol-Gasoline blended fuel
ELSA	Eulerian-Lagrangian Spray Atomization
F	The external forces
G100	Gasoline fuel
GASHOL	Gasoline-ethanol fuels
k	Kinetic energy
k_c	Constant taking into account losses in contraction corner
$k-H$	Kelvin-Helmholtz
L, D	Nozzle length and diameter, ,
LES	Large Eddy Simulation
LISA	Linearized Instability Sheet Atomization
LPT	Lagrangian Particle Tracking
RANS	Reynolds Averaged Navier-Stokes
RT	Rayleigh-Taylor
S	Area ratio at the nozzle contraction
SMD	Sauter Mean Diameter
SME	Soybean oil methyl ester
TAB	Taylor Analogy Breakup
3D	Three dimensional
c	Damping parameter
d	Particle diameter,
$f(d)$	Probability density function of d

k	Wave number
$m(t)$	Mass of the product droplet distribution
r	Droplet radius
t	Time after start of injection,
x	Displacement
a_d	Droplet acceleration
B_0, B_1	Constants and the drop radius decreases
C_d	Nozzle discharge coefficient,
C_D	Drag coefficient
C_d	Injector nozzle's discharge coefficient
C_{RT}	Modeling parameter
C_b, C_d, C_f, C_k	Dimensionless constants,
D_p	Diameter of particle
$d_{\max}, d_{\min}$	Maximum and minimum droplets diameters
d_{inj}	Injector nozzle diameter
F_D	Drag force,
k_s	Spring's constant
$k_{\max}$	Wave number corresponding to the maximum growth rate
k_ε	Constant for average turbulent energy dissipation, set to 0.27,
K_{br}	Constant – breakup regime
P_a	Ambient gas pressure,
P_{inj}	Fuel injection pressure,
S_1, S_2	Spray tip penetration lengths before and after breakup.
t_b	Breakup time,
μ_t	Turbulent viscosity
ε	Turbulence dissipation

$\overline{\Omega_{ij}}$	Mean rate-of-rotation tensor
ω_k	Angular velocity
ρ_L	Fuel density
ρ_a	Ambient gas density,
θ	Spray cone angle, and
ρ_g, ρ_l, σ	Gas and liquid densities and surface tension
$\omega_{\max}, h_b$	Sheet thickness at the breakup location
$\omega_{\max}$	Maximum growth rate
ρ_r	Air-fuel density ratio
μ	Velocity

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Atomization is a process of breaking up of bulk liquid into an ensemble of droplets, (sprays) with the attendant effect of increasing the volume to surface area ratio. External energy is required to overcome surface tension and such energy could be obtained through aerodynamics, mechanically, ultrasound or electrostatics. Atomizers are used for effecting atomization and several variants, including the air-assisted and pressure atomizers are employed in varies fields of application.

It is on this premise that the need for better understanding of primary atomization becomes imperative as the phenomenon spans nearly every major industry: agricultural irrigation and pesticides application, fluid catalytic cracking, spray drying and waste fuel reuse and medical application.

Despite this importance, exact mechanisms and process path for primary breakup in some application areas such as high speed sprays remain unresolved. This provides the impetus for the myriad of research efforts in both computational and experimental studies on atomization and breakup of diesel and associated liquid fuels.

In the wake of the dwindling fortunes of non-renewable sources of energy and the growing interests in the reduction of greenhouse gases, emphasis is shifting to the utilization of regenerative fuels. Gasoline-ethanol blends fuels as alternative strategy for replacing hydrocarbon fuels, have received considerable attention in developed economies of the world. Growing concerns about pollutants emissions from fossil fuel engines and that of rapid depletions of the world's crude oil reserves have necessitated alternative fuel sourcing. Studies on spray properties of various blends at ambient conditions, vapour pressure measurements and spatial analysis have been conducted. However, relative to studies on diesel and bio-ethanol, much less attention has been given to

atomization and spray modeling of gasoline-ethanol fuel blends, hence, different blends of Gashol are atomized in this work.

Gasoline is a mixture of hydrocarbons and does not exist in pure form and here, gasoline fuel is considered as heptane (G100) with emphasis with molecular formula (C_7H_{16}). It is similar to motor spirit, motor fuel and petrol. Ethanol which is also known as ethyl alcohol can be produced from sugarcane, corn, wood, beet, potato, cassava, wheat and agricultural waste through fermentation where sugar in these materials are converted to ethanol. The molecular formula for ethanol is C_2H_6O (CH_3CH_2OH). Ethanol when burnt as fuel emits water and carbon dioxide. Gasoline-ethanol blends also known as GASHOLS could be E10 to E85. E10 has been granted use in internal combustion engines based on the clean air act amendments of the United State of America and satisfies renewable fuel standard. E85 which is otherwise known as flex fuel contains 85% ethanol and 15% gasoline.

A sophisticated combustor process is required in order to meet the increasing stringent limitations on pollutant emissions in future. Essential to the design of a highly efficient combustion system are characteristic strategies to inject liquid fuel and to mix it with compressed air without local stoichiometric reactions.

Several breakup models are available in the open literature. Liquid spray formation and atomization studies are dealt with in physics. Spray modeling and atomization processes can be modeled experimentally and by using computation fluid dynamics (CFD) applications. But, to do a full engine simulation (Bravo *et al.*, 2014) including combustion, a three dimensional (3D) CFD analysis is required but in this work only CFD applications are adopted. Some of these models used herewith in analysis of the atomization and breakup processes are OpenFOAM applications. In the spray modelling and atomization process, the blob sheet model was used to model primary atomization while Kelvin-Helmholtz (KH) alongside Rayleigh-Taylor (RT) were combined (KH-RT) to model secondary breakup. The numerical simulation of the atomization was based on computational fluid dynamics which was adopted in Reynolds-Averaged Navier-

stokes equations together with realizable k- ϵ turbulence model which accounted for effects of turbulence fluctuations in the process flow. The spray characteristics considered in the analysis are spray development, spray tip penetration, injection cone angle, Sauter mean diameter with respect to different Gasohol blends of E15, E50, E85, E100 and G100.

1.2 Statement of the Problem

Blending of fossil fuels such as gasoline with renewable fuels is a plausible solution to sustaining global energy demands. In particular, Blending and spray atomization modeling of gasoline-ethanol could determine which of the different compositions would be the more environmentally friendly composition. In particular, the composition of gasoline and ethanol fuels can easily reduce the demand on gasoline. However, several questions need to be addressed to ascertain the suitability and the extent to which such blends are applicable. This thesis has attempted to answer the following questions:

- (i) In what proportions should gasoline and ethanol (GASHOL) be blended?
- (ii) How difficult/ easy would it be to energize and ethanol be blended?
- (iii) How would the breakup characteristics of such blends be described?
- (iv) How similar / different are the characteristics from those of pure gasoline on one hand and pure ethanol on the other hand.

The research work will add value to this advantage of gasoline-ethanol fuels (GASHOL) and improve the paucity of data for application of gasoline-ethanol fuels and thereby provide a comprehensive database of gasoline-ethanol fuels spray development.

1.3 Aim of the study

The aim of this thesis is to develop models and simulate the spray atomization characteristics of gasoline-ethanol fuel blends.

1.4 Objectives of the Study

The objectives of this study are as follows:

- 1.4.1 To establish relationship between flow patterns and droplet characteristics of gasoline-Ethanol blended fuel (GASHOL).
- 1.4.2 To study the effects of spray cone angle on jet penetration of GASHOL.
- 1.4.3 To study the effects of blending ratio on particle distribution.
- 1.4.4 To study the effects of pressure on particle distribution.

1.5 Methodology

The methodology is:

- 1.5.1: Present Modeling equations for primary and secondary atomization of fuels.
- 1.5.2: Set up an OpenFOAM CFD model for direct gasoline injectors using a simple mesh structure at constant volume.
- 1.5.3: Simulate the spray and atomization process using the SprayFOAM solver in the OpenFOAM code.
- 1.5.4: Evaluate the impact of injection pressure and spray cone angle on the axial spray tip penetration, spray width, and overall SMD.

1.6 Limitations of the Study

The major limitation of this study was financial insolvency. Gathering of data for the modeling was also a difficult task and therefore posed as a constraint to the study in that several physical and transport properties were required as input at the modeling stage which were not easily assessable. Although such properties are readily available for ethanol and gasoline respectively, they were not obtainable for the various blends that were studied in this work. The paucity of such data could affect the quality of the input data and by extension the performance of the models.

1.7 Thesis Layout

The layout of this thesis is stringed in order to have a consistent flow. Chapter 1 consists of introduction, aim and objectives of the study as well as the limitations. The next chapter which is chapter 2 contains the review of literature and the knowledge gap deduced from literature review. Chapter 3 x-rays the research methodology of different spray atomization models and numerical technique. The governing equations of spray atomization models as well as those of CFD. In chapter 4, different subsections contain specific atomization processes. The first subsection deals with numerical approach for simulating atomization process. Other subsections include numerical process, Sauter mean diameter (SMD) estimation, formulation of numerical simulation and model specification. Results and discussion are also embedded in this chapter. Conclusion, recommendations for future studies, contributions to knowledge are all encased in chapter 5 while references and appendices are listed at the tall end.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

This chapter concerns the review of pertinent literature on the subject matter and consists of three sub-sections: 2.1, 2.2 and 2.3. A review of earlier contributions regarding atomization is given in 2.1 (1987 to 2009) while recent advancements are presented in 2.2 (2010 to 2017). In 2.3 identified knowledge gaps are presented.

2.1 Early research works

Research efforts regarding atomization of fuels are reported in the open literature. These studies can broadly be classified into experimental, modeling and hybrid studies that incorporate experimental data into existing mathematical models. In what follows, an attempt has been made to briefly review notable research contributions, in no particular order of relevance to the proposed study. Use of gasoline-ethanol fuels in engines attracted global attention in the past decades[1], hence, the study of the spray characteristics and atomization performance of liquid fuels become imperative (Schmidt and Rutland, 2000; Zervas and Mantagne, 2002).

Ejim *et al* (2007) analyzed seven biodiesels as well as their binary and ternary blends at a constant temperature. The Sauter Mean Diameter (SMD) of droplet was reported but no attempt was made regarding correlation of injector geometry, fluid properties and atomization characteristics.

In Lebas *et al.* (2009), the atomization characteristics of sprays in the dense zone was studied by Direct Numerical Simulation (DNS) and the Eulerian-Lagrangian Spray Atomization (ELSA) models. This contribution is purely a simulation study in which experimental data drawn from previous work was used for parameter estimation. The study applied the Eulerian-Lagrangian spray atomization model

(ELSA) that was reported in Vallet and Borghi (1999) to study the atomization characteristics of diesel for higher Weber and Reynolds numbers. Direct numerical simulation in which the ELSA models were discretized in time and space, was employed as a tool for studying atomization in the dense zone of the spray. The velocity and pressure profiles showed reasonable agreement with experiments of diesel atomization. It was observed that for different temperatures, similar to the experiments, vapour penetration were unchanged but the corresponding equivalent ratio fields were modified strongly. However, the choice of grid lengths and time span in the discretization lends itself to experience and intuition.

Gao *et al.* (2007) studied the atomization and spray characteristics by modelling gasoline, ethanol and various blends of gasoline and ethanol. In particular blends consists of 75% gasoline and 25% ethanol (E25), 50-50% blend of gasoline and Ethanol (E50), 25% gasoline and 75% ethanol (E75) were studied under various ambient conditions, by means of high-speed Schlieren photography. Results from the study show that at high pressures, spray development patterns are not significantly different for the various blends and the zero blends. However, spray trip penetration decreases and spray angle increases with increases in ethanol fraction in the blended fuel, at low pressure. Although, the images clearly affirm the authors position, the authors were silent on the basis for volume of ethanol in the blends that were studied.

In Aleifens *et al* (2008), a study on the spray development of gasoline, iso-octane and ethanol in a spark-ignition engine was presented. According to the authors, the spray characteristics of fuels differ between hot and cold engine operation to a large extent. Regarding spray development, slight differences were noticed among all fuels at an engine head temperature of 20°C. However, spray cone angle was found to have reduced considerably at an engine head temperature of 80°C.

Reitz (1987) presented a theoretical basis and numerical implementation of KIVA, which is a multidimensional computer code for the simulation of atomization and vapourization processes in the injection of a liquid through a round hole. The author presented the prediction of KIVA for different regimes and compared same with published experimental data, and demonstrated good agreement with published data.

Although, boundary element and finite volume methods are well suited for, structural analysis and free surface flows, Hilbing and Heister (1994), Masheyek and Ashgriz applied the concepts in the simulation of sprays and atomization.

In Hassainpour and Ninesh (2009), computational fluid dynamics (CFD) code was adopted in a study of sprays in direct injection engines. The discrete droplet method, a statistical tool was employed for spray calculations by the authors. Based on experimental validation, the authors reported that spray penetration and emission characteristics are predicted better with modeling methodologies.

A study of droplet-gas system configured in a three-dimensional model which accounted for atomization of parent droplets was reported in Lijuan *et al.* (2009) Deduction from this study, point to the air-to-liquid ratio in the effervescent atomizer as having strong influence on droplet size and distribution.

Soybean oil methyl ester (SME) atomization was reported by Park *et al.*(2009) Their results showed similar SMD distribution patterns for biodiesel and diesel in comparison with experimental droplet size distribution.

Park *et al.*(2009b) studied conditions for atomization of soybean oil Methyl ester (SME) fuel, nozzle tip and SMD were calculated. SME physical properties were used as input in KIVA code (Torres and Trujilo, 2006) for the calculation of spray characteristics.

Several other studies on breakup models relied heavily on either existing open source KIVA-3V code or other models. Moreover, most of them are local to diesel fuel sprays and biodiesel which is good in that applying their results can account for specific spray patterns in specific fuels without ambiguity. Among this category are the contribution in Kawahara *et al* (2004)

2.2 Recent Advancements

In the last two years, several research efforts geared towards broadening the understanding of sprays, atomization and breakup have been reported in the open literature. This subsection is devoted to the review of such contributions as experimental, theoretical or hybrid methods that address the subject matter.

Other authors such as Juang *et al.* (2010) explained the use of CFD in complex processes.

Kim *et al* (2010) analyzed atomization performances of three fuels. Tip penetration of spray, width spray cone angle and SMD were determined by experiment and predicted by KIVA-3V code. Deductions from their study point to droplet size as being proportional to fuel physical properties.

Microscopic droplets behavior of diesel and biodiesel was studied by Htung *et al.*(2010) The KIVA-3V code, the Taylor Analogy Breakup (TAB) model and its modifications were used as numerical tools for quantifying experimental results. Other relevant experimental studies are those of Shinjo and Umemura (2011), Zhoulang *et al* (2012), Lee and Park (2014), Cipolat and Valentim (2013), Fox (1997).

Theoretical and experimental injection spray characteristics were compared in a study Zhao *et al*(2012).Two models that were drawn from the literature were compared on the basis of capacity to duplicate experimental data. A high speed

camera was used to observe the deformation and breakup behavior of coal water slurry cylindrical jet surrounded by an annular airflow. Four types of breakup models namely Rayleigh breakup, membrane breakup, fiber breakup and atomization were studied based on dimensionless numbers and experimental data. The authors drew several conclusions, one of which is that jet breakup length decreases with increase in Weber number and increases with increasing Ohnesorge number.

Jiang *et al*(2012) , Vita and Alloca (2012) ,Li *et al* (2014) also researched on breakup models by adopting existing open source codes. The merit in using open source code is that it provides a platform for preliminary study. However, the task of adopting such codes vis-à-vis editing to suit specific situations can be very time consuming, besides the computer programming expertise that is required.

In Xie *et al* (2015), an experimental study in the macroscopic spray characteristics of biodiesel and diesel was reported. Various blends of biodiesel and diesel ranging from 0% and 100% diesel was formulated and studied at five different injection pressures and ambient pressures, in a constant volume chamber and a high speed camera was used to capture spray images. Results from the study show that ambient and injection pressures have significant effects on spray characteristics. The contribution is purely experimental, requiring high precision gadgets and no attempt was made regarding correlations or modeling applications.

A study on the spray and combustion characteristics of bio-ethanol-gasoline blended fuel based on fuel temperature was reported in Park *et al* (2016). The bio-ethanol test fuel was blended at volume ratios of 10%, 20% and 100% while fuel temperature were set at -7.25°C and 35°C respectively. A visualization scheme that is similar to a high speed camera was used to capture spray images. The major conclusion from the study is that it is necessary to adjust the spray strategy and ignition timing to adopt bio-ethanol blended fuel as an alternative fuel.

Ghahremani et al (2016) reported an experimental and theoretical study on spray behaviours of modified bio-ethanol fuel. They employed an unnamed atomization model to study spray atomization indicators such as ohnesorg number, atomization index number and sauter mean diameter and used a high speed visualization method for capturing spray images. The major conclusion is that increasing percentage of ethanol in the fuel blend results in increase in spray top penetration and decreases the projected spray area.

Feng (2016) investigated the effects of ethanol and gasoline addition on the spray and atomization characteristics of diesel spray, in a constant volume chamber and at various ambient and injection pressures. The spray tip penetration and cone angle were extracted from spray evolution process that was recorded with high spatial and time resolution system. The results showed that the spray breakup and atomization process was promoted as gasoline blending ratio increased as gasoline blending ratio increased. However, they were silent about the optimum blending ratio and the corresponding spray characteristics.

Yoo et al (2017) studied the atomization and breakup characteristics of liquid jets at various spray conditions, using the large eddy simulation approach. A combined Eulenian-Lagrangiar approach was employed to describe the spray field dynamics. The liquid column and the droplet breakup processes were simulated using a Kelvin-Helmboltz and Rayleigh-Taylor (KH-RT) hybrid wave breakup model. Reasonable agreement between model predictions and experimental data was demonstrated by the authors. However, Range-Kutta method was used to solve the modeling equation without recourse to CFD codes.

In a related work, Garai et al (2017) reported an experimental investigation of spray characteristics of kerosene and ethanol-blended kerosene using a gas turbine hybrid atomizer. The breakup length, cone angle and street width of the fuel stream were said to have been analyzed directly from backlit imaging for

various fuel and air flow rates. It was concluded that breakup occurred earlier in the ethanol-blended kerosene.

2.3 Knowledge Gap

Experimental procedures for studying fuel breakup characteristics are documented in the open literature. However, the focus has been on diesel, biodiesel and bioethanol, while little attention has been given to gasoline-ethanol blends. Moreover, there is paucity of data of spray characteristics of diesel fuels in the dense region (near field) while such experimental data is non-existent for gasoline-ethanol fuel blends beyond Gashols (E10).

Regarding modelling efforts, the existing breakup and spray models centre around Kelvin-Helmholtz(kH), Rayleigh-Taylor (RT) instability, Rayleigh - Avereged Navier-Stokes, Taylor-Analog breakup, wave breakup and modified forms. Such modifications where they are introduced, are local to the fuel and the atomizer that is studied. Hence, the results from such modeling efforts can hardly be adopted for gasoline-ethanol fuel blends. More so, some of the simplifying assumptions such as droplets maintaining uniform temperature throughout a spray plume needs to be addressed. In internal combustion engines, atomization, transport and evaporation are necessary precursors to combustion. However, no models exist that capture each of the phenomena as they relate to gasoline-ethanol fuel blends.

Although the predictive accuracy of existing breakup models have been tested on diesel and other fuels, such tests on gasoline-ethanol fuel blends are either not documented or poorly attended to. Regarding, the use of spray distribution functions, no consensus has been reached on the most reliable one; even there is no information in the literature as to how well or poorly the existing functions aggregate gasoline-ethanol fuel blends.

CHAPTER 3

RESEARCH METHODOLOGY

3.0 Introduction

Liquid break up and atomization are complex phenomena that entail several interconnected stages. In order to bring to the fore the relationship between blobs that are associated with primary break up, secondary breakup and other complex phenomena, the modeling equations that form the basis for simulation are developed and presented in this chapter.

3.1 Spray Modeling and Atomization

Atomization modeling is one of the most important processes in the spray CFD simulation. The primary atomization model Kelvin-Helmholtz (KH) instability of Reitz (Blob Model) and secondary atomization modeled, the WAVE model as presented in Trinh (2007), the modified KH-RT models (Combination of the Kelvin-Helmholtz (KH) instability model and Rayleigh-Taylor (RT) instability model) presented in Chryssakis *et al* (2011) are considered in this study.

3.1.1 Blob Sheet Model

The blob sheet model is presented in figure 3.1 (Chryssakis *et al*, 2011) and the breakup rate is given as:

$$\frac{dD_p}{dt} = k_l \frac{L_A}{\tau_A} \quad (3-1)$$

Where D_p is the change in diameter of the particle, the proportionality constant k_l is subject to calibration as determined by the rate of atomization, L_A the dominant length scale of atomization. In equation 3.1, there are five (5) variables, so the degree of freedom is four (4). Equation 3.2 was used to calculate one of the variable L_A which is in equation 3.1; also equation 3.3 was used to calculate τ_A where the time for energizing is fixed, the change in particle diameter due to atomization can be determined from equation 3.1. The calibration of the

proportionality constant depends on the rate of breakup of blob with respect to dominant length over time.

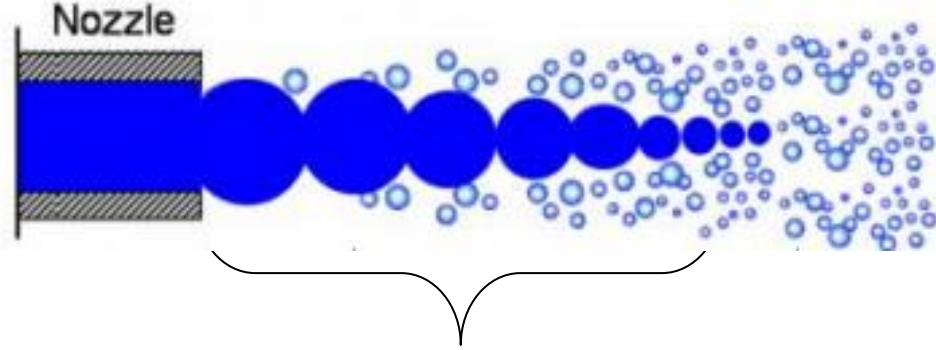


Figure 3-1: A typical representation of the blob-injection model (Chryssakis *et al* 2011).

The model assumptions are:

- The length L_A :

$$L_A = C_1 \times L_t = C_2 \times L_w \quad (3-2)$$

The atomization scale is the linear sum of the turbulence and wave growth time scales:

$$\tau_A = C_3 \times \tau_t + C_4 \times \tau_w \quad (3-3)$$

Turbulence quantity dissipation rate is given as:

$$L_t^0 = C_\mu \frac{k_{avg}^{3/2}}{\varepsilon_{avg}} \quad (3-4)$$

$$\tau_t^0 = C_\mu \frac{k_{avg}}{\varepsilon_{avg}} \quad (3-5)$$

$C_\mu=0.09$ and the average quantities are estimated as:

$$k_{avg} = \frac{u^2}{8(L/D)} \left[\frac{1}{C_d^2} - k_c - (1-s^2) \right] \quad (3-6)$$

$$\varepsilon_{avg} = k_\varepsilon \frac{u^2}{2L} \left[\frac{1}{C_d^2} - k_c - (1-s^2) \right] \quad (3-7)$$

$$\text{Turbulence length } L_t(t) = L_t^0 \left(1 + \frac{0.0828t}{\tau_t^0} \right)^{0.457} \quad (3-8)$$

$$\text{Time scale } \tau_t(t) = \tau_t^0 + 0.0828t \quad (3-9)$$

$$\text{Wave growth time scale } \tau_w = \frac{L_w}{U} \sqrt{\frac{\rho_L}{\rho_g}} \quad (3-10)$$

3.1.2 Linearized Instability Sheet Atomization (LISA) Model:

In section 3.1.1 the Blob sheet model was treated. In order to determine the more workable primary atomization model that could produce reliable results, two other primary atomization models, namely LISA is considered here in section 3.1.2 and TAB in 3.1.3.

Schmidt and Rufland (2000) developed LISA model for the simulation of primary breakup of liquid films, commonly called sheet. Originally intended for gasoline direct injection engines, the model is based on fluid mechanic principles that account for the centrifugal forces that are developed as a result of swirl component of velocity. The thickness of film, formed at the nozzle walls is calculated from the mass flow rate in according to equation 3.11 .

$$m_l = \pi \rho_l u h_0 (d_0 - h_0) \quad (3-11)$$

In the development of the model, it is assumed that the sheet thickness is ρ and it moves through a quiescent gas medium at a constant velocity, U and that breakup occurs due to wave disturbances. The growth rate of breakup is given by equation 3.12.

$$\omega_r = 2v_t k^2 + \sqrt{4v_t^2 k^4 + \rho_r U^2 k^2 - \frac{\sigma k^3}{\rho_l}} \quad (3-12)$$

This expression is numerically maximized to calculate the maximum growth rate, $\omega_{\max}$.

$$\text{Breakup time } \tau = \frac{1}{\omega_{\max}} \ln \left(\frac{\eta_b}{\eta_0} \right) \quad (3-13)$$

$$\text{Breakup length } L = U\tau = \frac{U}{\omega_{\max}} \ln \left(\frac{\eta_b}{\eta_0} \right) \quad (3-14)$$

Where, $\ln \left(\frac{\eta_b}{\eta_0} \right) = 12$. η_0 and η_b are infinitesimal perturbation at initial and breakup, respectively.

The liquid sheet half-thickness which is the diameter of the spray L is given by:

$$\text{Thickness of sheet (half)} \quad h = \frac{2h_0[d_0 - h_0] \cos \theta}{2L \sin \theta + d_0 - h_0} \quad (3-15)$$

Half sheet thickness is considered because only one face of the sheet is exposed in the direction of the atomization.

$$\text{Diameter at breakup} \quad d_L = \sqrt{\frac{16h_b}{k_{\max}}} \quad (3-16)$$

$k_{\max}$ = wave number corresponding to the maximum growth rate

$\omega_{\max}$ and h_b = sheet thickness at the breakup location.

The ligaments break up once the amplitude of the unstable waves is equal to the radius of the ligaments, giving droplets with diameter:

$$\text{Diameter droplet} \quad d_D = \left(\frac{3\pi d_L^3}{k_L} \right)^{1/3} \quad (3-17)$$

$$\text{With} \quad k_L = \left[\frac{1}{2} + \frac{3\mu_l}{2(\rho_l \sigma d_L)^{1/2}} \right]^{-1/2} \quad (3-18)$$

representing the Weber result for the wave number corresponding to the maximum growth rate. Weber number which is a dimensionless number is used to determine break up type, sequence and time.

3.1.3 TAB Model

Taylor Analogy Breakup (TAB) by O'Rourke and Amsden (1987) was adopted for spray breakup calculations. It depicts analogous relationship between oscillating and distorting droplet that penetrates through surrounding gas with a relative velocity and a forced oscillating spring-mass system resulting in equation 3.19:

$$m \frac{d^2 x}{dt^2} = F - k_s x - c \frac{dx}{dt} \quad (3-19a)$$

x = displacement (corresponding to the displacement of the equation of the droplet from its equilibrium point)

F = the external forces (corresponding to aerodynamic drag)

k_s = spring's constant (corresponding to surface tension)

c = damping parameter. (corresponding to viscous forces)

In the light of the analogy that is depicted in Figure 3.2, the physical relationship between the coefficient in (3.19a) are:

$$\frac{F}{m} C_F \frac{\rho_g U_2}{\rho_L r}, \quad \frac{Ks}{m} = C_k \frac{\sigma}{\rho_L r^3}; \quad \frac{d}{m} = Cd \frac{\mu_L}{\rho_L r^2} \quad (3-19b)$$

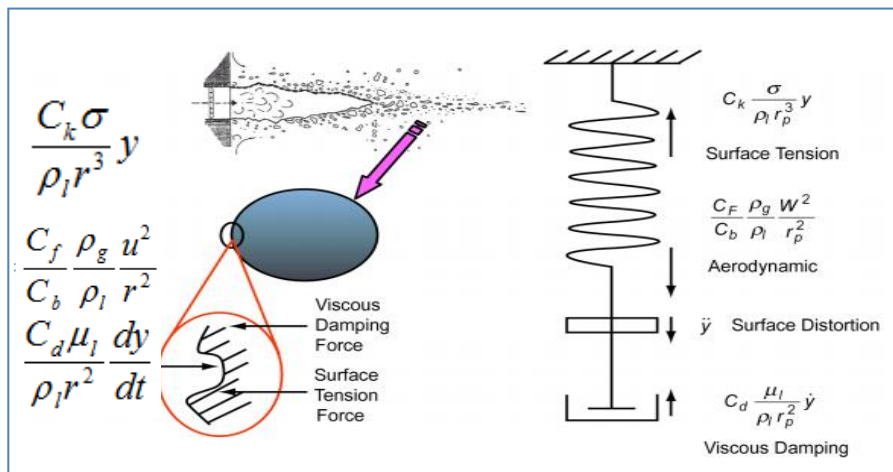


Figure 3.2: Schematic showing analogy of forces acting on a liquid droplet and spring-mass system [Leonardo et al., 2012].

By defining $y = \frac{x}{C_b r}$, which is the spray breakup domain and combining with

(3.19b), TAB model becomes.

$$\frac{d^2 y}{dt^2} = \frac{C_f}{C_b} \frac{\rho_g}{\rho_l} \frac{u^2}{r^2} - \frac{C_k \sigma}{\rho_l r^3} y - \frac{C_d \mu_l}{\rho_l r^2} \frac{dy}{dt} \quad (3-20)$$

Equation 3.20 is the equation of oscillation,

where, C_b , C_d , C_f and C_k are dimensionless constants, r is the droplet radius and ρ_g , ρ_l and σ are gas and liquid densities and surface tension, respectively

Typical values for the dimensionless constants are: $C_b=0.5$, $C_d=5$, $C_f=1/3$ and $C_k=8$ or $C_k=6$ (Trinh, 2007).

Solving the linear non-homogeneous second-order differential equation (Equation 3.20), gives the exact solution (Leonardo, Alfredo and Alvarez 2012).

$$y(t) = \frac{C_f}{C_k C_b} We + e^{-t/t_d} \left[\left(y_0 - \frac{C_f}{C_k C_b} We \right) \cos \omega t + \frac{1}{\omega} \left(\left(\frac{dy}{dt} \right)_{t=0} + \frac{y_0 - \frac{C_f}{C_k C_b} We}{t_d} \right) \sin \omega t \right]$$

Where, the Weber number, $We = \frac{\rho_g u^2 r}{\sigma}$, angular frequency of the oscillatory

motion, $\omega = C_k \frac{\sigma}{\rho_l r^3} - \frac{1}{t_d^2}$ and $\frac{1}{t_d} = \frac{C_d}{2} \frac{\mu_l}{\rho_l r^2}$. The values of y and its first derivative

at $t=0$ are y_0 and $\left(\frac{dy}{dt} \right)_{t=0}$, respectively.

According to O'Rourke and Ansden(1987), energy of the parent droplet before breakup is given as :

$$\frac{r}{r_{32}} = 1 + \frac{8k}{20} + \frac{\rho_l r^3}{\sigma} \left(\frac{dy}{dt} \right)^2 \left(\frac{6k-5}{120} \right) \quad (3-21)$$

r_{32} = Sauter Mean Radius (SMR) of the parent droplet

k = constant which is determined experimentally by measuring drop sizes.

The value of $k=10/3$ has been obtained by matching analysis data with experiment data (Reitz and Bracco,1986;Trinh,2007;Leonardo *et al*,2012

3.1.4 Enhanced-TAB Model (E-TAB)

The Enhanced-TAB Model (E-TAB) was developed by Tanner (1997) while a related model was presented by (Reitz and Bracco, 1986) in which droplet production was presented as equation (3.22):

$$\frac{d(m(t))}{dt} = -3K_{br}m(t) \quad (3-22)$$

$m(t)$ = mean mass of the product droplet distribution,

K_{br} = constant that depends on the breakup regime.

Relationship between the product and parent droplet radius, r and α respectively:

$$\frac{r}{\alpha} = e^{-K_{br}t} \quad (3-23)$$

3.1.5 Wave Model

The wave model (KH model) is where the stability analysis of round liquid jets is developed. The droplet breakup (Kelvin–Helmholtz instability) of liquid jet has initial radius r and η_0 is an infinitesimal initial perturbation as shown in Figure 3.3.

Radius change of this droplet is calculated as:

$$\frac{dr}{dt} = \frac{r - r_{new}}{\tau_{bu}} \quad (3-24)$$

Where, τ_{bu} is the characteristic breakup time scale defined by Beale and Reitz (1999) and is contained in equation 3.25.

$$\tau_{bu} = 3.788B_1 \frac{r}{\Lambda\Omega} \quad (3-25)$$

And the new droplet radius given as;

$$r_{new} = B_0\Lambda \quad (3-26)$$

Where B_0 and B_1 are constants and the drop radius decreases continuously if this Equation (3.27) is satisfied then both the maximum growth rate and wave length could be evaluated using equations 3.28 and 3.29 respectively.

$$B_0 \Lambda \leq r \quad (3-27)$$

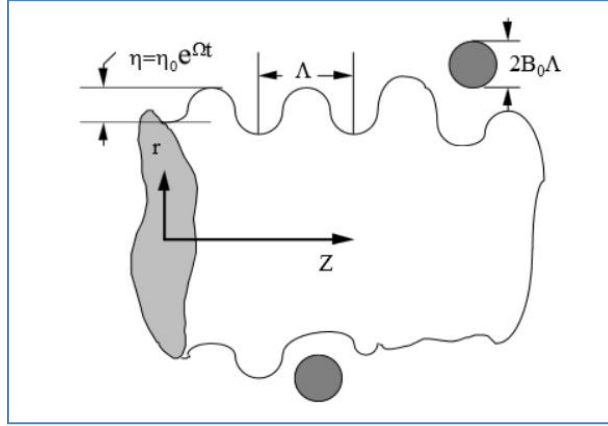


Figure 3.3: Kelvin-Helmholtz model

Beale and Reitz (1999) also determined the maximum growth rate and wavelength respectively as stated in equations 3.28 and 3.29

$$\text{Maximum growth rate } \Omega = \frac{0.34 + 0.38 We_g^{15}}{(1+z)(1+1.4T^{0.6})} \left[\frac{\sigma}{\rho_l r^3} \right]^{0.5} \quad (3-28)$$

$$\text{Wavelength } \Lambda = 9.02r \frac{(1+0.45Z^{0.5})(1+0.4T^{0.7})}{(1+0.865We_g^{1.67})^{0.6}} \quad (3-29)$$

Where, $Z = \frac{\sqrt{We_l}}{Re_l} = \frac{\mu_l}{\sqrt{\rho_l r \sigma}}$ Ohnesorge number, $T = Z \sqrt{We_g}$ Taylor number, and

$We_g = \frac{\rho_g r u_{rel}^2}{\sigma}$ and $We_l = \frac{\rho_l r u_{rel}^2}{\sigma}$ are gas and liquid Weber numbers, respectively

and u_{rel} velocity of liquid droplet relation to stationary gas phase (Beale and Reitz, 1999). Z , T , We_g and We_l are dimensionless numbers which are substituted into equations 3.28 and 3.29 to calculate maximum growth rate and wavelength respectively.

3.1.6 KH-RT Model

This model consists of two modes of breakup: The Kelvin-Helmholtz (KH) breakup which accounts for instability in the waves growing and Rayleigh-Taylor (RT) breakup. KH instability model which was described in section 3.1.5.

Rayleigh-Taylor (RT) breakup is governed by the rapidly growing disturbances on the surface of the droplet. Wave, Ω_{RT} wavelength, Λ_{RT} were given in equation (3.30) and (3.31), respectively (Jing, 2015):

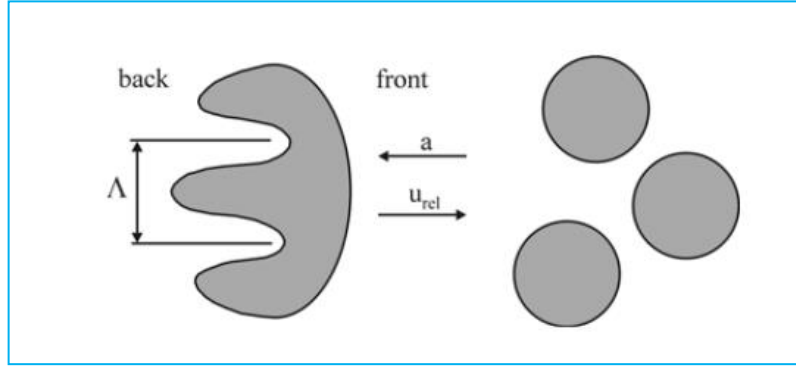


Figure 3.4 Rayleigh-Taylor (RT) instability.

$$\Omega_{RT} = \sqrt{\frac{2[a_d(\rho_l - \rho_g)]^{1.5}}{3\sqrt{3}\sigma(\rho_l + \rho_g)}} \quad (3-30)$$

$$\Lambda_{RT} = 2\pi C_{RT} \sqrt{\frac{3\sigma}{a_d(\rho_l - \rho_g)}} \quad (3-31)$$

$$a_d = \frac{3}{8} C_d \left(\frac{\rho_g u_{rel}^2}{\rho_l r} \right) \quad (3-32)$$

Where, a_d is the droplet acceleration, C_d is the injector nozzle's discharge coefficient and C_{RT} is the modeling parameter.

The breakup time scale is expresses as:

$$\tau_{RT} = \frac{C_1}{\Omega_{RT}} \quad (3-33)$$

Where, C_1 is the modeling constant.

When the growth time exceeds the characteristic Rayleigh-Taylor (RT) time, breakup occurs and the droplet is converted into parcels of smaller droplets. The new droplets formed are taken to be of uniform diameter.

Out of the models for atomization listed in this chapter, only the Blob sheet primary atomization model and secondary KHRT breakup model alongside CFD were employed for simulation which yielded the results contained in chapter four. The simulation failed when the primary atomization of LISA, TAB, WAVE models were attempted.

3.1.7 Numerical Techniques for Simulating Atomization Process Based on CFD

The spray injected into a constant volume cylinder is simulated using the Eulerian–Lagrangian approach. Small computational cells (μm) composing Meshes (8900) with fluid density, velocity, pressure and enthalpy were computed and stored on each computation cell.

Gas (continuous) is simulated using the Eulerian formulation in Reynolds–Averaged Navier–Stokes (RANS) equation alongside Realizable k– ϵ turbulence model which accounts for effect of turbulence fluctuations in the fluid phase. Similarly, the liquid (discrete or disperse) phase is treated using a Lagrangian formulation together with spray sub-models.

3.1.7.1 Governing Equations

The equations governing the spray and atomization process are expressed for both the gas and liquid phases which are known as Eulerian and Lagrangian phases respectively as follows:

- Continuity Equation

$$\frac{\partial \rho}{\partial t} - \frac{\partial}{\partial x_j} (\rho U_j) = S_m \quad (3-34)$$

- Momentum Equation

$$\rho \frac{\partial U_i}{\partial t} + \rho U_i \frac{\partial U_i}{\partial x_j} = - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} - \frac{2}{3} \frac{\partial U_k}{\partial x_k} \delta_{ij} \right) \right] + \frac{\partial}{\partial x_j} \left(- \rho \overline{u_i u_j} \right) + S_F \quad (3-35)$$

- Energy Equation

$$\rho \left(\frac{\partial \rho h}{\partial t} + \frac{\partial (\rho h U_j)}{\partial x_j} \right) = \frac{\partial}{\partial x_i} (U_j \tau_{ij}) + \frac{\partial}{\partial x_j} \left(\kappa_T \frac{\partial T}{\partial x_j} \right) + S_h \quad (3-36)$$

Where, the mean properties of continuous phase denoted by $\rho, U_j, h, T, \kappa_T$ and P are the density, velocity component in x_j direction, enthalpy, temperature, thermal conductivity and pressure, respectively. τ_{ij} represents the viscous stress tensor given by;

$$\tau_{ij} = \mu \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} - \frac{2}{3} \frac{\partial U_k}{\partial x_k} \delta_{ij} \right) \quad (3-37)$$

And S_m accounts for mass transfer between discrete (liquid) to continuous (gas) which is due to droplet evaporation. The momentum and energy interactions between discrete and continuous are represented by source terms S_F and S_h , respectively.

The Reynolds stresses which account for turbulent fluctuations in fluid momentum are determined based on the Boussinesq hypothesis. Reynolds stresses in relation to the mean velocity gradient is given by equation 3.38 following literature(Ghasem *et al*,2014;Hashem *et al*,2014)

$$-\rho \overline{u'_i u'_j} = \tau_{ij}(\text{turbulence}) = \mu_t \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) - \frac{2}{3} \left(\rho k + \frac{\partial U_k}{\partial x_k} \right) \delta_{ij} \quad (3-38)$$

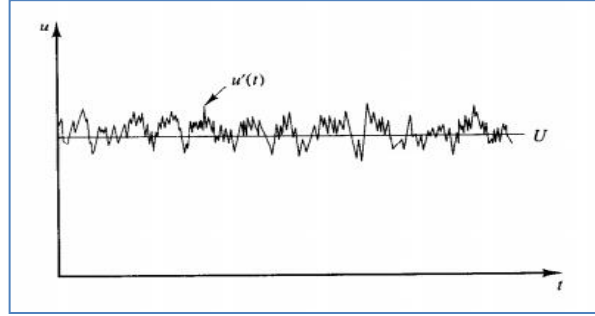


Figure 3.5: Velocity measurement in turbulent flow [Versteeg and Malalasekera, 1995]

In this study, the Realizable k-e turbulence modeling was adopted in simulation of turbulence fluctuations of continuous phase.

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (3-39)$$

3.1.7.2 Disperse (Lagrangian) Phase

Fuel spray droplets determination could be described by Newton's equations of motion which show that particle inertia balances other forces acting on each particle. The trajectories of droplets are determined by solving the

following equations:
$$\frac{dU_i^p}{dt} = F_D (U_i - U_i^p) + g_i \frac{\rho_p - \rho}{\rho_p} + F_i \quad (3-40)$$

$$\frac{dx_i^p}{dt} = U_i^p \quad (3-41)$$

$$F_D = \frac{C_D \text{Re}}{24} \frac{18\mu}{\rho_p d_p^2} \quad (3-42)$$

$$\text{Re} = \rho d_p \frac{|U_i^p - U_i|}{\mu} \quad (3-43)$$

C_D = drag coefficient [Morsi and Alexander 1972] for smooth spherical droplets is expressed by following equations:

$$C_D = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re} \quad (3-44)$$

Where, a_1 , a_2 and a_3 are constant whose values are dependent on Reynolds number.

$g_i \frac{\rho_p - \rho}{\rho_p}$ = Gravitational force per unit mass on acting on each spray droplet.

F_i = Additional acceleration caused by other forces per unit particle mass.

U_i^p , ρ_p and d_p are the particle velocity in a given direction, particle density and particle diameter, respectively.

The droplet velocity at each point along the trajectory is determined by integration of equation (3.40) over discrete time steps (yields equation (3.41) which is solved for each coordinate direction to predict the particles trajectory).

3.1.7.3 Turbulence Modeling

The realizable k-epsilon modeled turbulence effect on atomization. The transport equations described below depict (www.cfd-online.com/wiki/realisable_k-epsilon_model):

Turbulence kinetic energy k :

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k + P_b - \rho \varepsilon - Y_M + S_K \quad (3-45)$$

Turbulence dissipation energy ε :

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho C_1 S \varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} + C_{1\varepsilon} \frac{\varepsilon}{k} C_{3\varepsilon} P_b + S_\varepsilon \quad (3-46)$$

Where,

$$C_1 = \max \left[0.43, \frac{S \frac{k}{\varepsilon}}{S \frac{k}{\varepsilon} + 5} \right] \quad (3-47)$$

$$S = \sqrt{2S_{ij}S_{ij}} \quad (3-48)$$

$$P_k = \overline{\rho u_i u_j} \frac{\partial u_j}{\partial x_i} \quad (3-49)$$

$$P_k = \mu_t S^2 \quad (3-50)$$

$$P_b = \beta g_i \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i} \quad (3-51)$$

$$\beta = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p \quad (3-52)$$

Modeling turbulence viscosity:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (3-53)$$

Where,

$$C_\mu = \frac{1}{A_0 + A_s \frac{kU^*}{\varepsilon}} \quad (3-54)$$

$$U^* \equiv \sqrt{S_{ij}S_{ij} + \tilde{\Omega}_{ij}\tilde{\Omega}_{ij}} \quad (3-55)$$

$$\tilde{\Omega}_{ij} = \Omega_{ij} - 2\varepsilon_{ijk}\omega_k \quad (3-56)$$

$$\Omega_{ij} = \overline{\Omega_{ij}} - \varepsilon_{ijk}\omega_k \quad (3-57)$$

Where,

$\overline{\Omega}_{ij}$ = mean rate-of-rotation tensor

ω_k , = angular velocity $A_0 = 4.04$ and $A_s = \sqrt{6} \cos \phi$

$$\phi = \frac{1}{3} \cos^{-1} \left(\frac{\sqrt{S_{ij} S_{jk} S_{ki}}}{(S_{ij} S_{ij})^{\frac{3}{2}}} \right); \quad S_{ij} = \frac{1}{2} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \quad (3-58)$$

The computational fluid dynamics process solutions are then feed into Blob sheet and RH-RT models for the simulation.

Model Constants of Realizable K- ϵ

C_μ	0.09
A_0	4
C_2	1.9
σ_k	1
σ_ϵ	1.2
Pr_t	1

3.2 Data

The density, surface tension and viscosity of gasoline and ethanol fuels were computed internally and imported as input data. The inlet and exit temperatures and pressures were defined. A cylindrical system atomizer with consideration of all boundaries as walls and mesh coordinates were set to be symmetrical with an assumption of no heat loss. The mesh generation was taken to be one-quarter of a cylinder which was simulated by defining the process to be a transient compressible system where there were variations of pressure. The reason for assuming symmetry in the cylinder is because of the use of cone injector model, hence it is considered a hollow injector atomizer so it can be symmetrical at 45°C

per cross section. The inner nozzle diameter which was obtained from standard nozzle design is taken to be 100 μ m. A dimensionless length of atomizer defined as $Z = x/LA$ was considered in this work. Here, x is any distance away from the nozzle while LA is the physical length of the atomizer. Z varies between 0 and 1 for any numerical value of LA that is used as input data.

CHAPTER 4

RESULTS AND DISCUSSION

4.0 Introduction

Different approaches as listed in the knowledge gap and mathematical models are adopted in this chapter for result realization and analysis. The different subsections contain specific atomization processes hence the first section deals with numerical approach for simulating atomization process. In the numerical process Sauter mean diameter (SMD) estimation, formulation of numerical simulation, model specification, results and discussion are discussed.

4.1 Sauter mean diameter (SMD)

The Sauter mean diameter (SMD or d_{32}) was used in estimating mean size of given particle distribution. This work describes it as diameter of a droplet having the same volume/surface area ratio and expressed mathematically as;

$$SMD = d_{32} = \frac{\int_{d_{\min}}^{d_{\max}} d^3 f(d) dd}{\int_{d_{\min}}^{d_{\max}} d^2 f(d) dd} \quad (\text{Leonardo, et al, 2012}) \quad (4-1)$$

Where,

d = particle diameter,

$d_{\max}$ and $d_{\min}$ = maximum and minimum droplets diameters

$f(d)$ = probability density function of d , particle size.

4.2 Numerical Simulation Formulation:

The spray characteristics of gasoline fuel ((G100) - C_7H_{16}) was performed by simulation using OpenFOAM source code which runs on Linux platform. This analysis was performed using Simflow (Gullman 2010) to generate meshes for the simulation and run. The mesh and results files were saved to the OpenFOAM file format and visualized in ParaView software. Further analysis was done with MatLab by saving in the MatLab directory. Details regarding computer programs and computational schemes that were developed in this work as well as results are given in the appendices. Appendix A has simflow/openFOAM computer codes while Appendix B is Matlab scripts for spray simulation. Appendix C contains spray penetration results, Appendix D has fuel properties and Appendix E is validation of results.

In the simulation, only a quarter of cylinder was used in the simulation. Two of the boundaries were set to symmetry and the remaining boundary set to wall.

4.2.1 Modeling Specification

The **sprayfoam** solver is the solver type that was used to simulate a transient, compressible, reacting and non-combustible fuel injection process. High pressured fuel at 5MPa at 300°K was injected into high temperature (800°K) stagnant air at a velocity of 100m/s. The bases for the selection of the input data was premised on the fact that from literature it was found that 7mPa was adopted as injected fuel pressure, hence, similar value of 5MPa was employed so as to be able to do comparison.

The Turbulence Model of RANS - Realizable k-e model, with heat transfer model of Ranz-Marshall as well as phase change model which is liquid evaporation-boil model was adopted in boundary interaction (rebound) in secondary atomization.

4.3 Discussion of Results of different atomization processes

4.3.1 Spray Evolution of the Gasoline (G100) Fuel (ParaView)

The result files generated in simFlow/OpenFOAM were post processed in ParaView. The Figures 4.1a - d, show the images of the spray development for the Gasoline (G100) fuel.

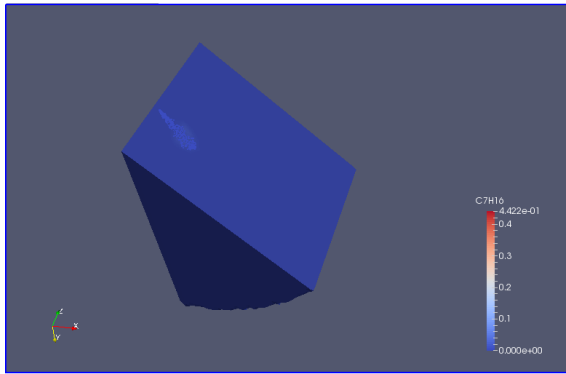


Figure 4.1a: Energizing time (0.00015 μ s)

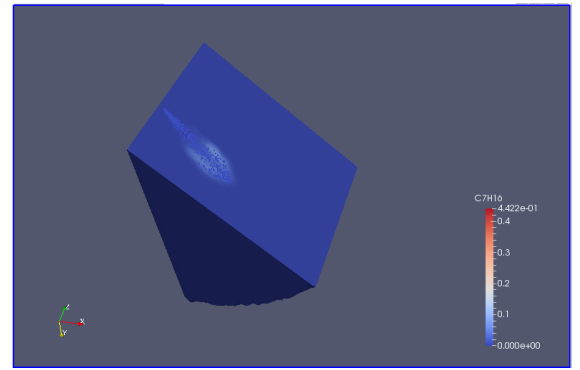


Figure 4.1b Energizing time (0.00032 μ s)

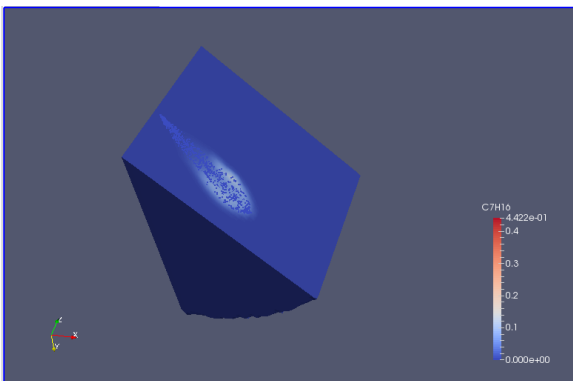


Figure 4.1c: Energizing time (0.000445 μ s)

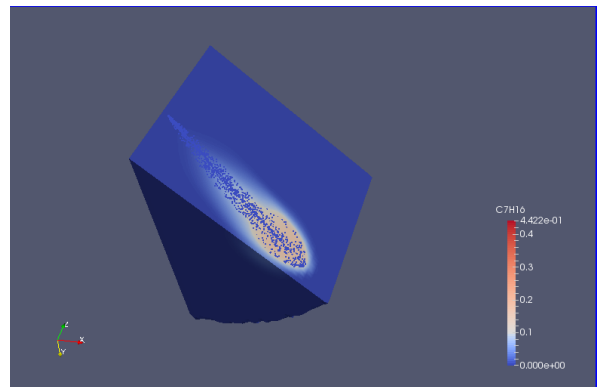


Figure 4.1d Energizing time (0.0008 μ s)

Figures 4.1a, 4.1b, 4.1c and 4.1d show the penetration length of atomization in relation to time frames of $0.00015\mu\text{s}$, $0.00032\mu\text{s}$, $0.000445\mu\text{s}$ and $0.0008\mu\text{s}$ respectively. The inference drawn from these figures was that the more time the atomization lasted the more the atomization took place in terms of penetration length.

4.3.2 Spray Evolution at four Cone Injection Angles at time steps of $0.0001\mu\text{s}$, $0.0002\mu\text{s}$, $0.0003\mu\text{s}$ and $0.00075\mu\text{s}$ respectively:

The computational time was determined using Blob Sheet model for primary atomization process. Figure 4.2a to 4.2d describe the spray evolution at four cone injection angles (20° , 30° , 40° and 50°) at time steps of $0.0001\mu\text{s}$, $0.0002\mu\text{s}$, $0.0003\mu\text{s}$ and $0.00075\mu\text{s}$. This injection process represents time frame of injection with respect to injection angular variations. It was discovered that with longer injection time frame and wider injection angle, the penetration width was wider and the penetration length deeper (longer) resulting in better atomization. The choice of this steps and injection angles were dictated by the desire to know the influence of the regular differentials in injection time and angle on rate atomization. The particular choice of equal incremental energizing time was to determine if that will make any different in the rate of atomization and whether increasing the rate phenomena from $0.0003\mu\text{s}$ to $0.00075\mu\text{s}$ ($2\frac{1}{4}$ times) would accelerate the rate of atomization and this happen to be the case as shown in Figs 4.1c and 4.1d.

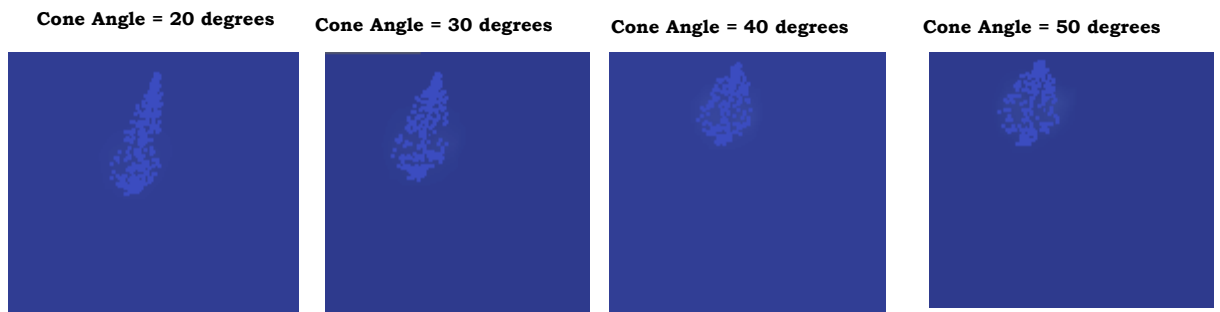


Fig 4.2a. 0.0001 μ s after injection

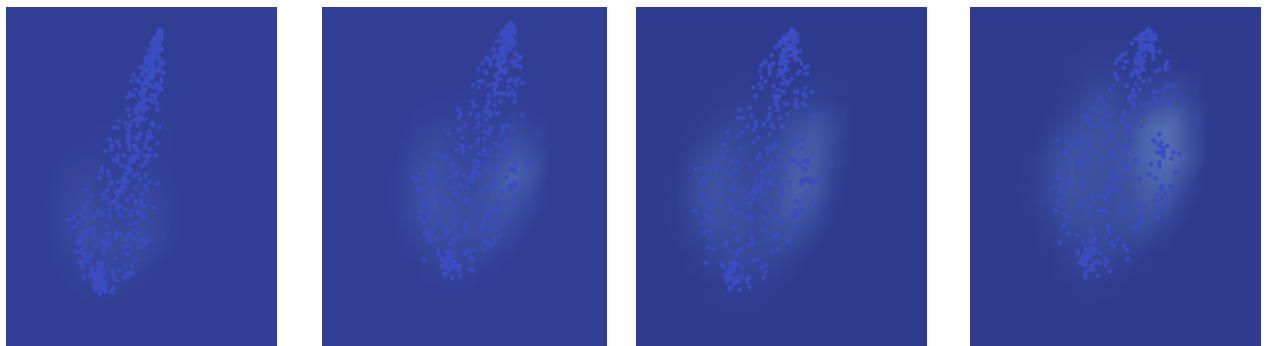


Fig 4.2b. 0.0002 μ s After Injection

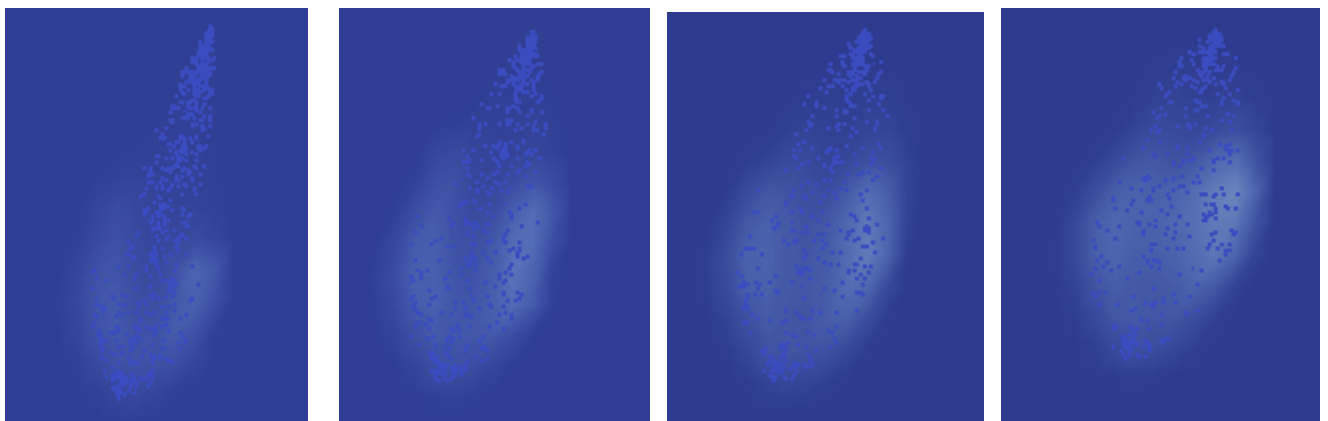


Fig 4.2c. 0.0003 μ s After Injection

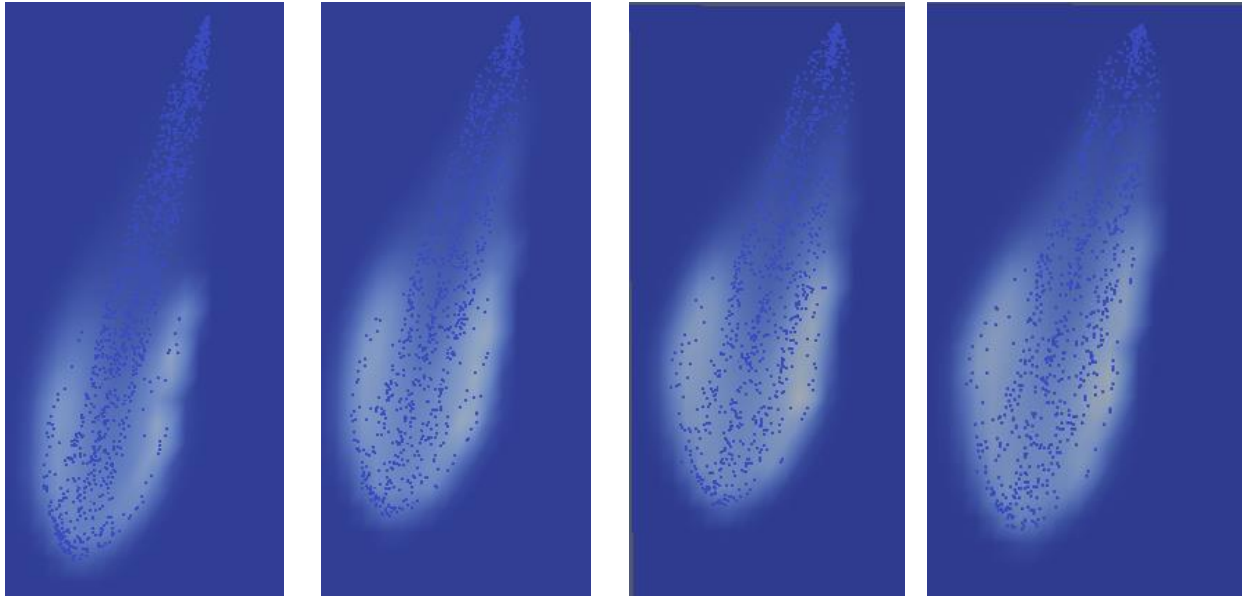


Fig 4.2d. 0.00075 μ s After Injection

4.3.3 Post Processing Using MATLAB

The results below were generated in MATLAB, from the output files of the simulation process. Figure 4.3 shows the droplet diameter against number of particles. It indicates that as the droplet diameter increases the particles density decreases. This depicts that where the particle size is small the electrostatic force of attraction between them increases because the ionic radii becomes small. The droplet diameter increases up to 1.75×10^{-5} m after which it drops because the particle density even in this range decreases to go. This is was indication that most of the particles pumped could go out as off gas without combustion if the atomized fuel was to be pumped from the atomizer to the combustion chamber in the event that combustion has taking place chamber and this indicates that it could be waste of fuel hereafter.

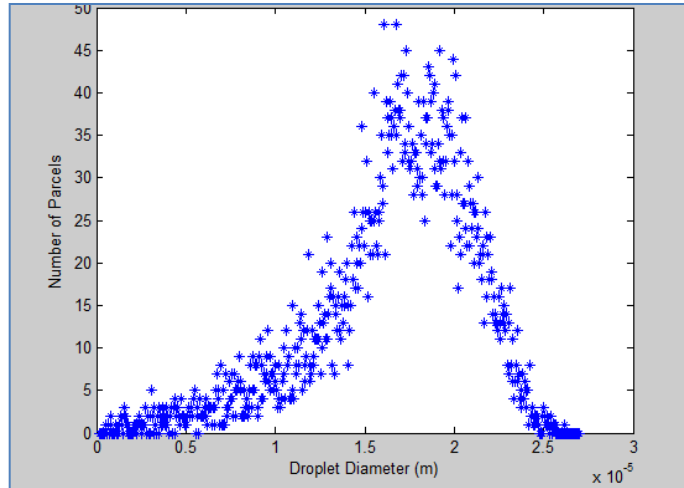


Fig 4.3 G100 Droplet size distribution at 5.0e-3(ms) after energizing

In fig 4.3, when the particle diameter is small the voidage between particles are small, hence particles tend to cluster in a particular zone. As the diameter increases, the density of the clusters become smaller. The number of particles increases while the particle density decreases as a result of atomization. It peaks at diameter between 1.5 and 2.0 μm at particle range of 45. Beyond this point the particle density begins to build again due to coaliscence because when the particles become small there is the tendency to cling. Hence the curve is a normal distribution curve which is skewed a little. The apex of this plot shows some noise before the plot descends downwards.

The Rosin Rammler distribution model was used to generate the number of spray particles injected into the cylinder as shown in figure 4.4. Rosin Rammler distribution is adopted because its well suited for spray atomization distributions. The Rosin Rammler cumulative particle size distribution plot for spray droplets depicts that with an exponential rise of the particle diameter, the cumulative effect increases which shows that there will be better combustion up to the pick $2 \times 10^{-5}\text{m}$ of droplet diameter.

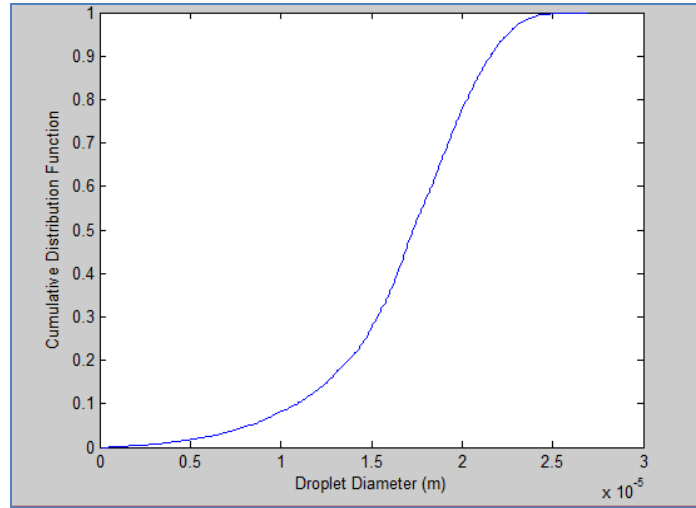


Figure 4.4: Rosin Rammler Distribution for the Spray droplets at 5 μ s after energizing.

This figure (4.4) is derived from figure 4.3 and it is the summation of particle diameter over the range of number of particles. The curve is exponentially distributed.

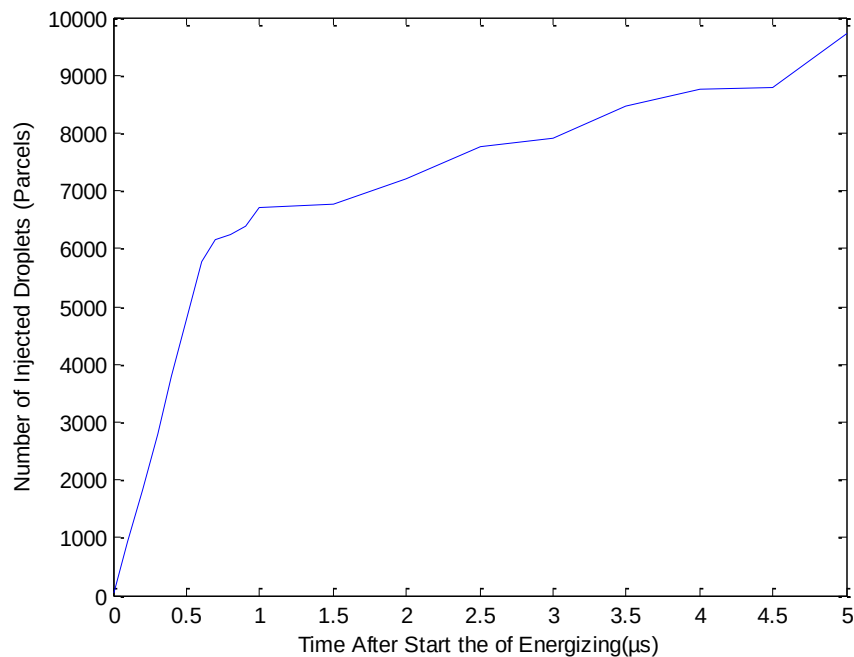


Figure 4.5: Injected droplets profile with time at pressure of 5MPa

Figure 4.5 is the injected droplets profile with time at pressure of 5MPa. This graph shows the engine performance in terms of atomization. From the zero axis between 0.00 to 0.5 μ s the number of injected droplet upto 6000 increased linearly. This means that in this region injected parcels were proportional to time of energizing (μ s). Inference here is that the more the number of droplets injected the more atomization took place.

This graph shows the effectiveness of atomization within a short period of time of 0.5 – 1 μ s when atomization takes place close to 7000 injected droplet particles. The most essential range to assess the extent of atomization of fuel is therefore 7000 droplet particles released into the combustion chamber. Beyond this time there is only a marginal increase in the number of particle.

The analysis following is the Sauter mean diameter (SMD) at injection pressure of 5MPa and injection cone angle of 20° as contained in figure 4.6.

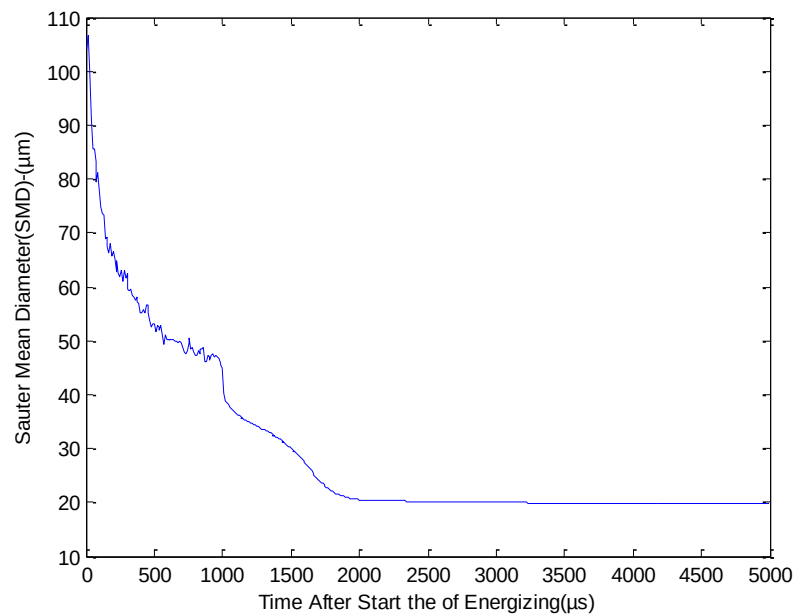


Figure 4.6: Sauter Mean Diameter (SMD) at injection pressure of 5MPa and injection cone angle of 20°

Analysing figure 4.6 from the top of the y-axis for Sauter mean diameter (SMD) between 100 and 50 μm shows that SMD drops and experiences decay exponentially in this range between time intervals of 0 to 1000 μs . From 50 μm down to 40 μm , the SMD drops sharply- linearly and then from 40 μm to 20 μm displays negative exponential curve and does not experience any further change beyond 2000 μs . This shows that SMD is insensitive to change with time in the value ranges of 2000 μs to 5000 μs .

Despite the cone injection angle variation of 20°, 30°, 40° and 50°, the SMD profile behaves similarly with varying energizing times at 5mPa injection pressure as in figure 4.6. Figure 4.7 just like figure 4.6 shows four distinct atomization regimes. Reading the plot in fig 4.7 from the y axis show that injection angle of 30°, 40°, 50° and 20° present better atomization in that order in relation to 250 μs time after injection. Between 250 μs and 1000 μs time after injection, atomization rate shows more and differently by presenting 30°, 20°, 40° and 50° in that order, but from 1000 μs to 1700 μs injection angles depict that 20° atomizes most, followed sequentially by 30°, 40° and 50°. The fourth and final distinct regime show that from injection time of 1750 μs through 5000 μs atomization is dominated by angular injection in the following pattern 50°, 40°, 30° and 20°.

Furthermore, in figure 4.6, the SMD dropped from 110 μm to about 45 μm in 1000 μs in the first leg. It decreased from 45 μm to 20 μm in 500 μs in the second leg and remained flat for the rest of the simulation process. The rate of change of particles diameter in the first leg is 0.065 $\mu\text{m}/\mu\text{s}$ while that in the second leg is 0.05 $\mu\text{m}/\mu\text{s}$. It could be deduced from the computed rates that primary atomization gets more difficult as the particular sizes get smaller.

The reduction in SMD was for a period of 500 μs during which SMD for E100 dropped from about 1109 μm by 79 μm at a cone angle of 20°, by 78 μm at a cone angle of 30° and by 76 μm at a cone angle of 40°. The salient point deduced from

figure 4.6 is that the rate of change of SMD decreased with increase in cone angle.

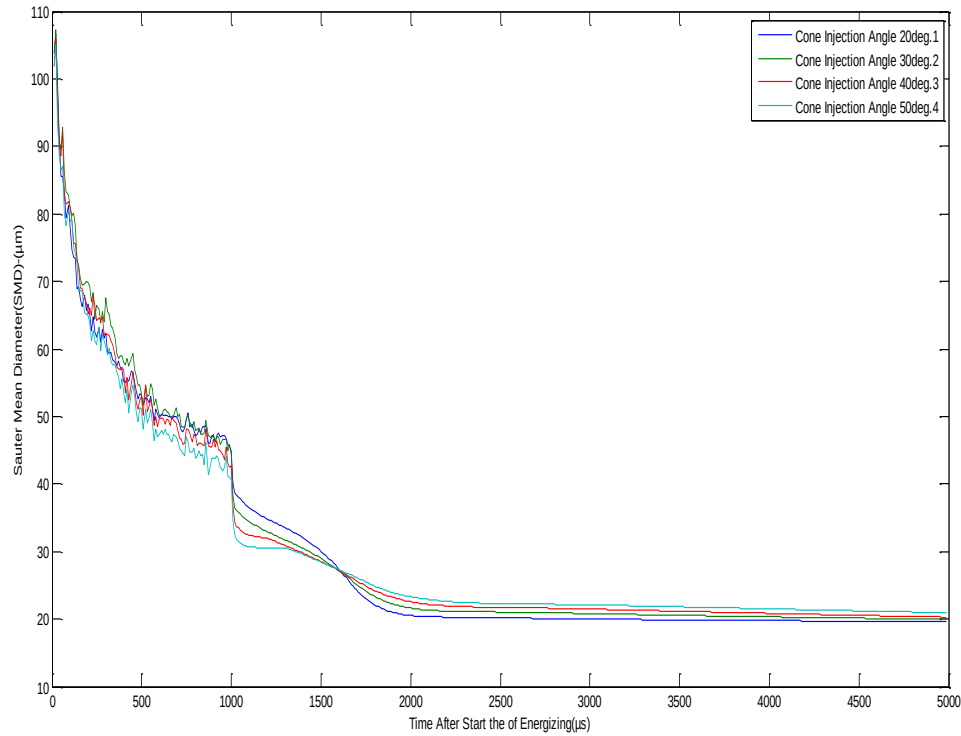


Figure 4.7: Sauter Mean Diameter (SMD) at injection pressure of 5MPa for four cone injection angles for gasoline

4.3.4 Blending of Gasoline and Ethanol (GASHOL)

The blending of gasoline and ethanol was done by adopting a mixing rule.

4.3.5 Mixing Rule

The gasoline and ethanol blended fuel properties were obtained by a combination of the gasoline and ethanol fuel properties based on their combining mixture mole fractions.

The mixing rule for the binary mixture is given by the following expression:

$$K_{mix} = \sum_{i=1}^2 x_i K_i \quad (4-2)$$

Where,

K_{mix} is the mixture property,

x_i is a liquid mole fraction and

K_i is the pure property of the pure component of the mixture (liquid or vapour) because while the fuel is liquid, the gas is in vapour form.

The properties of the mixture were used to determine the SMDs of the proportions of the different blends. Figures 4.8 and 4.9 depict the SMDs of different proportions of GASHOL at different injection cone angles.

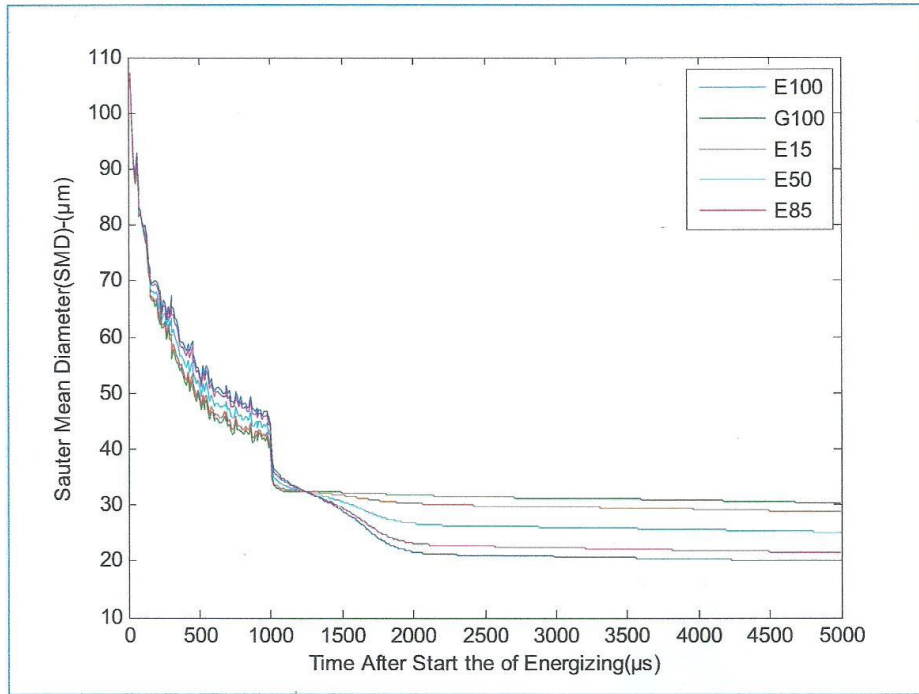


Figure 4.8: Comparison of the Sauter Mean Diameter (SMD) for different blends of fuel at cone injection angle of 30 degrees

There are four regimes in this plot. Describing the plot from the y-axis, the particle diameter experiences exponential decay until a point of stability is reached at

40 μ m then there is no further drop taking place. The optimal particle diameter for G100 is 30 μ m, which is the reference point of the pure gasoline. 30 μ m is optimal because beyond this point no further atomization takes place in gasoline despite the extra length of time of atomization from 1000 μ s to 5000 μ s.

At 1000 μ s energizing time, pure gasoline is the most stable in that it has the highest and stable SME of about 30 μ m while the blends are more turbulent and therefore atomize continuously more. E85 at 200 μ s present as best atomizing blend. Also between 200 μ s and 1000 μ s the best atomizing blends are in the order of E85, E15, E50, G100 and E100. At 1250 μ s is a point of convergence where all the blends atomize at the same rate. Beyond 1250 μ s time after start of energizing E100, E15, E50, E85 and G100 show in that sequence. The plot also showed that major atomization of the blends conclude at 1250 μ s. The closest SMD to that of pure ethanol is E15 after which is E50 then E85 at 1250 μ s to 5000 μ s. The implication and interpretation in the exhibited patterns of Gashol is that E15 would be the best blend or the best product mix in terms of atomization. Figure 4.9 represents comparison of the Sauter Mean Diameter (SMD) for different blends of fuel at cone injection angle of 40 degrees.

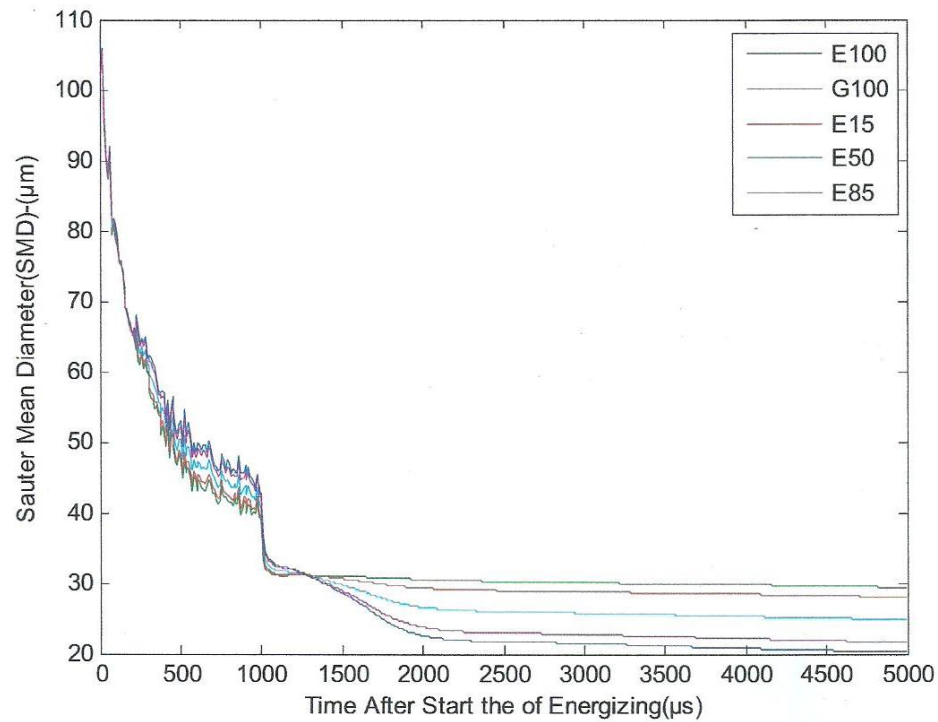


Figure 4.9: Comparison of the Sauter Mean Diameter (SMD) for different blends of fuel at cone injection angle of 40 degrees.

The main difference between Figures 4.8 and 4.9 is the display of the effect of change in injection cone angle. Figure 4.9 shows that SMDs have finer particle diameters and atomization continues more steadily and intensely than at injection cone angle of 30 degrees.

Figure 4.9 is extracted and presented as thus:

Fuel blend		Injection cone angle		
		30°	40°	20°
E10	SMD	32	34	31
E15		30	32	27
E50		25	27	23
E85		22	24	21
G100		21	22	20

A 10° change in cone angle from 20° to 30° caused a $1\mu\text{m}$ SMD change in E100, $2\mu\text{m}$ change in E15, $2\mu\text{m}$ change in E50, $1\mu\text{m}$ in E85 and $1\mu\text{m}$ change in G100. Using the SMD at 20° cone angle as a basis, the changes so reported represent 3.2% in E100, 11.11% in E15, 8.7% in E50, 4.76% in E85 and 5.0% in G100.

However, a further 10° change in cone angle from 20° to 40° is expected to cause a 9.67% SMD change in E100, 18.5% in E15, 17.39% in E50, 14.29% in E85 and 10% change in the SMD of G100. This changes in SMD as a result of varying cone angles is remarkable.

The prediction of the overall SMD is important in that it tells the overall average diameters which were obtained as point values by taking the average of all the SMDs at each domain of atomization of the droplets of the mixture after atomization hence, figure 4.10 describes the overall SMDs.

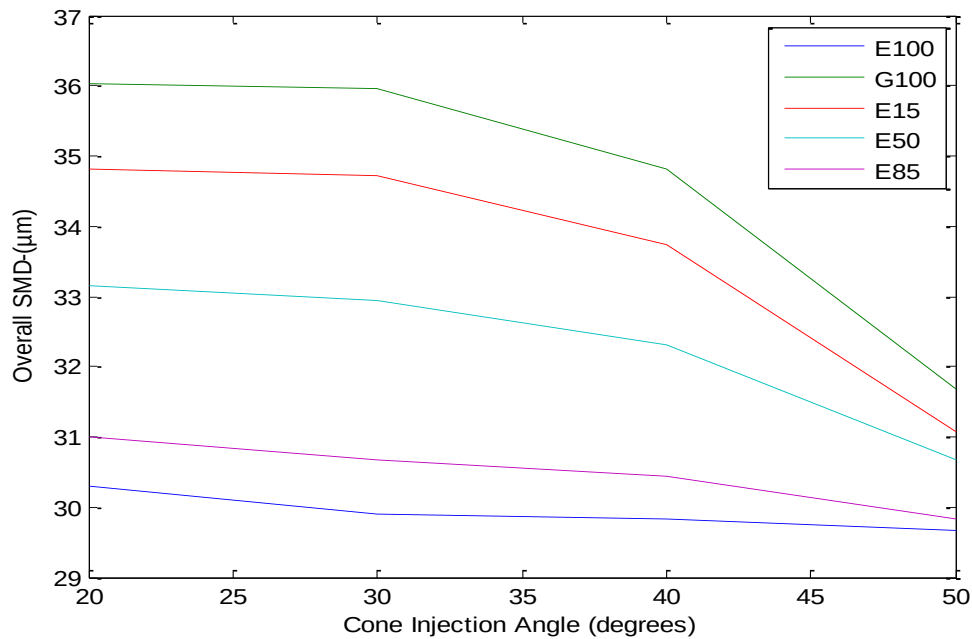


Figure 4.10: Overall Sauter Diameter (SMD) for Gashol at different cone injection angles.

Figure 4.10 represents the behaviour of cone injection angle in relation to overall SMDs of E100, G100, E15, E50 and E85. In order to determine overall SMDs, one droplet per micro second for every injection cone angle was adopted. Overall SMD was obtained by taking the average of all the droplets in the cylinder at each injection and so for each injection obtains one point value. This culminates to the total droplet sizes known as overall SMD. Where the overall SMD is decreasing with increase in cone injection angle, the interpretation is better occurrence of atomization.

The properties of mixture of Gasholarekey to determining the spray tip penetration. The pressure, density and viscosity were obtained from secondary sources for the analyses of spray tip determination.

4.3.6 Spray tip penetration

The spray tip penetration can be said to be the maximum distance considered within the spray axis to which the spray can advance from the nozzle tip [Hiroyasu and Arai, 1990] and [Kumar and Kumar, 2013]. It is one of the macroscopic characteristics that have been studied especially in diesel fuel application.

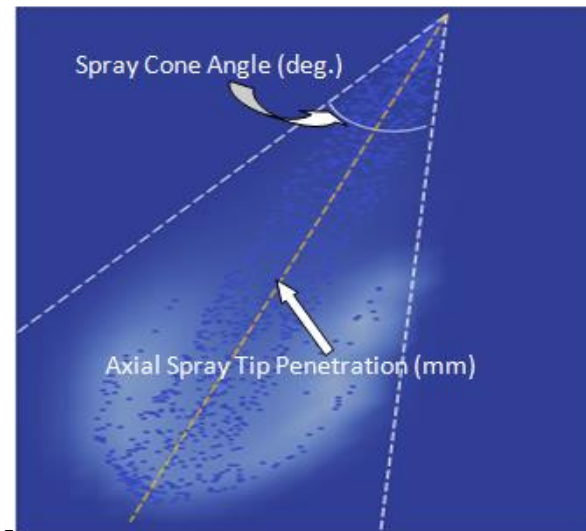


Figure 4.11: Definition of spray characteristics (cone injection angle and spray tip penetration).

The following correlations were proposed by Hiroyasu and Aria (1990) for determination of the spray penetration before and after breakup.

$$t_b = \frac{28.65 \rho_L d_{inj}}{[\rho_a (P_{inj} - P_a)]^{0.5}} \quad (4-3)$$

$$S_1 = \left[\frac{2(P_{inj} - P_a)}{\rho_L} \right]^{0.5} \times t, \quad 0 < t < t_b \quad (4-4)$$

$$S_2 = 2.95 \left[\frac{(P_{inj} - P_a)}{\rho_a} \right]^{0.25} (d_{inj} t)^{0.5}, \quad t \geq t_b \quad (4-5)$$

Siebers and Naber (1996) studied the effects in relationship to ambient gas density and fuel vaporization of diesel sprays for different gas densities. Their results demonstrated that ambient gas density significantly has effect on spray penetration length. The following correlations describe these relationships.

$$S_1 = C_v \left[\frac{2(P_{inj} - P_a)}{\rho_L} \right]^{0.5} \times t, \quad 0 < t < t_b \quad (4-6)$$

$$S_2 = \left(\frac{C_v C_a^{0.5}}{0.66 \tan\left(\frac{\theta}{2}\right)} \right)^{0.5} \left[\frac{(P_{inj} - P_a)}{\rho_a} \right]^{0.25} (d_{inj} t)^{0.5}, \quad t \geq t_b \quad (4-7)$$

Where, ρ_L = Fuel density,

ρ_a = Ambient gas density,

P_a = Ambient gas pressure,

P_{inj} = Fuel injection pressure,

t = Time after start of injection,

t_b = Breakup time,

d_{inj} = Injector nozzle diameter

θ = Spray cone angle, and

S_1 and S_2 = spray tip penetration lengths before and
after breakup, respectively.

The discussion of results of spray tip penetration analyses are depicted in figures 4.12, 4.13 and 4.14.

Figure 4.12 shows that spray tip penetration characteristics of the injected fuel is not affected by the difference in the fuel properties of E100, E15, E50, E85 and G100 fuels.

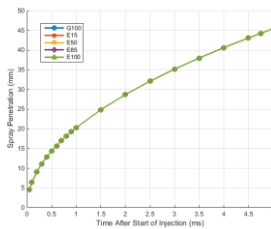


Figure 4.12: Effect of gashol properties on spray tip penetration at different times after start of injection.

Figure 4.13 shows the effects spray cone angle has on the spray penetration length. These results indicate that larger penetration lengths are obtained with higher injection angles. The influence of the cone angle is highly significant compared to that of the injection pressure.

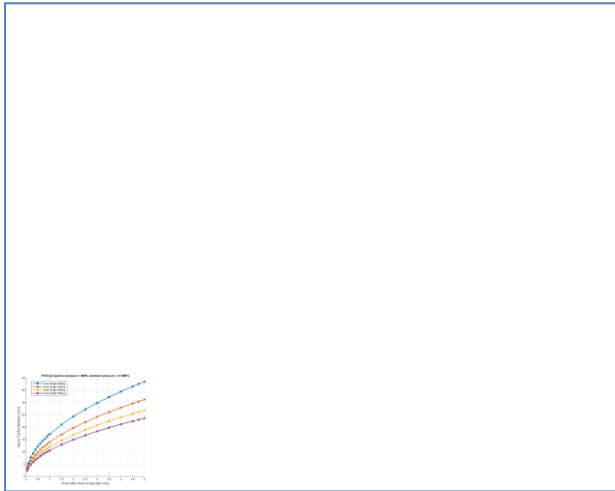
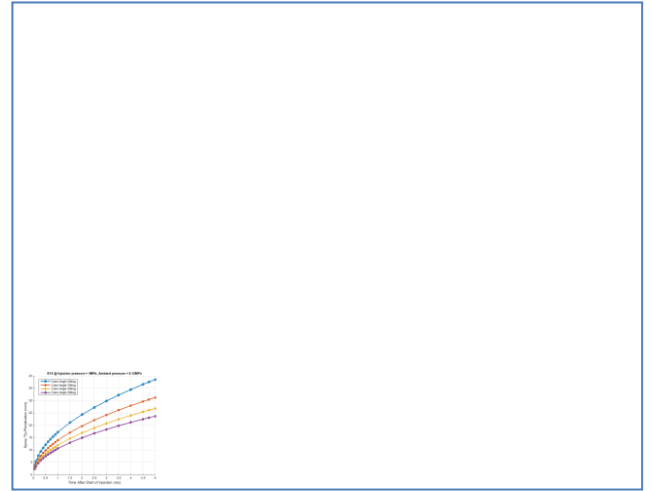
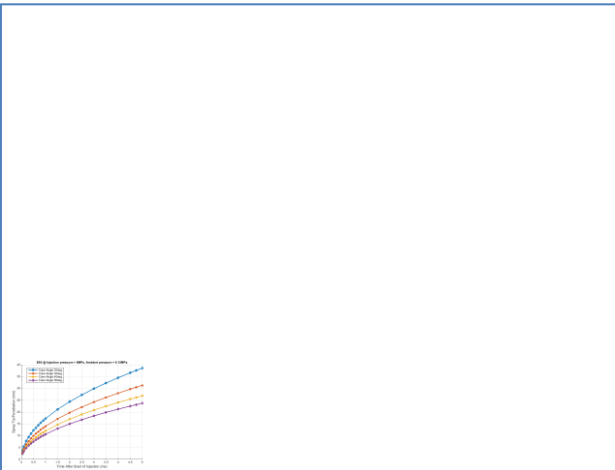
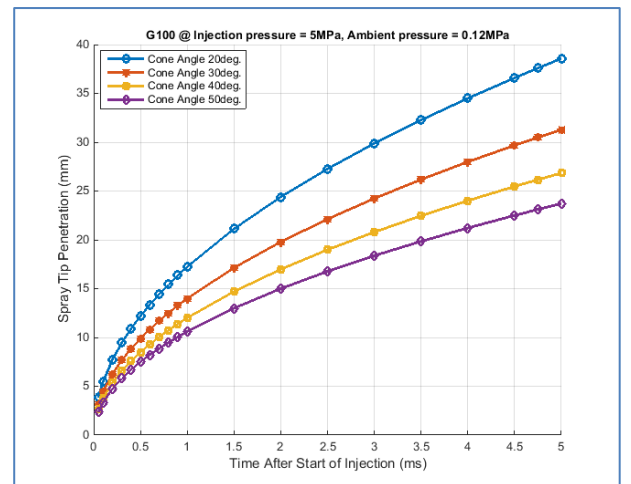
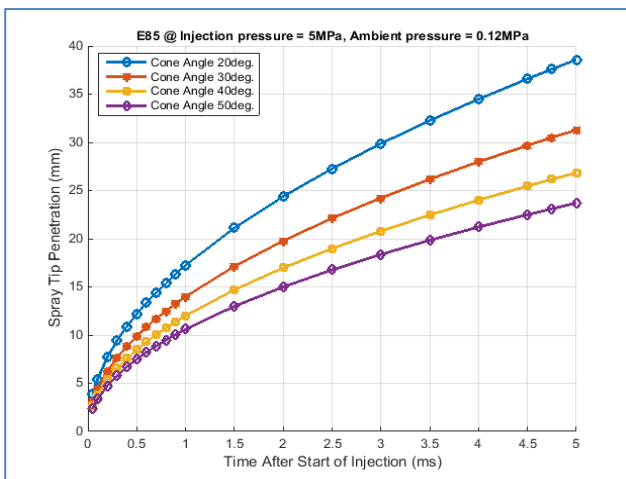


Figure 4.13 Effect Cone Injection Angle on Spray Tip Penetration at different times after start of injection.

Figure 4.14 describes the effects of fuel injection pressure on the spray penetration. The increase of the injection pressure induced an increase of the relative velocity between the injected spray and ambient gas. Thus, higher penetration lengths are obtained at higher injection pressures.

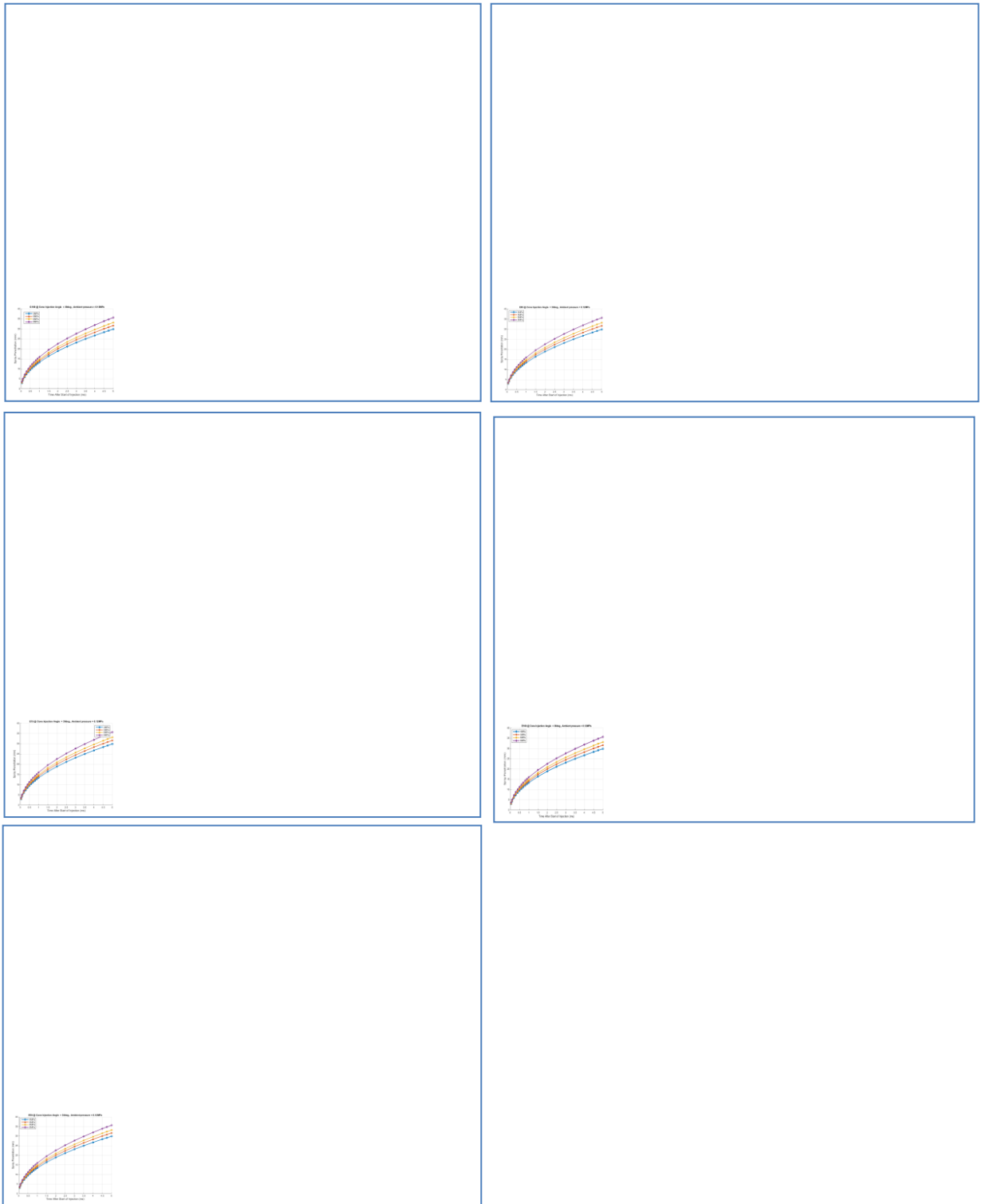


Figure 4.14: Effect Injection Pressure on Spray Tip Penetration at different times after start of injection.

4.3.7 Validation of Results

The technical journal article by Su Han Park et al (2009b) titled “Atomization and spray characteristics of bioethanol and bioethanol blended gasoline fuel injected through a direct injection gasoline injector” was the one found to be closest to this work. Their work experimentally investigated spray characteristics as well as atomization of gasoline (G100), bioethanol (E100) and gasoline-bioethanol blend (E85) in a direct gasoline injector using KIVA 3V code at 7mpa. The results of this experimental study revolved around measurement of SMD, spray tip penetration and spray width which showed that the axial spray tip penetration of the fuels were similar, the spray width and spray cone angle of E100 were slightly larger than others while in terms of atomization E100 also had the largest droplet size.

Figures 4.15 to 4.20 display the validation of the results of the experimental work of Park et al [2009b] against the modeling results of this research work.

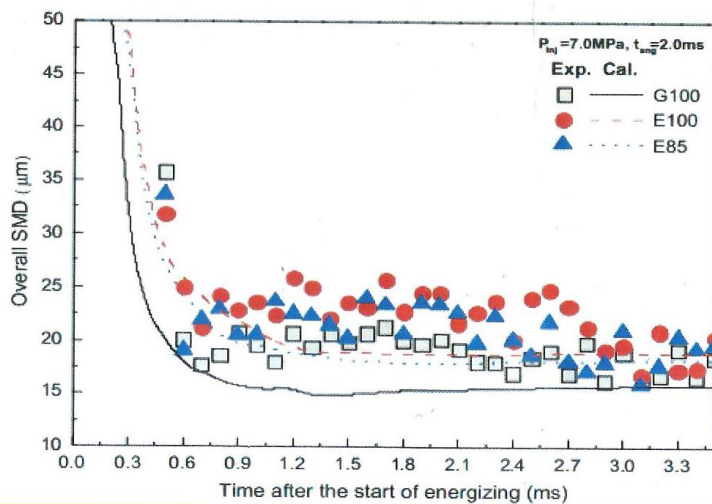


Fig 4.15 Comparison of experimental and modeling of atomization of G100, E100 and E85 at 7MPa

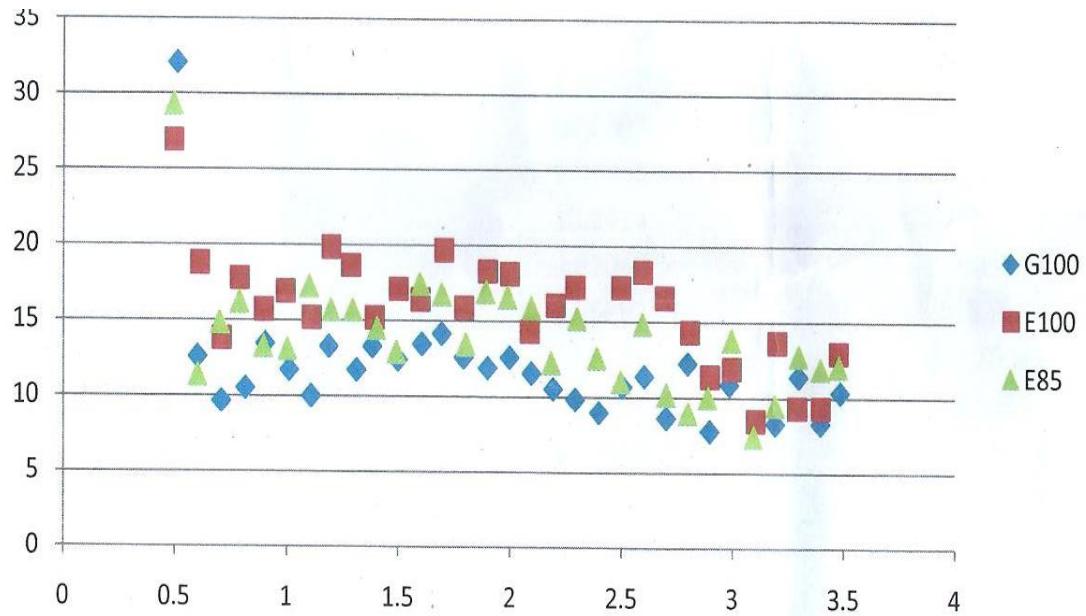


Fig 4.16 Modeling results of G100, E100 and E85 at 7MPa

Considering that the experimental results and the modeling results plotted in figures 4.15 and 4.16 respectively are very similar, it could be said that predictions of this work are valid.

SMDs against time plotted in figures 4.17 and 4.18 represent both the modeling results and experimental results of pure gasoline and ethanol respectively.

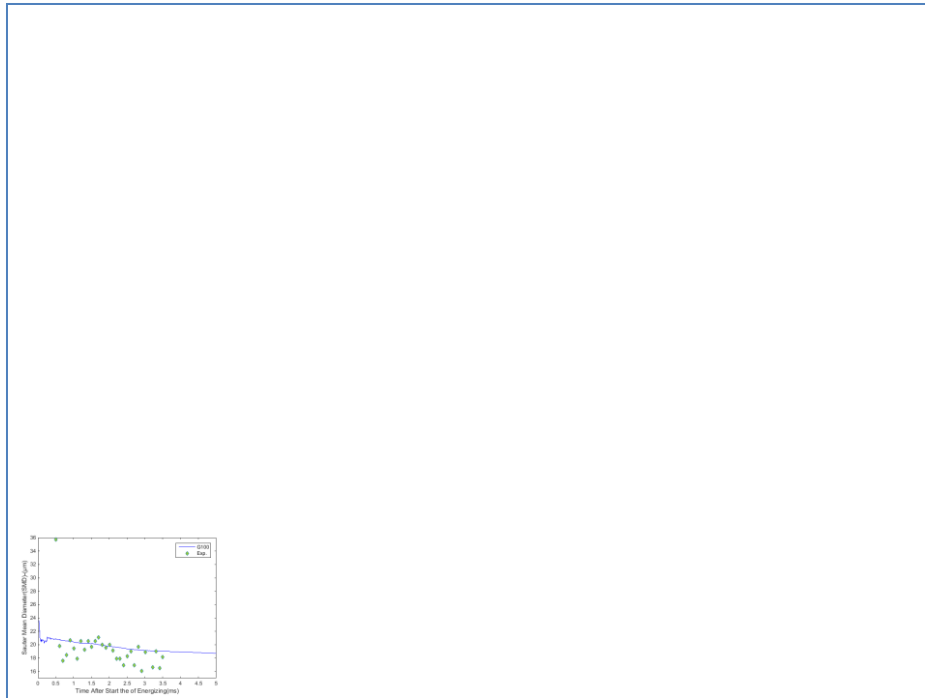


Fig. 4.17 Comparison of experimental and modeling results of SMDs of G100

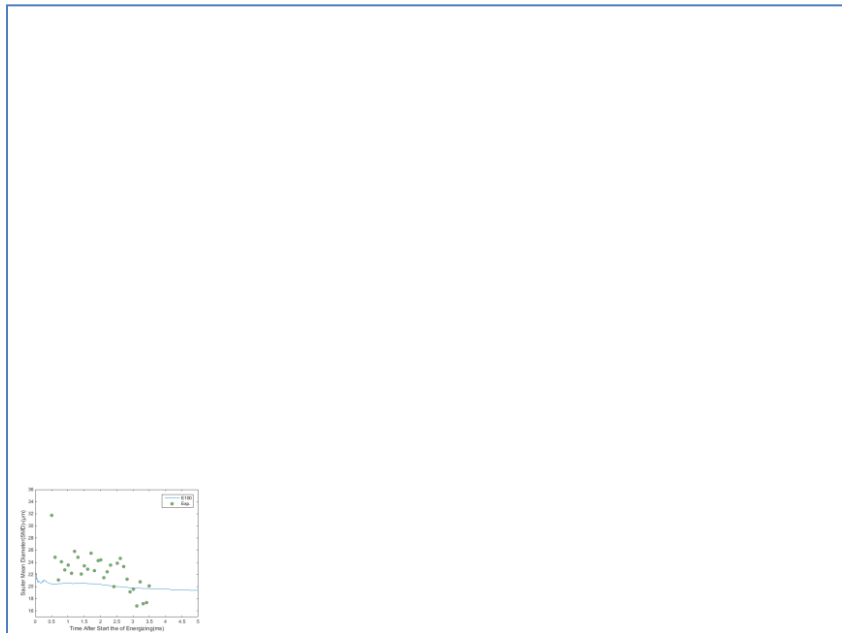


Fig. 4.18 Comparison of experimental and modeling results of SMDs of E100

Figure 4.19 represent experimental and analytical results of SMDs of E85 due to atomization. Figure 14.20 displays both experimental and modeling of G100, E100 and E85.

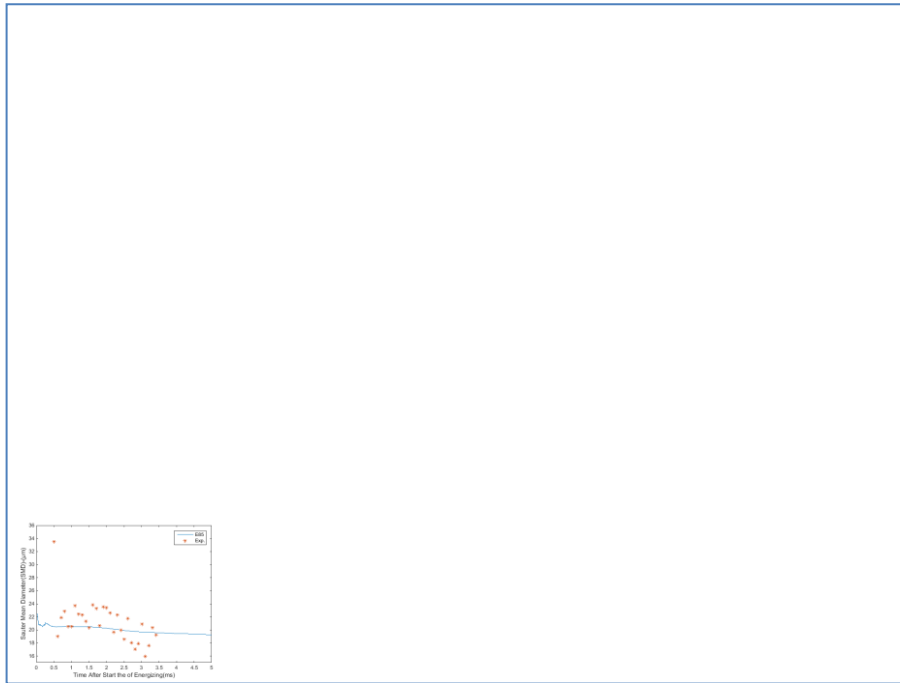


Fig. 4.19 :Comparison of experimental and modeling results of SMDs of E85

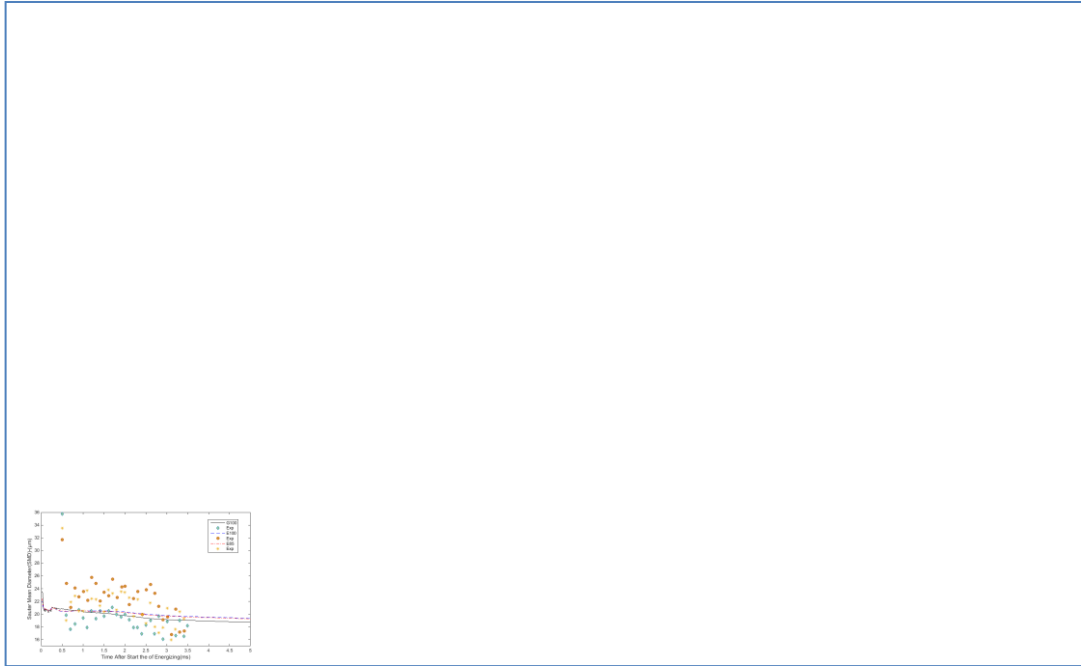


Fig. 4.19 Comparison of experimental and modeling results of SMDs of G100, E100 and E85

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Spray and atomization characteristics of Gasoline-Ethanol fuel blends have been studied in this work. Three fuel blends: E85, E50 and E10 were studied within the framework of six types of break-up and atomization models.

The computational time was determined using Blob Sheet model for primary atomization process. The spray evolution at four cone injection angles (20° , 30° , 40° and 50°) at time steps of $0.0001\mu\text{s}$, $0.0002\mu\text{s}$, $0.0003\mu\text{s}$ and $0.00075\mu\text{s}$ adopted resulting in the images of the spray development for the Gasoline (G100) fuel. This injection process represented time frame at injection with respect to injection angular variations. It was discovered that with longer injection time frame and wider injection angle, the penetration width was wider and the penetration length deeper (longer) resulting in better atomization.

This work entailed analysis of gasoline (G100) droplet size distribution at $5.0\text{e-}3(\mu\text{s})$ after energizing, Rosin Rammler distribution showed an exponential curve for the spray droplets at $5\mu\text{s}$ after energizing injected droplets profile with time differential at pressure of 5MPa.

The salient conclusions drawn from the modeling is that as the number of particles diameter increased, the density of clusters became smaller. Injected droplets profile in terms of engine performance showed a significant effectiveness up to 6000 parcels and the time frame of injection was directly proportional to the number of droplets injected.

The inference here is that the more the number of droplet injected the more atomization took place until 6000 parcels were injected beyond which only marginal atomization occurred.

It was discovered that the SMD was affected by varying the degree of injection cone angle. It was also observed that the SMDs obtained were at

variance in relation to the different blend ratios of gashol. The spray tip penetration lengths were larger for higher injection cone angles. Furthermore, higher penetration lengths were obtained at higher injection pressures.

5.2 Recommendations for Further Studies

The determination of rate of atomization using reaction kinetics will help give more insight into the fastness or slowness of atomization, so it is recommended herewith that further studies incorporate this process.

Atomization is a prerequisite to combustion process and this is determined by the degree of atomization. Therefore, it will not be out of place to take do further studies to predict the rate of combustion.

It is necessary to supply initial conditions in the atomization process according to McCartly and Malloy (1974). This work therefore provided initial conditions for its simulation. It is suggested hereby that different initial conditions could be provided for modeling of atomization to determine whether different initial conditions adopted could result in varied process solutions.

This research work modeled cone angles penetration of 20°c, 30°c, 40°c and 50°c and SMD using openfoam and the results are different for different cone angle penetrations. It will be a welcome development to model cone angles different from what has been adopted in this work so as to find out the most probable highest penetration length and SMD.

In the literature only G100, E100, E85 and E10 were seen to have been modeled to determine the atomization of GASHOL. This work extended the GASHOL mix to E85, E50 and E15. It is pertinent to recommend other proportions of GASHOL mix in order to determine whether some other blends based on the combining mixture mole fractions of this product can atomize better and faster.

5.3 Contributions to knowledge

This research work was able to determine spray characteristics of E85, E50 and E15 and has contributed to knowledge by considering the spray characteristics of these fuels at the dense region which were hitherto not available in literature.

Atomization is specific to fuels and type of atomizer, hence modeling of these specific blends of GASHOL has contributed to knowledge.

It was discovered that no models exist that capture a combination of atomization, transport and evaporation in spray modelling but this work considered all of these phenomena.

Gasoline-ethanol (gashol) fuel blends were modeled using temperature differentials as the droplets atomize through the spray. In the literature, the assumption posited is that during atomization the temperature remains uniform throughout the plume of the spray but in this work it was discovered that temperature changes actually occur as droplets atomize.

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Appendix A:

(simFlow/openFOAM)

Mesh File

```
FoamFile
{
    version 2.0;
    class dictionary;
    format ascii;
    location "constant/polyMesh";
    object blockMeshDict;
}
convertToMeters 1;
edges
(
);
vertices (
    ( 0 0 - 0.02 )
    ( 5.05 0 - 0.02 )
    ( 5.05 5.05 - 0.02 )
    ( 0 5.05 - 0.02 )
    ( 0 0 4.02 )
    ( 5.05 0 4.02 )
    ( 5.05 5.05 4.02 )
    ( 0 5.05 4.02 )
);
boundary
(
    boundaries
    {
        type wall;
        faces
        (
            (2 6 5 1)
            (3 7 6 2)
            (0 3 2 1)
            (4 5 6 7)
        );
    }
    symmetry
    {
        type symmetry;
        faces
        (
            (0 4 7 3)
            (1 5 4 0)
        );
    }
};
blocks
(
    hex (0 1 2 3 4 5 6 7) (45 45 40) simpleGrading (1 1 1)
);
```

Appendix B

MATLAB Script

```
clear
clc
format short

Legendnames = cell(4,1);
Legendnames{1} = ['Cone Injection Angle 20deg.' num2str(1)];
Legendnames{2} = ['Cone Injection Angle 30deg.' num2str(2)];
Legendnames{3} = ['Cone Injection Angle 40deg.' num2str(3)];
Legendnames{4} = ['Cone Injection Angle 50deg.' num2str(4)];
strval2 = cell(499,4);

for k = 1: 4
    Appendf = 'fileLocation';
    Appendb = '\lagrangian\sprayCloud\d';

    T = 5e-3;
    dt = 1e-5;
    N = T/dt;

    smdArray =zeros(N,1);
    timeArray =zeros(N,1);
    for n = 1:N
        tstep = n*dt;
        timeArray(n) = tstep*1000000;
        dstr = num2str(tstep);
        name = [Appendf,dstr,Appendb];
        fid =fopen(name, 'r'); % opens the RSM file
        i=0;
        while 1 % Starting reading the file for
            % all boxes with ignoring the empty lines.
            tline = fgetl(fid);
            if~ischar(tline), break,end
                a = str2num(tline);
            ifi> 19
                break;
            end
            i=i+1;
        end
        dp =zeros(a,1);
        j=0;
        while 1
            tline = fgetl(fid);
```

```

if ~ischar(tline), break, end
if i > 20 && i <= 20 + a
dp(i-20) = str2num(tline);
end
i = i + 1;
end
dp = dp';
smdArray(n) = 1000000 * histline(dp, a, tstep);
strval2{n,k} = smdArray(n);
fclose(fid);
end
    strval2
end
figure;
plot(timeArray, cell2mat(strval2)); hold all
xlabel('Time After Start the of Energizing( $\mu$ s)');
ylabel('Sauter Mean Diameter(SMD)-( $\mu$ m)');
legend(Legendnames);

function d32 = histline(A, N, time)
As = sort(A);
Amin = As(1);
Amax = As(end);
Arange = linspace(Amin, Amax, N + 1);
freq = zeros(N, 1);
for n = 1:N
    x = As(As < Arange(n + 1));
    y = x(x > Arange(n));
    freq(n) = numel(y);
end
Amid = 0.5 * (Arange(1:end-1) + Arange(2:end));

figure
plot(Amid, freq, 'b*');
xlabel('Droplet Diameter (m)');
ylabel('Number of Parcels');
cc = num2str(time);
title(strcat('G100 Droplet size distribution at ', ' ', cc, ' ( $\mu$ s) after energizing'));

cumfreq = cumsum(freq);
cumfreqpercent = cumfreq / cumfreq(end);

sum1 = 0; sum2 = 0;
for n = 1:N
    sum1 = sum1 + freq(n) * Amid(n).^3;
    sum2 = sum2 + freq(n) * Amid(n).^2;

```

```
end
d32 = sum1/sum2;

figure
plot(Amid,cumfreqpercent,'b'); hold on
xlabel('Droplet Diameter (m)');
ylabel('Cumulative Distribution Function');
title('Rosin Rammler Cumulative Particle Size Distribution');
end
```

Time(μ s) SMD(μ m)-(Cone Injection Angle: 20, 30, 40, 50)
1.0e+003 *

0.01	103.9770	103.8165	101.8326	101.9338
0.02	106.6359	107.2334	105.8554	104.9587
0.03	99.5149	97.6590	96.2817	93.4390
0.04	91.2106	90.9102	90.3137	88.7285
0.05	85.5415	89.4693	88.5140	86.5784
0.06	85.5350	92.8427	92.0765	86.9861
0.07	83.1244	86.2435	83.1750	80.0577
0.08	79.3907	83.2851	81.4330	78.3467
0.09	81.2064	82.7001	81.7667	80.4340
0.1	77.8402	80.9635	80.7916	78.9574
0.11	74.7483	79.7833	79.0804	78.9373
0.12	73.5930	80.1342	75.7056	75.0179
0.13	73.3454	78.2474	75.6502	74.1617
0.14	68.8937	73.1759	73.4564	72.5519
0.15	69.2668	72.2689	71.8514	68.5575
0.16	67.4897	70.3105	69.1271	68.7151
0.17	66.2182	69.5034	68.9398	68.6114
0.18	67.9691	69.6806	67.4914	65.3296
0.19	65.7901	70.0713	66.8297	65.2043
0.2	66.6381	69.8607	65.1152	64.9521
0.21	65.1253	69.2454	66.0899	63.8543
0.22	62.7279	66.9985	64.9868	61.2803
0.23	64.8341	68.2548	67.8967	62.6977
0.24	62.5489	64.4592	66.4276	61.1906
0.25	61.7918	66.4595	64.1318	60.6797
0.26	63.0466	65.8653	64.6611	63.1894
0.27	60.9384	63.8222	64.1285	59.6507
0.28	62.9455	65.4659	64.8260	62.1643
0.29	61.6343	64.0933	62.2356	61.2642
0.3	62.3741	67.5514	62.0604	60.3678
0.31	59.4990	65.4879	62.2291	59.0946
0.32	59.3213	65.1757	61.9734	60.0316
0.33	59.4703	63.4472	61.2686	58.2584
0.34	58.3182	63.1306	60.7167	57.6214
0.35	58.1134	61.6648	58.9024	57.7515
0.36	57.5639	59.3339	57.3095	56.5663
0.37	58.2360	58.5594	57.1029	55.9289
0.38	57.2634	58.9357	56.9850	54.1515
0.39	56.9996	58.9314	57.2637	55.5109
0.4	55.2959	58.0495	56.9440	53.5581
0.41	55.1143	57.5656	53.4876	52.0959
0.42	55.6560	58.6619	55.8535	54.1824
0.43	55.1479	57.3835	52.4445	50.6283
0.44	56.6341	58.5715	54.9160	53.5594

0.45	56.5288	59.3630	56.5414	54.6505
0.46	55.0536	56.8245	54.3535	52.9351
0.47	53.8066	56.0518	52.0492	50.5508
0.48	52.6576	54.6062	51.1149	49.2431
0.49	53.2721	54.5829	52.3947	51.3583
0.5	53.1258	53.3957	52.9042	51.1251
0.51	51.5766	51.6831	50.1385	48.1853
0.52	52.8397	54.7525	54.5821	51.1397
0.53	52.5527	53.0700	50.6859	48.9956
0.54	51.9819	53.0983	51.4361	49.7308
0.55	52.9718	54.8384	52.6406	51.1764
0.56	51.2169	54.1567	51.1951	49.0495
0.57	49.4732	51.7508	48.6553	46.4094
0.58	51.1049	52.5590	49.8929	48.1654
0.59	50.2802	51.1985	48.4465	46.9449
0.6	49.8497	50.1406	49.6076	47.3883
0.61	50.3472	50.2033	49.7572	47.9891
0.62	50.2387	50.9147	49.6110	47.4180
0.63	50.2567	51.0441	48.9388	48.0921
0.64	50.0752	50.7700	49.6870	47.3209
0.65	49.9073	50.5440	49.4805	47.3200
0.66	49.9163	49.9746	48.6016	46.6600
0.67	49.6453	49.8962	50.0641	46.2189
0.68	50.0135	50.0948	49.3484	47.3306
0.69	50.0077	51.2419	49.0034	46.8966
0.7	49.5462	49.9593	47.8732	46.3873
0.71	48.8202	50.3828	46.7638	45.2404
0.72	47.8935	48.4110	46.5283	44.9816
0.73	47.6581	48.5628	45.8520	44.4826
0.74	48.2941	48.2545	46.0679	44.2006
0.75	49.5776	49.6362	48.1771	46.9812
0.76	50.4522	50.1874	48.0957	46.2108
0.77	48.4719	49.2839	47.4842	44.7787
0.78	48.7734	48.2737	46.3065	44.6582
0.79	47.8485	49.2477	47.4324	45.3707
0.8	47.2462	47.9090	46.9273	43.7266
0.81	47.3927	48.0713	45.7564	44.1825
0.82	48.1772	48.2163	46.1314	44.8647
0.83	47.5883	47.2730	45.9748	44.2410
0.84	48.4629	47.3447	45.7855	44.4229
0.85	48.3935	47.5333	45.6942	42.8373
0.86	48.7361	49.4501	48.1114	46.2070
0.87	46.1248	47.1862	45.6054	41.3091
0.88	46.1023	46.9763	45.5321	42.5036
0.89	47.1365	46.7991	45.5706	43.8401
0.9	47.0793	47.2940	46.6183	43.7956

0.91	46.3285	46.2372	45.3991	43.8393
0.92	47.1524	46.8927	46.3620	44.2532
0.93	47.4572	46.9732	45.0932	43.5725
0.94	47.0005	45.9023	44.8812	42.4802
0.95	47.1511	46.6045	44.3870	41.9664
0.96	47.1246	46.5706	43.6575	42.4266
0.97	46.7924	46.6738	45.4459	44.2236
0.98	45.8108	45.0107	43.0723	41.0894
0.99	45.5396	45.8514	42.5819	40.8995
1	44.9129	44.2945	42.6924	40.6531
1.01	40.1780	38.3079	36.9409	34.6432
1.02	38.7364	36.4275	34.5275	32.4851
1.03	38.4136	36.0649	33.7552	31.7764
1.04	38.0746	35.7515	33.4197	31.4932
1.05	37.7657	35.4794	33.1646	31.2692
1.06	37.4715	35.2385	32.9559	31.0940
1.07	37.1959	35.0230	32.7882	30.9553
1.08	36.9363	34.8267	32.6476	30.8489
1.09	36.6986	34.6448	32.5292	30.7683
1.1	36.4783	34.4699	32.4337	30.7060
1.11	36.2710	34.2945	32.3569	30.6614
1.12	36.0768	34.1231	32.2940	30.6315
1.13	35.8984	33.9603	32.2458	30.6048
1.14	35.7290	33.7951	32.1974	30.5891
1.15	35.5686	33.6380	32.1574	30.5756
1.16	35.4129	33.4848	32.1193	30.5689
1.17	35.2651	33.3381	32.0795	30.5648
1.18	35.1199	33.1998	32.0404	30.5626
1.19	34.9848	33.0615	31.9951	30.5579
1.2	34.8481	32.9314	31.9314	30.5556
1.21	34.7151	32.8040	31.8480	30.5607
1.22	34.5839	32.6757	31.7538	30.5593
1.23	34.4511	32.5526	31.6526	30.5608
1.24	34.3196	32.4308	31.5472	30.5600
1.25	34.1862	32.3172	31.4365	30.5609
1.26	34.0543	32.2009	31.3256	30.5547
1.27	33.9247	32.0821	31.2147	30.5443
1.28	33.7953	31.9636	31.1056	30.5262
1.29	33.6635	31.8439	30.9965	30.5026
1.3	33.5323	31.7221	30.8912	30.4705
1.31	33.3988	31.5993	30.7817	30.4299
1.32	33.2625	31.4759	30.6700	30.3738
1.33	33.1218	31.3519	30.5587	30.2983
1.34	32.9779	31.2268	30.4465	30.2076
1.35	32.8283	31.1027	30.3339	30.1052
1.36	32.6725	30.9768	30.2198	29.9972

1.37	32.5118	30.8514	30.1076	29.8880
1.38	32.3467	30.7250	29.9908	29.7781
1.39	32.1781	30.5950	29.8730	29.6673
1.4	32.0044	30.4642	29.7556	29.5567
1.41	31.8239	30.3293	29.6375	29.4476
1.42	31.6392	30.1919	29.5191	29.3394
1.43	31.4536	30.0524	29.3983	29.2291
1.44	31.2638	29.9097	29.2760	29.1171
1.45	31.0709	29.7640	29.1524	29.0045
1.46	30.8747	29.6150	29.0283	28.8918
1.47	30.6733	29.4618	28.9058	28.7792
1.48	30.4668	29.3050	28.7823	28.6658
1.49	30.2562	29.1453	28.6568	28.5527
1.5	30.0358	28.9842	28.5332	28.4386
1.51	29.8096	28.8204	28.4097	28.3231
1.52	29.5737	28.6528	28.2863	28.2073
1.53	29.3276	28.4808	28.1583	28.0925
1.54	29.0738	28.3059	28.0275	27.9794
1.55	28.8133	28.1275	27.8954	27.8665
1.56	28.5440	27.9451	27.7613	27.7525
1.57	28.2677	27.7602	27.6236	27.6414
1.58	27.9851	27.5712	27.4844	27.5313
1.59	27.6933	27.3792	27.3402	27.4196
1.6	27.3908	27.1839	27.1957	27.3070
1.61	27.0830	26.9853	27.0456	27.1934
1.62	26.7685	26.7853	26.8926	27.0773
1.63	26.4455	26.5823	26.7356	26.9603
1.64	26.1165	26.3771	26.5793	26.8436
1.65	25.7907	26.1703	26.4217	26.7291
1.66	25.4674	25.9611	26.2649	26.6117
1.67	25.1454	25.7479	26.1079	26.4890
1.68	24.8308	25.5346	25.9512	26.3650
1.69	24.5295	25.3222	25.7938	26.2431
1.7	24.2428	25.1110	25.6379	26.1208
1.71	23.9722	24.9053	25.4837	25.9946
1.72	23.7134	24.7038	25.3304	25.8660
1.73	23.4689	24.5067	25.1791	25.7405
1.74	23.2357	24.3175	25.0290	25.6132
1.75	23.0178	24.1380	24.8835	25.4852
1.76	22.8135	23.9667	24.7415	25.3605
1.77	22.6196	23.8010	24.6040	25.2374
1.78	22.4361	23.6448	24.4682	25.1172
1.79	22.2654	23.4949	24.3325	25.0001
1.8	22.1034	23.3531	24.2015	24.8862
1.81	21.9511	23.2159	24.0822	24.7760
1.82	21.8085	23.0848	23.9704	24.6669

1.83	21.6751	22.9599	23.8626	24.5620
1.84	21.5501	22.8394	23.7596	24.4615
1.85	21.4344	22.7237	23.6621	24.3651
1.86	21.3287	22.6141	23.5700	24.2718
1.87	21.2318	22.5096	23.4807	24.1811
1.88	21.1439	22.4106	23.3961	24.0943
1.89	21.0639	22.3157	23.3104	24.0104
1.9	20.9916	22.2261	23.2284	23.9302
1.91	20.9265	22.1418	23.1513	23.8551
1.92	20.8668	22.0621	23.0767	23.7818
1.93	20.8099	21.9891	23.0028	23.7130
1.94	20.7562	21.9208	22.9296	23.6475
1.95	20.7063	21.8583	22.8584	23.5826
1.96	20.6613	21.8012	22.7904	23.5209
1.97	20.6198	21.7494	22.7264	23.4637
1.98	20.5816	21.7005	22.6670	23.4089
1.99	20.5471	21.6546	22.6106	23.3553
2	20.5172	21.6124	22.5591	23.3033
2.01	20.4898	21.5743	22.5093	23.2540
2.02	20.4647	21.5393	22.4608	23.2082
2.03	20.4426	21.5078	22.4150	23.1632
2.04	20.4233	21.4777	22.3727	23.1195
2.05	20.4069	21.4493	22.3341	23.0781
2.06	20.3924	21.4221	22.2975	23.0374
2.07	20.3793	21.3962	22.2634	22.9981
2.08	20.3679	21.3721	22.2316	22.9612
2.09	20.3582	21.3498	22.2011	22.9267
2.1	20.3489	21.3289	22.1718	22.8938
2.11	20.3404	21.3096	22.1445	22.8628
2.12	20.3327	21.2917	22.1188	22.8317
2.13	20.3259	21.2754	22.0938	22.8019
2.14	20.3198	21.2600	22.0709	22.7725
2.15	20.3137	21.2456	22.0498	22.7432
2.16	20.3078	21.2323	22.0298	22.7150
2.17	20.3022	21.2199	22.0106	22.6883
2.18	20.2973	21.2081	21.9923	22.6630
2.19	20.2925	21.1967	21.9748	22.6391
2.2	20.2878	21.1860	21.9581	22.6171
2.21	20.2833	21.1764	21.9422	22.5962
2.22	20.2792	21.1675	21.9275	22.5761
2.23	20.2750	21.1592	21.9140	22.5570
2.24	20.2707	21.1516	21.9013	22.5388
2.25	20.2664	21.1442	21.8894	22.5219
2.26	20.2623	21.1373	21.8777	22.5057
2.27	20.2586	21.1308	21.8664	22.4903
2.28	20.2547	21.1246	21.8557	22.4759

2.29	20.2505	21.1188	21.8457	22.4619
2.3	20.2467	21.1134	21.8363	22.4488
2.31	20.2430	21.1080	21.8274	22.4373
2.32	20.2390	21.1028	21.8187	22.4265
2.33	20.2353	21.0982	21.8101	22.4162
2.34	20.2316	21.0938	21.8020	22.4063
2.35	20.2281	21.0897	21.7943	22.3965
2.36	20.2245	21.0858	21.7872	22.3866
2.37	20.2210	21.0819	21.7803	22.3768
2.38	20.2175	21.0783	21.7737	22.3679
2.39	20.2140	21.0748	21.7674	22.3593
2.4	20.2104	21.0713	21.7614	22.3510
2.41	20.2068	21.0679	21.7555	22.3430
2.42	20.2031	21.0646	21.7499	22.3353
2.43	20.1994	21.0614	21.7446	22.3279
2.44	20.1958	21.0582	21.7396	22.3210
2.45	20.1922	21.0550	21.7347	22.3144
2.46	20.1885	21.0520	21.7301	22.3083
2.47	20.1847	21.0488	21.7256	22.3024
2.48	20.1810	21.0456	21.7214	22.2967
2.49	20.1774	21.0425	21.7173	22.2912
2.5	20.1737	21.0395	21.7133	22.2860
2.51	20.1700	21.0362	21.7093	22.2809
2.52	20.1663	21.0329	21.7054	22.2760
2.53	20.1627	21.0295	21.7016	22.2710
2.54	20.1589	21.0259	21.6980	22.2665
2.55	20.1553	21.0221	21.6944	22.2621
2.56	20.1517	21.0183	21.6907	22.2579
2.57	20.1481	21.0144	21.6872	22.2540
2.58	20.1446	21.0105	21.6837	22.2500
2.59	20.1410	21.0065	21.6802	22.2461
2.6	20.1374	21.0025	21.6766	22.2424
2.61	20.1338	20.9983	21.6730	22.2387
2.62	20.1302	20.9940	21.6694	22.2351
2.63	20.1267	20.9897	21.6657	22.2315
2.64	20.1232	20.9854	21.6620	22.2280
2.65	20.1197	20.9812	21.6582	22.2245
2.66	20.1162	20.9769	21.6544	22.2211
2.67	20.1128	20.9727	21.6505	22.2176
2.68	20.1093	20.9685	21.6465	22.2141
2.69	20.1059	20.9641	21.6425	22.2106
2.7	20.1025	20.9597	21.6383	22.2073
2.71	20.0992	20.9552	21.6340	22.2042
2.72	20.0959	20.9506	21.6296	22.2010
2.73	20.0925	20.9460	21.6251	22.1978
2.74	20.0891	20.9414	21.6206	22.1946

2.75	20.0858	20.9368	21.6162	22.1914
2.76	20.0825	20.9321	21.6117	22.1884
2.77	20.0792	20.9273	21.6070	22.1853
2.78	20.0758	20.9225	21.6024	22.1819
2.79	20.0724	20.9177	21.5978	22.1785
2.8	20.0691	20.9128	21.5931	22.1750
2.81	20.0659	20.9079	21.5882	22.1714
2.82	20.0626	20.9030	21.5834	22.1679
2.83	20.0593	20.8981	21.5785	22.1641
2.84	20.0561	20.8933	21.5735	22.1602
2.85	20.0529	20.8883	21.5684	22.1565
2.86	20.0497	20.8833	21.5632	22.1527
2.87	20.0465	20.8783	21.5578	22.1489
2.88	20.0434	20.8733	21.5523	22.1449
2.89	20.0402	20.8683	21.5468	22.1409
2.9	20.0371	20.8633	21.5412	22.1369
2.91	20.0339	20.8583	21.5356	22.1328
2.92	20.0307	20.8531	21.5300	22.1286
2.93	20.0276	20.8480	21.5241	22.1243
2.94	20.0245	20.8428	21.5182	22.1200
2.95	20.0215	20.8376	21.5124	22.1156
2.96	20.0184	20.8325	21.5064	22.1111
2.97	20.0153	20.8273	21.5004	22.1066
2.98	20.0123	20.8221	21.4944	22.1020
2.99	20.0093	20.8169	21.4884	22.0974
3	20.0063	20.8116	21.4824	22.0928
3.01	20.0034	20.8065	21.4763	22.0883
3.02	20.0005	20.8013	21.4702	22.0837
3.03	19.9977	20.7962	21.4641	22.0790
3.04	19.9948	20.7910	21.4580	22.0742
3.05	19.9920	20.7859	21.4520	22.0694
3.06	19.9891	20.7807	21.4458	22.0646
3.07	19.9862	20.7755	21.4396	22.0598
3.08	19.9833	20.7703	21.4333	22.0547
3.09	19.9804	20.7651	21.4270	22.0497
3.1	19.9775	20.7600	21.4207	22.0446
3.11	19.9747	20.7548	21.4144	22.0394
3.12	19.9719	20.7497	21.4080	22.0343
3.13	19.9690	20.7446	21.4017	22.0290
3.14	19.9662	20.7394	21.3953	22.0238
3.15	19.9634	20.7344	21.3889	22.0184
3.16	19.9605	20.7293	21.3825	22.0130
3.17	19.9576	20.7243	21.3760	22.0075
3.18	19.9548	20.7192	21.3695	22.0021
3.19	19.9519	20.7142	21.3630	21.9966
3.2	19.9490	20.7090	21.3564	21.9912

3.21	19.9462	20.7039	21.3499	21.9858
3.22	19.9434	20.6986	21.3433	21.9802
3.23	19.9406	20.6935	21.3369	21.9746
3.24	19.9378	20.6884	21.3304	21.9690
3.25	19.9351	20.6832	21.3239	21.9633
3.26	19.9324	20.6780	21.3174	21.9576
3.27	19.9297	20.6728	21.3109	21.9517
3.28	19.9271	20.6676	21.3042	21.9460
3.29	19.9245	20.6624	21.2975	21.9402
3.3	19.9219	20.6571	21.2907	21.9344
3.31	19.9194	20.6520	21.2839	21.9286
3.32	19.9168	20.6468	21.2772	21.9229
3.33	19.9142	20.6417	21.2704	21.9172
3.34	19.9116	20.6366	21.2637	21.9115
3.35	19.9090	20.6315	21.2570	21.9057
3.36	19.9065	20.6265	21.2504	21.8998
3.37	19.9040	20.6214	21.2437	21.8938
3.38	19.9015	20.6163	21.2371	21.8878
3.39	19.8990	20.6113	21.2305	21.8818
3.4	19.8965	20.6062	21.2240	21.8757
3.41	19.8940	20.6012	21.2175	21.8696
3.42	19.8916	20.5962	21.2111	21.8635
3.43	19.8892	20.5912	21.2047	21.8573
3.44	19.8867	20.5862	21.1984	21.8512
3.45	19.8843	20.5812	21.1921	21.8451
3.46	19.8820	20.5762	21.1859	21.8391
3.47	19.8797	20.5713	21.1797	21.8331
3.48	19.8774	20.5663	21.1735	21.8270
3.49	19.8750	20.5614	21.1671	21.8211
3.5	19.8726	20.5565	21.1607	21.8151
3.51	19.8703	20.5516	21.1542	21.8090
3.52	19.8680	20.5468	21.1478	21.8030
3.53	19.8657	20.5419	21.1414	21.7971
3.54	19.8634	20.5371	21.1349	21.7911
3.55	19.8611	20.5323	21.1285	21.7851
3.56	19.8589	20.5275	21.1220	21.7791
3.57	19.8567	20.5226	21.1156	21.7730
3.58	19.8544	20.5177	21.1091	21.7669
3.59	19.8522	20.5128	21.1026	21.7607
3.6	19.8500	20.5080	21.0962	21.7546
3.61	19.8478	20.5032	21.0898	21.7485
3.62	19.8455	20.4984	21.0833	21.7423
3.63	19.8433	20.4937	21.0769	21.7362
3.64	19.8411	20.4889	21.0704	21.7301
3.65	19.8389	20.4842	21.0639	21.7240
3.66	19.8367	20.4795	21.0575	21.7178

3.67	19.8345	20.4748	21.0510	21.7116
3.68	19.8323	20.4701	21.0445	21.7054
3.69	19.8302	20.4654	21.0381	21.6990
3.7	19.8280	20.4607	21.0317	21.6927
3.71	19.8259	20.4561	21.0253	21.6863
3.72	19.8238	20.4514	21.0189	21.6799
3.73	19.8217	20.4468	21.0127	21.6736
3.74	19.8196	20.4422	21.0064	21.6674
3.75	19.8175	20.4376	21.0001	21.6611
3.76	19.8154	20.4330	20.9938	21.6549
3.77	19.8133	20.4285	20.9874	21.6487
3.78	19.8112	20.4239	20.9811	21.6425
3.79	19.8091	20.4194	20.9748	21.6364
3.8	19.8070	20.4148	20.9684	21.6303
3.81	19.8049	20.4103	20.9620	21.6242
3.82	19.8028	20.4058	20.9557	21.6181
3.83	19.8009	20.4013	20.9494	21.6120
3.84	19.7988	20.3968	20.9431	21.6060
3.85	19.7968	20.3923	20.9369	21.6000
3.86	19.7949	20.3879	20.9306	21.5940
3.87	19.7929	20.3834	20.9244	21.5880
3.88	19.7909	20.3790	20.9182	21.5820
3.89	19.7890	20.3746	20.9120	21.5760
3.9	19.7870	20.3702	20.9059	21.5700
3.91	19.7851	20.3657	20.8997	21.5640
3.92	19.7832	20.3614	20.8935	21.5580
3.93	19.7812	20.3569	20.8875	21.5520
3.94	19.7793	20.3526	20.8814	21.5461
3.95	19.7774	20.3482	20.8753	21.5401
3.96	19.7755	20.3439	20.8692	21.5340
3.97	19.7736	20.3395	20.8631	21.5280
3.98	19.7718	20.3352	20.8570	21.5219
3.99	19.7699	20.3309	20.8510	21.5160
4	19.7680	20.3266	20.8449	21.5101
4.01	19.7662	20.3224	20.8389	21.5041
4.02	19.7644	20.3181	20.8329	21.4982
4.03	19.7626	20.3138	20.8270	21.4923
4.04	19.7608	20.3096	20.8210	21.4864
4.05	19.7591	20.3053	20.8150	21.4805
4.06	19.7574	20.3010	20.8089	21.4746
4.07	19.7557	20.2968	20.8028	21.4686
4.08	19.7541	20.2925	20.7968	21.4626
4.09	19.7525	20.2883	20.7908	21.4566
4.1	19.7508	20.2841	20.7847	21.4507
4.11	19.7491	20.2799	20.7787	21.4448
4.12	19.7475	20.2757	20.7727	21.4389

4.13	19.7458	20.2715	20.7666	21.4330
4.14	19.7441	20.2673	20.7606	21.4272
4.15	19.7425	20.2631	20.7545	21.4213
4.16	19.7409	20.2589	20.7485	21.4154
4.17	19.7393	20.2548	20.7425	21.4094
4.18	19.7377	20.2506	20.7366	21.4034
4.19	19.7361	20.2465	20.7307	21.3974
4.2	19.7346	20.2424	20.7248	21.3914
4.21	19.7331	20.2383	20.7189	21.3854
4.22	19.7316	20.2341	20.7130	21.3794
4.23	19.7301	20.2300	20.7070	21.3734
4.24	19.7286	20.2259	20.7011	21.3674
4.25	19.7271	20.2218	20.6953	21.3615
4.26	19.7256	20.2177	20.6894	21.3555
4.27	19.7242	20.2136	20.6836	21.3496
4.28	19.7227	20.2096	20.6777	21.3438
4.29	19.7213	20.2056	20.6719	21.3379
4.3	19.7199	20.2015	20.6661	21.3321
4.31	19.7185	20.1976	20.6603	21.3262
4.32	19.7172	20.1936	20.6545	21.3203
4.33	19.7158	20.1896	20.6487	21.3144
4.34	19.7145	20.1857	20.6429	21.3086
4.35	19.7132	20.1817	20.6372	21.3027
4.36	19.7118	20.1778	20.6314	21.2969
4.37	19.7105	20.1739	20.6257	21.2911
4.38	19.7092	20.1700	20.6199	21.2853
4.39	19.7079	20.1662	20.6142	21.2796
4.4	19.7065	20.1624	20.6084	21.2737
4.41	19.7052	20.1585	20.6026	21.2680
4.42	19.7039	20.1548	20.5969	21.2622
4.43	19.7027	20.1510	20.5912	21.2565
4.44	19.7014	20.1472	20.5854	21.2508
4.45	19.7002	20.1435	20.5796	21.2450
4.46	19.6990	20.1397	20.5738	21.2392
4.47	19.6978	20.1360	20.5681	21.2334
4.48	19.6967	20.1322	20.5623	21.2276
4.49	19.6956	20.1285	20.5566	21.2218
4.5	19.6945	20.1247	20.5508	21.2161
4.51	19.6934	20.1210	20.5451	21.2104
4.52	19.6923	20.1173	20.5394	21.2046
4.53	19.6913	20.1135	20.5337	21.1989
4.54	19.6902	20.1098	20.5280	21.1932
4.55	19.6891	20.1060	20.5223	21.1876
4.56	19.6881	20.1023	20.5167	21.1819
4.57	19.6870	20.0986	20.5110	21.1761
4.58	19.6860	20.0950	20.5054	21.1704

4.59	19.6850	20.0913	20.4998	21.1647
4.6	19.6840	20.0877	20.4942	21.1590
4.61	19.6830	20.0841	20.4886	21.1533
4.62	19.6821	20.0805	20.4829	21.1476
4.63	19.6811	20.0769	20.4773	21.1420
4.64	19.6801	20.0734	20.4718	21.1363
4.65	19.6791	20.0698	20.4661	21.1307
4.66	19.6781	20.0663	20.4605	21.1250
4.67	19.6771	20.0628	20.4549	21.1194
4.68	19.6762	20.0593	20.4493	21.1136
4.69	19.6752	20.0559	20.4438	21.1080
4.7	19.6743	20.0524	20.4382	21.1023
4.71	19.6733	20.0489	20.4326	21.0966
4.72	19.6724	20.0455	20.4271	21.0910
4.73	19.6716	20.0420	20.4216	21.0853
4.74	19.6707	20.0387	20.4160	21.0796
4.75	19.6698	20.0353	20.4105	21.0740
4.76	19.6690	20.0320	20.4049	21.0684
4.77	19.6681	20.0286	20.3994	21.0628
4.78	19.6673	20.0253	20.3939	21.0572
4.79	19.6664	20.0219	20.3883	21.0517
4.8	19.6655	20.0186	20.3828	21.0462
4.81	19.6646	20.0152	20.3773	21.0408
4.82	19.6638	20.0119	20.3717	21.0353
4.83	19.6630	20.0086	20.3661	21.0298
4.84	19.6621	20.0053	20.3606	21.0244
4.85	19.6613	20.0020	20.3551	21.0190
4.86	19.6605	19.9987	20.3496	21.0136
4.87	19.6597	19.9955	20.3441	21.0082
4.88	19.6589	19.9923	20.3387	21.0028
4.89	19.6582	19.9891	20.3332	20.9973
4.9	19.6574	19.9860	20.3278	20.9919
4.91	19.6566	19.9828	20.3223	20.9865
4.92	19.6559	19.9797	20.3168	20.9810
4.93	19.6552	19.9765	20.3113	20.9756
4.94	19.6545	19.9733	20.3058	20.9703
4.95	19.6538	19.9702	20.3003	20.9648
4.96	19.6531	19.9671	20.2948	20.9594
4.97	19.6524	19.9640	20.2893	20.9541
4.98	19.6518	19.9609	20.2838	20.9487
4.99	19.6512	19.9579	20.2784	20.9434

Appendix C:

Spray Penetration Data:

File Edit Format View Help				
Time After Start of Injection (ms)		Spray Tip Penetration (mm)		
	20 deg.	30 deg.	40 deg.	50 deg.
0.05	3.85679424	3.128669073	2.684435178	2.37164445
0.1	5.454330722	4.424606235	3.796364636	3.354011747
0.2	7.713588481	6.257338146	5.368870355	4.743288901
0.3	9.447177932	7.663642803	6.575496433	5.809318754
0.4	10.90866144	8.849212471	7.592729271	6.708023493
0.5	12.19625427	9.893720316	8.488929393	7.499798263
0.6	13.36032716	10.83802759	9.299156235	8.215617371
0.7	14.43080266	11.70640775	10.04423671	8.873880976
0.8	15.42717696	12.51467629	10.73774071	9.486577801
0.9	16.36299217	13.27381871	11.38909391	10.06203524
1	17.24810819	13.99183345	12.00515908	10.60631642
1.5	21.12453205	17.13642626	14.70325701	12.99003164
2	24.39250853	19.78744063	16.97785879	14.99959653
2.5	27.27165361	22.12303118	18.98182318	16.77005873
3	29.87459972	24.23456643	20.79354547	18.37067892
3.5	32.26825571	26.1763235	22.45959607	19.84260109
4	34.49621639	27.98366691	24.01031815	21.21263284
4.5	36.5887628	29.68116095	25.46678818	22.49939479
4.75	37.59138029	30.49449403	26.16463761	23.11593072
5	38.5679424	31.28669073	26.84435178	23.7164445
....				
....				

File Edit Format View Help						
Time After Start of Injection (ms)				Spray Tip Penetration (mm)		
	G100	E15	E50	E85	E100	
0.05	2.714884435		2.714884435		2.714884435	2.714884435
0.1	3.839426388		3.839426388		3.839426388	3.839426388
0.2	5.42976887		5.42976887		5.42976887	5.42976887
0.3	6.650081576		6.650081576		6.650081576	6.650081576
0.4	7.678852776		7.678852776		7.678852776	7.678852776
0.5	8.585218398		8.585218398		8.585218398	8.585218398
0.6	9.404635556		9.404635556		9.404635556	9.404635556
0.7	10.1581674		10.1581674		10.1581674	10.1581674
0.8	10.85953774		10.85953774		10.85953774	10.85953774
0.9	11.51827916		11.51827916		11.51827916	11.51827916
1	12.14133229		12.14133229		12.14133229	12.14133229
1.5	14.87003446		14.87003446		14.87003446	14.87003446
2	17.1704368		17.1704368		17.1704368	17.1704368
2.5	19.19713194		19.19713194		19.19713194	19.19713194
3	21.02940441		21.02940441		21.02940441	21.02940441
3.5	22.71435283		22.71435283		22.71435283	22.71435283
4	24.28266459		24.28266459		24.28266459	24.28266459
4.5	25.75565519		25.75565519		25.75565519	25.75565519
4.75	26.46142026		26.46142026		26.46142026	26.46142026
5	27.14884435		27.14884435		27.14884435	27.14884435
....						
....						

File Edit Format View Help					
Time After Start of Injection (ms)				Spray Tip Penetration (mm)	
	4MPa	5MPa	6MPa	8MPa	
0.05	2.987865416		3.164157227	3.315106092	3.566848426
0.1	4.225479793		4.474794064	4.688267996	5.044285419
0.2	5.975730831		6.328314454	6.630212183	7.133696853
0.3	7.318745688		7.750570672	8.120318368	8.736958634
0.4	8.450959586		8.949588128	9.376535991	10.08857084
0.5	9.448460055		10.00594371	10.48328593	11.2793651
0.6	10.35026941		10.96096216	11.48386437	12.35592539
0.7	11.1795687		11.83919226	12.4039912	13.34592476
0.8	11.95146166		12.65662891	13.26042437	14.26739371
0.9	12.67643938		13.42438219	14.06480399	15.13285626
1	13.36214035		14.1505413	14.82560515	15.95143109
1.5	16.36521287		17.33080289	18.15758387	19.53643342
2	18.89692011		20.01188742	20.96657187	22.55873019
2.5	21.12739897		22.37397032	23.44133998	25.2214271
3	23.14390599		24.50945649	25.67870137	27.62868911
3.5	24.99827558		26.4732387	27.73616751	29.84239499
4	26.72428071		28.3010826	29.65121029	31.90286219
4.5	28.34538017		30.01783114	31.4498578	33.83809529
4.75	29.12210973		30.84038977	32.31165731	34.76533807
5	29.87865416		31.64157227	33.15106092	35.66848426
....					
....					

APPENDIX D

FUEL PROPERTIES

```
// temperature independent properties  
liquid (239, 658.0, 1.82e+6, .716, 0.238, 263.57, 6.152e  
    -1, 560, 0, 0.5764, 1.59e+4),  
// temperature dependent properties coefficients  
rho_(974.1240, -0.678, 0, 0, 0, 0),  
pv_(17.82, -3540.0, -43.0, 3700.4),  
hl_(354.3664e+6, -0.3768e+6, 974.1240, -0.678),  
cp_(382.0119854650, 9.3069177541, -0.0209904809,  
    0.0000194215, 0, 0),  
...  
h_(-2755166.838320769, 2983.53861146661,  
    -4.01760030057885, 0.00606930534192801, 0, 0),  
...  
mu_(5.9276680593, 1127.3117029224, -3.1038204141, 0, 0),  
...  
sigma_(0.0190339361, -0.0000221014, 0, 0, 0, 0),  
D_(147.18, 20.1, 170.338, 28) // NN: Same as nHaptane
```

New Fuel Realization

The interested fuels, n-haptane, EN 590 and HVO, are not available in the fuel library of OpenFOAM. Hence, it is necessary to realize these fuels into the OpenFOAM fuel library. The properties of the fuels include the thermal physical properties and the chemical reaction properties. In this work, only non-evaporating and evaporating sprays are considered without the chemical reactions. Hence, the chemical reaction properties of the fuels are not interested. Details about the chemical reaction properties refer to Ref.

Temperature independent thermal physical properties

Sign	Name	Units
W	Molecular weight	[kg/kmol]
T _c	Critical temperatures	[K]
P _c	Critical pressure	[Pa]
V _c	Critical volume	[m ³ /mol]
Z _c	Critical compressibility factor	[]
T _t	Triple point temperature	[K]
P _t	Trip point pressure	[Pa]
T _b	Normal boiling temperature	[K]
Dipm	Dipole moment	[]
ω	Pitzer'sascentric factor	[]
δ	Solubility parameter	[J ^{1/2} /m ^{3/2}]

$$\text{Density } \rho = \frac{a}{b^{1+(1-T/T_c)^d}}$$

$$\text{Vapour pressure } P_v = e^{a+b/T+\ln(T)+dT_e}$$

$$\text{Heat of vapourization } h_t = a(1-Tr)^{b+cTr+dT_r^2+eT_r^3}, Tr = T/T_c$$

$$\text{Specific heat } c_p = a + bT + cT^2 + dT^3 + eT^4 + fT^5$$

$$\text{Enthalpy } h = a + bT + cT^2 + dT^3 + eT^4 + fT^5$$

$$\text{Ideal gas heat capacity } cp_g = a + b\left(\frac{c}{T \sinh(c/T)}\right)^2 + d\left(\frac{c}{T \cosh(e/T)}\right)^2$$

$$\text{Second viral coefficient } B = a + \frac{b}{T} + \frac{c}{T^3} + \frac{d}{T^8} + \frac{e}{T^9}$$

$$\text{Dynamic viscosity } \mu = e^{a+b/T+c \ln(T)+dT^e}$$

$$\text{Vapour dynamic viscosity } \mu_g = \frac{aT^b}{1 + \frac{c}{T} + \frac{d}{T^2}}$$

$$\text{Thermal conductivity } K = a + bT + cT^2 + dT^3 + eT^4 + fT^5$$

$$\text{Thermal conductivity } K_g = \frac{aT^b}{1 + \frac{c}{T} + \frac{d}{T^2}}$$

$$\text{Surface tension } \sigma = a(1-Tr)^{b+cTr+dT_r^2+eT_r^3}, Tr = T/T_c$$

$$\text{Vapour diffusivity } D = \frac{3.6059e - 3(1.8T)^1.75\sqrt{1/W_f + 1W_a}}{p(a^{1/3} + b^{1/3})^2}$$

Kerosene (pre-heat 75°C)

Gasoil (pre-heat 75°C)

25% RFO + 75% Gasoil (pre-heat 75°C)

50% RFO +50% Gasoil (pre-heat 75°C)

RFO (Pre heat 75°C)

Kerosene (FN=22.4E-8 m2; pre-heat 75°C)

Kerosene (FN=11.2E-8 m2; pre-heat 75°C)

RFO (FN=22, 4E-8 m2; pre-heat 75°C)

RFO (FN=11.2E-8 m2; pre-heat 75°C)

RFO (FN=22, 4E-8 m2; pre-heat 92°C)

Gasoil (FN=6.25E-8 m2)

Gasoil (FN=12.5E-8 m2)

Gasoil (FN=25E-8 m2)

Gasoil (FN=6.25E-8 m2; p=3E5 Pa)

Water

Gasoil (half spray angle 45°)

Comparison of fuel properties b

Characteristics	Bioethanol (E100)	Gasoline (G100)	Blend (E85)
Chemical formula	C ₂ H ₅ OH	C ₄ to C ₁₂ chains	a
Main constituents (% by weight)	C: 52 H : 35 O: 35	C : 85~88 H: 12~15 O : 0	C: 57 H: 13 O: 30
Fuel density (kg/m ³ @20°C)	789.67	718.33	778.33
Kinematic viscosity (mm ² /s@20°C)	1.57	0.84	1.42
Surface tension (N/m @20°C)	0.027	0.024	0.026
Octane	98~100	86~94	105
Lower heating value (MJ/kg)	26.8	41.9~44.2	29.1
Reid vapour pressure (kPa)	15.8	55.2~103.4	41.5 ~82.7
Ignition point-fuel in air (%)	3~19	1~8	a
Stoichiometric air/fuel ratio (by weight)	9	14.7	10
Blending ratio (%)	Bioethanol 100%	Gasoline 100%	Bioethanol 85% gasoline 15%

a Depends on percentage and type of the hydrocarbon fraction

b Handbook for handling, storing, and dispensing E85, U.S Department of Energy, Energy Efficiency and Renewable Energy, July 2006, DOE/GO-102006-2343.

APPENDIX E
VALIDATION OF RESULTS

20.4748	1.34
20.47834	1.35
20.48965	1.36
20.48055	1.37
20.502	1.38
20.48815	1.39
20.47469	1.4
20.47212	1.41
20.48988	1.42
20.47912	1.43
20.47002	1.44
20.46277	1.45
20.4753	1.46
20.47383	1.47
20.4685	1.48
20.4693	1.49
20.48431	1.5
20.47211	1.51
20.4772	1.52
20.47048	1.53
20.46889	1.54
20.47089	1.55
20.46861	1.56
20.45889	1.57
20.45537	1.58
20.45306	1.59
20.44795	1.6
20.44452	1.61
20.43116	1.62
20.43635	1.63
20.42853	1.64
20.41941	1.65
20.41648	1.66
20.4045	1.67
20.40507	1.68
20.40621	1.69
20.39702	1.7
20.39327	1.71
20.38821	1.72

20.38683	1.73
20.37898	1.74
20.37804	1.75
20.37488	1.76
20.36805	1.77
20.36595	1.78
20.35684	1.79
20.3501	1.8
20.34908	1.81
20.34814	1.82
20.33726	1.83
20.33344	1.84
20.3303	1.85
20.32978	1.86
20.31451	1.87
20.31686	1.88
20.31352	1.89
20.3076	1.9
20.29787	1.91
20.29904	1.92
20.30006	1.93
20.29319	1.94
20.28382	1.95
20.29933	1.96
20.30283	1.97
20.28938	1.98
20.29107	1.99
20.27449	2
20.26347	2.01
20.25824	2.02
20.25263	2.03
20.2372	2.04
20.23316	2.05
20.22219	2.06
20.21206	2.07
20.20434	2.08
20.19124	2.09
20.19419	2.1
20.19098	2.11
20.18246	2.12
20.17551	2.13
20.17347	2.14

20.16174	2.15
20.156	2.16
20.15462	2.17
20.14879	2.18
20.14203	2.19
20.13021	2.2
20.12447	2.21
20.1161	2.22
20.10529	2.23
20.09696	2.24
20.09571	2.25
20.09077	2.26
20.08948	2.27
20.07194	2.28
20.06845	2.29
20.05845	2.3
20.05537	2.31
20.05195	2.32
20.04642	2.33
20.03611	2.34
20.02422	2.35
20.02166	2.36
20.01781	2.37
20.01121	2.38
19.99818	2.39
19.993	2.4
19.98456	2.41
19.97704	2.42
19.97196	2.43
19.9641	2.44
19.96053	2.45
19.95433	2.46
19.95037	2.47
19.94368	2.48
19.93311	2.49
19.9231	2.5
19.91383	2.51
19.90587	2.52
19.89095	2.53
19.88856	2.54
19.88703	2.55
19.87757	2.56

19.87527	2.57
19.87312	2.58
19.86719	2.59
19.86343	2.6
19.85698	2.61
19.85569	2.62
19.85384	2.63
19.84727	2.64
19.83791	2.65
19.83591	2.66
19.82955	2.67
19.82784	2.68
19.81885	2.69
19.81506	2.7
19.80699	2.71
19.80251	2.72
19.79669	2.73
19.79683	2.74
19.79755	2.75
19.79314	2.76
19.78556	2.77
19.78408	2.78
19.77995	2.79
19.77266	2.8
19.7625	2.81
19.75705	2.82
19.75116	2.83
19.74472	2.84
19.74383	2.85
19.7383	2.86
19.7377	2.87
19.73554	2.88
19.72878	2.89
19.72306	2.9
19.71775	2.91
19.71617	2.92
19.70854	2.93
19.71385	2.94
19.70759	2.95
19.70322	2.96
19.69782	2.97
19.69544	2.98

19.69544	2.99
19.69141	3
19.68547	3.01
19.68366	3.02
19.6806	3.03
19.67963	3.04
19.67701	3.05
19.67267	3.06
19.67274	3.07
19.66414	3.08
19.66334	3.09
19.65856	3.1
19.65853	3.11
19.65582	3.12
19.64586	3.13
19.65101	3.14
19.64698	3.15
19.64716	3.16
19.64308	3.17
19.63546	3.18
19.63699	3.19
19.63026	3.2
19.63255	3.21
19.62624	3.22
19.62638	3.23
19.62279	3.24
19.62209	3.25
19.61681	3.26
19.61636	3.27
19.61191	3.28
19.61074	3.29
19.61329	3.3
19.60792	3.31
19.60498	3.32
19.60225	3.33
19.60098	3.34
19.59996	3.35
19.5961	3.36
19.59379	3.37
19.59242	3.38
19.58363	3.39
19.58262	3.4

19.58394	3.41
19.58419	3.42
19.57953	3.43
19.57613	3.44
19.57474	3.45
19.56821	3.46
19.56788	3.47
19.56762	3.48
19.56638	3.49
19.56103	3.5
19.55905	3.51
19.56032	3.52
19.55631	3.53
19.55409	3.54
19.55406	3.55
19.54955	3.56
19.5483	3.57
19.5457	3.58
19.54228	3.59
19.5424	3.6
19.53724	3.61
19.53761	3.62
19.53926	3.63
19.53518	3.64
19.53147	3.65
19.52926	3.66
19.52691	3.67
19.52503	3.68
19.52027	3.69
19.5191	3.7
19.51327	3.71
19.51026	3.72
19.50745	3.73
19.50729	3.74
19.5042	3.75
19.50102	3.76
19.50295	3.77
19.50222	3.78
19.49797	3.79
19.49181	3.8
19.48853	3.81
19.48675	3.82

19.48408	3.83
19.48079	3.84
19.47666	3.85
19.47741	3.86
19.47488	3.87
19.46964	3.88
19.46894	3.89
19.46967	3.9
19.47032	3.91
19.46813	3.92
19.46698	3.93
19.4646	3.94
19.46384	3.95
19.46175	3.96
19.45958	3.97
19.45627	3.98
19.45547	3.99
19.4521	4
19.45119	4.01
19.45105	4.02
19.44981	4.03
19.44849	4.04
19.44665	4.05
19.44478	4.06
19.44364	4.07
19.44122	4.08
19.43998	4.09
19.43808	4.1
19.43825	4.11
19.43526	4.12
19.43604	4.13
19.43211	4.14
19.4333	4.15
19.42978	4.16
19.42914	4.17
19.42871	4.18
19.42966	4.19
19.42962	4.2
19.42831	4.21
19.42624	4.22
19.4245	4.23
19.42177	4.24

19.42396	4.25
19.42426	4.26
19.41963	4.27
19.41978	4.28
19.41822	4.29
19.4138	4.3
19.40877	4.31
19.41001	4.32
19.4076	4.33
19.40604	4.34
19.40115	4.35
19.40134	4.36
19.39619	4.37
19.39461	4.38
19.39155	4.39
19.39106	4.4
19.38841	4.41
19.3869	4.42
19.38367	4.43
19.37973	4.44
19.38021	4.45
19.37719	4.46
19.37173	4.47
19.36746	4.48
19.36611	4.49
19.36471	4.5
19.36131	4.51
19.35674	4.52
19.35548	4.53
19.35466	4.54
19.35459	4.55
19.3511	4.56
19.3504	4.57
19.34668	4.58
19.34569	4.59
19.34098	4.6
19.3391	4.61
19.33725	4.62
19.33205	4.63
19.33004	4.64
19.3293	4.65
19.32668	4.66

19.32464	4.67
19.32141	4.68
19.3185	4.69
19.31549	4.7
19.3132	4.71
19.31169	4.72
19.30855	4.73
19.30475	4.74
19.30613	4.75
19.30132	4.76
19.30145	4.77
19.29521	4.78
19.293	4.79
19.2909	4.8
19.29026	4.81
19.29028	4.82
19.28965	4.83
19.28453	4.84
19.28484	4.85
19.28177	4.86
19.28168	4.87
19.27813	4.88
19.2737	4.89
19.27409	4.9
19.26859	4.91
19.27045	4.92
19.26627	4.93
19.26602	4.94
19.26406	4.95
19.26036	4.96
19.26002	4.97
19.25845	4.98
19.25767	4.99
19.25556	5

