-Spray Characterization of twin-fluid atomizer using Phase Doppler Particle Analyzer-

-Mohit Bharti -

A Dissertation Submitted to

Indian Institute of Technology Hyderabad

In Partial Fulfillment of the Requirements for

The Degree of Master of Technology

भारतीय प्रौद्योगिकी संस्थान हैदराबाद

Indian Institute of Technology Hyderabad

Department of Mechanical and Aerospace Engineering

June, 2019

Declaration

I declare that this written submission represents my ideas in my own words, and where others' ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources that have thus not been properly cited, or from whom proper permission has not been taken when needed.

(Signature)

(Mohit Bharti)

(ME17MTECH11029)

Approval Sheet

This thesis entitled – Spray Characterization of twin-fluid Atomizer using Phase Doppler Particle Analyzer – by – Mohit Bharti – is approved for the degree of Master of Technology from IIT Hyderabad.

-Dr. Narasimha Mangadoddy
Associate Professor,
Department of Chemical Engineering, IIT Hyderabad
Examiner

-Dr. Saravanan Balusamy
Assistant Professor
Department of Mechanical & Aerospace Engg., IIT Hyderabad
Examiner

-Dr. Pankaj S Kolhe
Associate Professor
Department of Mechanical & Aerospace Engg., IIT Hyderabad
Adviser

- Dr. Narasimha Mangadoddy
Associate Professor,

,

Acknowledgements

Firstly, I would like to thank my research advisor Dr. Pankaj Sharadchandra Kolhe, for his proper guidance and advice throughout my project work. Thank you, sir, for giving me the freedom to do work in my own way. I would also want to thank my fellow researcher, Surendra Kumar Soni for assisting and helping me. I also like to thank committee members Dr. Saravanan Balusamy and Dr. Narasimha Mangadoddy, for their valuable comments. My very special thanks to IITH friends for their unconditional support and friendship. Lastly, I would like to thank my Parents and other family members for their support and believe in me.

Dedicated to

This dissertation is dedicated to My Parents and My family members.”.

Abstract

Spray Characterization of Air-blast and Flow-blurring atomizer are studied using water and Soya oil as surrogate fuels. The Phase Doppler Particle Analyzer (PDPA), point measurement technique was utilized to do experiments. The regular spray characteristics like Mean axial velocity and Sauter mean diameter (SMD) are presented and also some important alternate statistics like volume weighted diameter and volume weighted velocity are explored for diameter and velocity of droplets. Effect of Air to Liquid mass ratio on diameter and velocity of droplets is discussed. We observed that as ALR increases, the velocity of droplet increases due to high-pressure drop in the injector, and high aerodynamic force reduces droplet diameter in the spray. So spray become more atomized at high ALR.
Non-reacting vegetable oil and water sprays are compared for AB and FB atomizer. High viscous force in VO increases the optimum wavelength of jet break up, which results in bigger drop size compared to water. In AB atomizer, there is a huge difference in SMD, but in the case of FB atomizer, there is less difference in SMD between sprays. Results indicate that even though viscosity of VO is 50 times that of water, FB atomization is less affected by the viscosity of fuels compared to AB atomization. Next, spray characteristics of Flow-blurring atomizer is compared with Air-blast atomizer for water and VO liquid fuels. Flow-blurring atomizer produces sprays with a narrower range of drop sizes compared to Air-blast atomizer, which signifies larger surface area creation per unit volume of atomized liquid indicating better atomizing efficiency compared to AB atomizer. This happens due to the intense mixing of fuel and air at the liquid fuel tip in FB atomizer and prior to exiting the orifice.

Nomenclature & Abbreviations

GLR or ALR	Gas / Air to the liquid ratio by mass
AB	Air Blast
FB	Flow-Blurring
PDPA	Phase Doppler Particle Analyzer
Pl	Liquid Pressure
Pg	Gas Pressure
Ua	Mean Axial Velocity
SMD	Sauter Mean Diameter
αD	Volume weighted Diameter
αUa	Volume weighted Velocity
VO	Soya Vegetable Oil
Z	Axial location
r	Radial location
MLPM	Mili liter per minute
SLPM	Standard liter per minute

Contents

List of Figures

List of Tables

Overview

1) In Chapter 1 atomization, types of atomizers are explained. Also, the previous contribution of researchers, experimental setup, and methodologies are discussed.
2) In chapter 2, detailed spray characterization of Air-blast atomizer is discussed using water as a liquid fuel. Conventional and alternate statistics for droplet diameter and velocity is explored.
3) In chapter 3, detailed spray characterization of Flow-blurring atomizer is discussed using water as a liquid fuel. Conventional and alternate statistics for droplet diameter and velocity is explored.
4) In chapter 4 effect of viscosity on Air-blast and Flow blurring atomizer is discussed using Soya-Oil (VO) as high viscosity fuel and water as low viscosity fuels at fixing Air to Liquid mass ratio (ALR).
5) In chapter 5, Spray characteristics of Air-blast and Flow-blurring atomizer are compared for both water and VO fuels.

Chapter 1

Introduction

1.1 Background

Most of the world's energy need is still fulfilled by combustion of liquid fuels. Improper Combustion of fuels results in the pollutant emission of CO, NOx, and soot. Accordingly, clean and efficient combustion has been the focus of past investigations by various groups of researchers. Combustion of fuels plays a significant role in application such as gas turbine, spark ignition engine, diesel engine. Liquid fuels burning requires effective atomization, and vaporization mixing of fuel and air. Atomization increases the surface area to volume ratio of fuel for achieving proper mixing rate of fuel and air, which results in a high evaporation rate of spray and adequate combustion. The device used for atomization is called atomizer. Atomization process and different atomizers used in the various application are discussed in paragraphs to follow.

1.1.1 Atomization

Atomization is the process in which the bulk of the liquid is converted into the smaller droplets. Different process in atomization is shown in Figure 1-1. Atomization comprises two separate processes; firstly, bulk liquid is converted into broad ligaments or bigger droplets, which is called the primary atomization process. These bigger droplets subjected to moving gas phase, the aerodynamic force exerted by gas phase overcomes the surface tension force and viscosity force tries to deform bigger droplet into smaller droplets, which is called secondary atomization process[16] [15]. That is mainly governed by three forces i) Viscosity force ii) Surface tension force iii) Aerodynamic force. Formation of tiny droplets from the liquid core is called spray formation region. Then droplets form a spherical shape due to surface tension phenomenon. Fine droplets result in faster evaporation when reacts with the surrounding air.

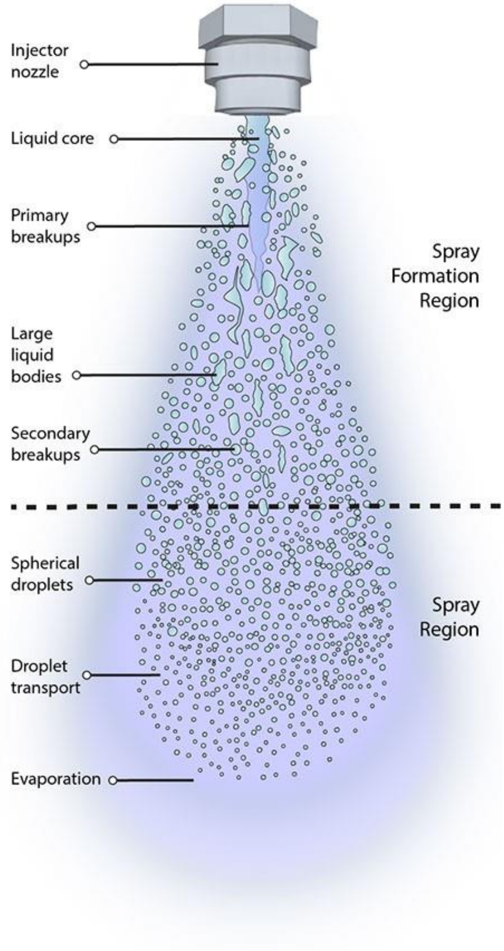


Figure 1-1- Various processes in Atomization

(**Image Source- Spray Diagnostics and Advanced imaging**)

1.1.2 Types of Atomizers

There are broadly classified into two types-

1) **Single Fluid Atomizer-** In this atomizer, a single fluid is atomized and produce a spray. Various examples of the single fluid atomizers are plain orifice atomizer, simplex atomizer, dual orifice atomizer.

2) **Twin fluid atomizer-** In this atomizer, two different types of fluid is mixed and atomized to produce a spray. The liquid is formed into sheets by nozzle then air is supplied against the layer to produce atomization. Various mechanics have been used for mixing two fluids. Based on mechanics we can classify into two types-

i) **Air Assist Atomizer-** In this atomizer, low amounts of air is supplied at high velocity to low fuel rates to produce spray based on the mixing of air and liquid. This atomizer can be divided into two types. The first type is Internal mixing atomizer in which air and liquid mixed in the nozzle before getting off the outlet orifice. The Second one is external mixing atomizer as the name suggest high-velocity air impinges on liquid downstream of discharge orifice. The problem of back pressure averted in externally mixing atomizer because there is no internal contact between air and fuel.

ii) **Air-Blast atomizer-** In this atomizer high amount of air is supplied at low velocity to low fuel rates to produce a spray. Air-blast atomizer works as same as air assist atomizer the main difference is that the amount of air and magnitude of the velocity of air. These atomizers require very low fuel pump pressure and produce an atomized spray. This atomizer ensures proper mixing of fuel. and air, ensuring less soot formation after combustion. This atomizer has an application in an industrial gas turbine, a wide range of aircraft and marine.

a) **Plain Jet Atomizer-** this is one of the simplest type of air blast atomizer. The jet of liquid is inserted along the axis of an atomizer, and the jet of air is supplied externally.

b) **Prefilming Air-blast Atomizer-** In this type of atomizer liquid is expanded out into a thin continuous sheet and then exposed to atomizing action of flowing air. This atomizer is in fully working when both inlet ports are working. In this atomizer two swirl inlet port for air is used for swirling air and proper atomization is obtained, but complex geometry of this atomizer is the main drawback of this atomizer

c) **Air blast simplex atomizer-**To take advantage of both atomizers plain air blast and Prefilming atomizer Air blast simplex atomizer is used in which pressure swirling nozzle is surrounded by a co-flowing stream of swirling air. In the Present study, Air blast simplex atomizer is used in which atomization is attained when the shear is produced between the liquid jet and very high-velocity air via six tangential swirl slot [2].

iii) **Flow Blurring atomizer-** Ganan- Calvo in 2005 [11] introduced an injector called flow-blurring injector. It consists of an orifice plate and a liquid nozzle. The orifice plate is situated below the nozzle. Atomizing air passes through a gap between nozzle and orifice. The tapered nozzle at the outlet and the orifice plate diameter is same as of nozzle inner diameter (d), and the axial distance between the orifice and nozzle exit is less than 0.25d (h<0.25d). The schematic diagram of flow blurring injector is shown in Figure 1-2. Between fuel tube tip and exit orifice, turbulent mixing of fuel and air takes place inside the injector only. According to literature, primary atomization takes place inside the nozzle only; secondary atomization takes place after leaving the injector.

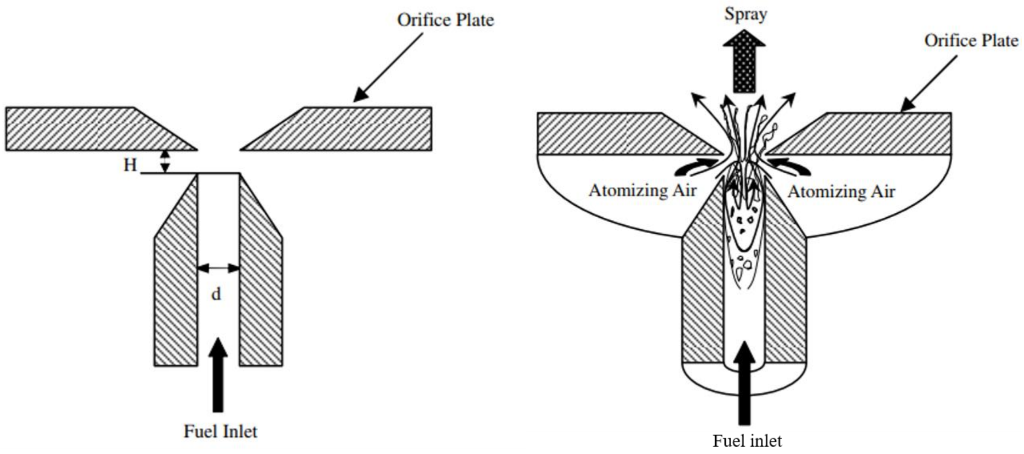


Figure 1-2 Schematic Diagram of Flow-Blurring Injector [12]

1.1.3 Literature Review

Various studies have been developed in the past decades related to different Atomizer Lefebvre & Rizk [1] in 1984 studied the effect of viscosity of a liquid, air pressure, ALR on droplets diameter of a plain jet Air-blast atomizer and uses kerosene, gas oil to develop SMD correlation. They observed that with an increase in ALR, spray quality improved in terms of drop size distribution. Bachalo and Houser [3] in 1984 carried out PDPA experimental study with swirl chamber pressure atomizer with water, they derived the size-velocity co-relation and use this co-relation to evaluate the effect of velocity relaxation on size distribution. Chong & Hochgreb [2] studied the effect of atomizing air flow on atomization carried out experiments on commercial available Delavan SNA 30611model with surrogate fuel diesel in non-reacting condition. They measured axial location 30mm and 50mm and reported the effect of ALR on SMD and axial velocity by using Phase Doppler Anemometer technique. Lorenzetto & Lefebvre (1997) [4] used plain jet air blast atomizer for drop size measurement by using the optical technique. They measure the effect of liquid viscosity, surface tension, liquid flow rate on SMD of droplets. They reported that the reduction in mean drop size of the spray with an increase in liquid density, gain in drop size with an increase in liquid viscosity and surface tension. Santolaya et al**.** (2007) [5] used PDPA technique to study pressure swirl hollow cone nozzle and show axial velocity and SMD radial distribution in the non-dimensional form at axial location 18mm, 36mm, 72mm below the injector. They showed axial velocity follow Gaussian distribution and show the radial distribution of radial velocity at the various axial location. They dynamically characterize spray by Sauter mean diameter and axial velocity and radial velocity for pressure hollow cone nozzle. Gad et al. (2018) [27] studied the diesel fuel atomization of AB atomizer used particle imaging velocimetry (PIV) technique. Four air swirler with vane angels: 45°, 30°, 15°, and 0° have been used, and they showed spray concentration is increased with increasing swirl vane angel. They showed the effect of ALR and L/D (Nozzle-orifice distance to nozzle diameter ratio) ratio on spray concentration and cone angle. They showed spray quality increases with increasing ALR and decreases with increasing L/d ratio. Roudini & Wozniak (2018) [6] used the Phase Doppler Anemometer (PDA) technique to study spray characteristics of pre-filming air blast atomizer, and they showed the effect of nozzle design, air pressure, liquid flow rate, on a break up the length, on SMD of droplets, and Axial velocity in axial and radial direction of atomizer. Kulkarni & Deshmukh (2017) [9] experimented with Air blast atomizer using particle /droplet image analysis (PDIA) technique. Radial and axial variation of SMD with GLR 1-5 have shown. They showed with increasing GLR, droplet diameter reduced, and spray become atomized. We can conclude from the past literature related to Air Blast atomizer.

In 2005, Gañán-Calvo [11] introduced a novel flow blurring injector with some modification in plain Air Blast injector. He showed FB injector creates 5 to 50 times more surface area than 'plain air-blast injector'. Flow blurring injector showed ten-fold atomizer efficiency than air-blast injector without considering pressure drop. Panchasara et al. [20] in 2009 compared pollutant emissions in the flow-blurring injector and air blast injector and they showed 3-5 times less CO and NOx emission in diesel and kerosene flames using flow blurring injector compared to air blast injector. Fisher et al**.** [13] in 2018 studied the effect of fuel properties like the viscosity of liquid and surface tension on spray characteristics like drop size and droplet velocity using the conventional statistics SMD and axial velocity in the flow-blurring injector. They showed that spray from flow blurring injector much not affected by viscosity and surface tension. Simmons et al.[21] in 2009, compared spray characteristics of high viscosity liquid vegetable oil from flow blurring injector and air blast injector using Phase Doppler Particle Analyzer Technique. They showed flow blurring injector produced spray with smaller droplet diameter compared to air blast injector. They showed Flow blurring injector atomized liquid at low ALRs in a better way compared to Air Blast injector. Simmons et al. (2018) [12] has experimented with high viscosity fuels like vegetable oil, bio-diesel, and diesel using flow blurring injector. They showed flow blurring injector produces smaller droplets without preheating spray. FB injector creates clean burning of the spray of high viscosity of spray without preheating.

1.2 Motivation For Study

Combustion of liquid fuels supplies the majority of world energy needs. Spray produces fine liquid droplets, which easily vaporize and mix with air to satisfy the requirement for clean and efficient combustion. Clearly spray quality is linked with the combustion efficiency and emissions. Spray quality can be ascertained only through its statistical characteristics such as droplet size, velocity, etc. For characterizing spray, previous researches focussed mainly on conventional statistics like SMD, Mean diameter, Mean & RMS Axial Velocity, swirl velocity for diameter and velocity of droplets, which are number density based statistic. Number density-dependent based characteristic skew the perception in relation to spray quality. At the periphery of the spray, generally the number density of bigger droplets may be very low, but the volume fraction associated with it may be high. So alternate statistics should be focussed to study spray. Note that for liquid fuel combustion, residence time in reaction zone and droplet size are important from combustion efficiency and emissions perspective, and hence the number density based statistics cannot be a true representative to determine the velocity of bulk of liquid with which it is moving or average droplet size for the bulk of fluid atomized.

1.3 Experimental Set up

Figure 1-3 is showing the schematic arrangement to study spray in the stand-alone injector. It has four components-

1) Compressed Airline to the injector- The compressed air is supplied after the filter and drier by controlling through needle valve from the main compressed air line. The air is coming to the injector through mass flow controller ranges 0-100 slpm (standard litre per minute).

2) The Liquid supply line to injector- liquid is supplied to the injector through a peristaltic pump which is a positive displacement pump which worked between 0 to 2 bar. Due to gearing action of this pump, it adds fluctuation in the liquid flow. For removing fluctuation in the flow, the pulse damper has been added.

3) 3-D transverse system with stand-alone injector- in this study Air blast injector is connected to the 3-d transverse system which is used to move injector in all radial and axial direction to study spray through the nozzle. We can operate a traverse system by software with a resolution of 1mm in xyz direction. The Injector is connected with two pressure gauge (with a resolution of 0.2 bar) in the liquid and airline to note air and fluid pressure at the injector.

4) Diagnostic technique PDPA- Phase Doppler Particle Analyser is a non-intrinsic laser diagnostic device based on the principle of light scattering interferometry. PDPA is a single point measurement tools used to acquire a time history data for droplet size and velocity measurement simultaneously. The transmitter unit is integrated with laser and optics. The laser beam created by diode pumped solid-state TSI laser. Three different wavelengths are generally employed to measure 3 velocity components. In present investigation 2-velocity components are measured with 532 nm and 561 nm laser wavelengths. Note that each laser beam is split into two and a frequency and phase shift is introduced by employing Bragg cell in one of the beams. This frequency and phase shifted beam produces interference pattern with the unshifted laser beam when the two beams intersect. The alternate dark & bright fringes are formed and create a probe volume. The receiver position was set such that the slit position should be in between the intersection of both beams. When the spray droplets pass from the intersection region of the laser beams, the scattered signal is received by the receiver. The Doppler burst is generated when the drop passes through dark and bright fringes. The spatial frequency of this Doppler burst is proportional to the velocity of the droplet. The phase shift from the Doppler burst signal from different detectors is proportional to the drop diameter.

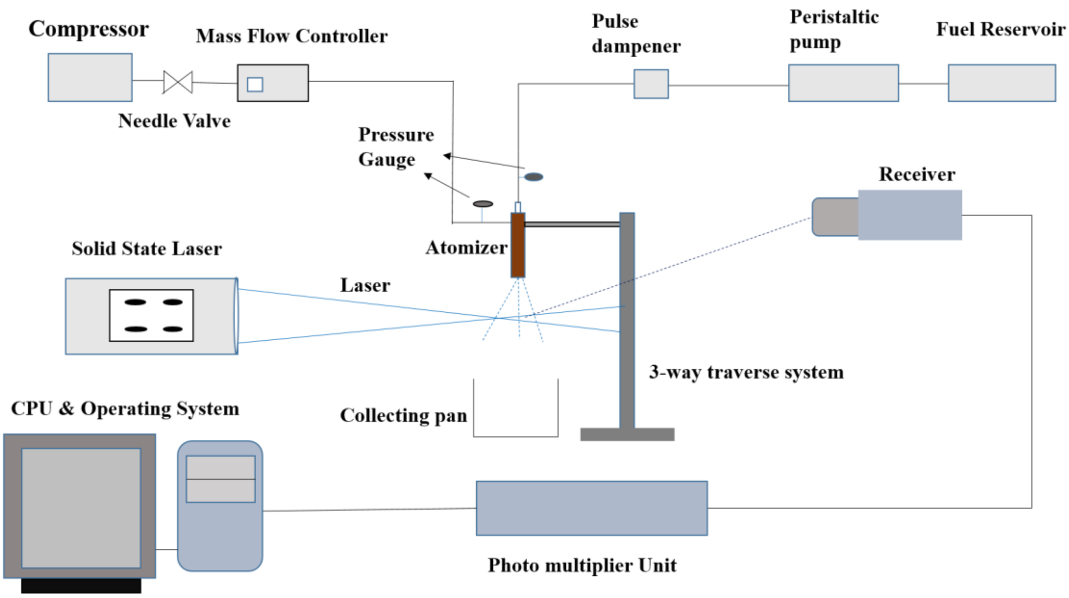


Figure 1-3 Experimental Set up

PDPA Setting

- Bragg cell frequency (frequency shift) : 40 MHz
- Transmitting optic focal length: 512 mm
- Beam separation at the frontal lens: 50 mm
- Beam diameter at the frontal lens, after beam expander: 2 mm
- Fringe spacing: 5.7548 µm
- Receiving optic focal length: internal for refocusing 250 mm, external 300 mm,.[26]
- Scattering angle: 30°
- Slit aperture: 150 µm (refocused on the measurement volume to +20%.)
- Velocity range: -5 to 201 m/s (with maximum filter bandwidth 20-175 MHz, without downmixing.
- Diameter range: up to 0.6 µm to 260 µm with refractive fuel index.

PDPA setting during droplet diameter measurements

Diameter difference bound: The diameter is measured always based on phase difference detected by two detectors. By setting the bounds on the allowable diameter, difference system can reject the data point where the system failed to perform good sizing measurements. For current experiments, the bound limit was set 7 %, that means that the maximum diameter difference measured by both the size measurements is 7 %.

Intensity validation: Generally, there are two slopes of intensity, the upper slope, and lower slope. The measured data should be within the intensity envelop & the upper slope should generally follow the diameter square relationship. If this criterion failed, data would go for the invalid counts.

Experiments were performed with stand-alone injectors (Air Blast Injector and Flow Blurring Injector) attached to the three-way transverse system. This system can move with software, and the nozzle was swept along traverse direction, and a horizontal plane by using an electronically controlled traverse system and PDPA system was kept constant at a fixed location. The software was configured as to collect 10,000 valid droplet sample or 180 seconds time limit. PDPA data were exported with coincident mode for getting the drop size and velocity data at the same point.

1.4 Methodologies of Droplet diameter and velocity

Sauter Mean Diameter- In spray different size ranges of droplets are there so in this kind of situation mean, or average diameter is considered instead of total drop size distribution, most convenient way of representing mean diameter is Sauter Mean Diameter (SMD). It represents the ratio of droplets volume to droplet surface area. SMD is an equivalent diameter of all spherical droplets in the spray.

$$D_{32} = \frac{\sum_{i=1}^{N} N_i D_i^3}{\sum_{i=1}^{N} N_i D_i^2}$$

where *i* indicate the size range

N_i is the number of droplets in size range *i*

D*i* is the individual droplet diameter

Mean Axial Velocity- It is the average of the velocity of all the droplets.

$$U_a = \frac{U_i}{N}$$

Volume Weighted Diameter (αD) - It is the summation of the product of individual droplet diameter multiplied by its volume fraction is referred to as volume weighted diameter at a particular location.

Volume weighted diameter (αD) $= \sum_0^N \alpha_i D_i$

Volume weighted diameter is de Brouckere mean diameter noted as D43.

Volume weighted Velocity (αUa) - It is the summation of the product of individual droplet velocity multiplied by its volume fraction is referred to as volume weighted velocity at a particular location.

Volume weighted velocity $= \sum_0^N \alpha_i U_i$

U_i is the individual droplet velocity

α is a volume fraction of droplets.

The volume fraction is the ratio of the volume of an individual droplet to the total volume of droplets.

$$\alpha = \frac{V_i}{\sum_0^N V_i}$$

V_i = Volume of individual droplet

$\sum_0^N V_i$ = Total volume of droplets

PDPA measures individual drop size-velocity, which is used to create volume weighted diameter-and velocity at a fixed location. Volume weighted diameter-velocity defined as the size of the chunk of liquid (αD) moving with velocity (αU).

Chapter 2

Spray Characterization of Air-Blast Atomizer

2.1 Background

Spray characterization of the internal-mix twin-fluid atomizer is discussed in this chapter using water as a liquid fuel. For twin fluid atomizers spray formation is a turbulent process with significantly large turbulent intensity in the immediate downfield region of the atomizer exit. To provide description of spray, statistical characteristics are used to characterize the turbulent process involved in the spray formation. Mean droplet velocity and diameters are the essential characteristics of the spray. Conventional representation of mean diameter is Sauter Mean Diameter (SMD), and usually mean axial velocity is specified. In the past decades, most of the researches have focused mainly on Prefilming and Plain jet air-blast atomizer and. Lefebvre and their group [1][4] used plain jet air-blast atomizer and studied the effect of air to liquid mass ratio, effect of geometry, etc. Researches [6][7][8] characterize spray of Prefilming air blast atomizer using conventional statistics like SMD, Axial Velocity, radial velocity, RMS axial velocity is studied. So to take advantage of both Prefilming air-blast and plain jet air-blast atomizer. In the present study, internally mixed air-blast injector with swirling air is analyzed using the PDPA technique (discussed in chapter 1). Previous investigations have not focused on providing the alternate representation of droplet diameter and droplet velocity. Number density based statistics fail to truly represent bulk of fluid motion with representative mean droplet size and velocity. In the present study, the traditional statistics and volume weighted statistics (alternative statistics) are compared. It was shown how the volume weighted statistics are a better representative for droplet diameter and velocity. Effect of operating parameter such as ALR on drop-size and droplet velocity is also studied.

2.2 Geometry of Air-Blast Atomizer

The schematic geometry of Delavan: SN type 30609 atomizer has been shown in Figure 2-1. It is an Internal-mix Air-blast atomizer which has been used in the present study. It has a central tube of jet diameter 0.3mm, which is surrounded by a stream of swirling air to break up the liquid jet via six tangential swirl slots [2]. Air-blast atomization is achieved when high-velocity swirl air exerts aerodynamic strain on the liquid jet. The exit orifice diameter of the injector is 1.8 mm.

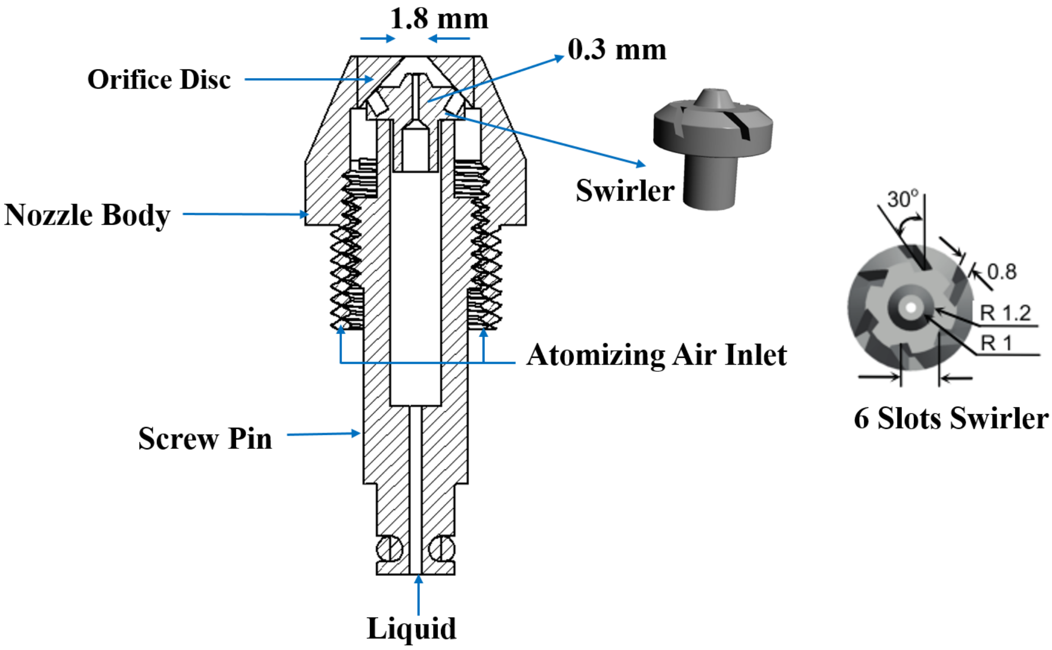


Figure 2-1 Schematic Geometry of Air-Blast Atomizer

2.3 Operating Parameters

Experiments were carried out using the standalone injector configuration for air blast atomizer. In this study, the air is used as gas and water is taken as a liquid fuel, and, a peristaltic pump provides the constant liquid flow rate at 12mlpm. Airflow rate is changed to change operating ALR for the standalone injector setup. Alicat mass flow controller was used to meter the air flow rate. The properties of fuel and air are shown in Table 2-1, and operating parameters are shown in Table 2-2.

Table 2-1- Properties of Air and Water

Properties	**Gas Phase (air) Condition**	**Liquid Phase (Water) Condition**
Refractive Index	1	1.33
Density (kg/m3)	1.2	1000
Viscosity (Ns/m2)	1e-5	1e-3

Table 2-2-Operating Parameters

Air to Liquid mass ratio (ALR)	**Mass of Water in (MLPM)**	**Mass of Water in (kg/s)**	**Mass of Air in (SLPM)**	**Mass of Air in (kg/s)**
1	12	0.0002	10	0.0002
2	12	0.0002	20	0.0004
3	12	0.0002	30	0.0006
4	12	0.0002	40	0.0008

2.4 Result and Discussion

2.4.1 Pressure Drop Measurement

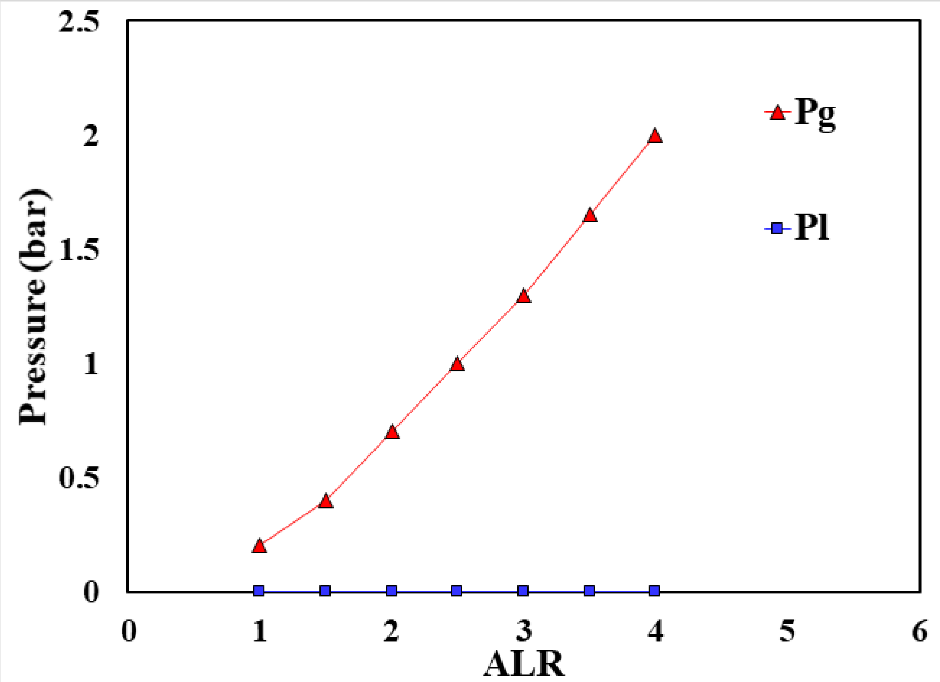


Figure 2-2 - Pressure drop in air and liquid line

The pressure drop across the injector is shown in Figure 2-2. It is important in many aspects because it is used for the calculation of atomizing efficiency. Liquid fuel atomization is happening at the expense of pressure energy of atomizing air. Pressure gauge was installed just upstream of the nozzle to accurately measure pressure drop occurring in the nozzle. In air-blast injector pressure drop in liquid line is negligible as shown in the figure. As ALR increases, the pressure drop in the airline increases, which indicates larger energy input to the atomizer, and finer spray is expected for this increased input energy operating conditions.

2.4.2 Droplet size and velocity distribution

Radial variation of SMD and Mean axial velocity at ALR 2

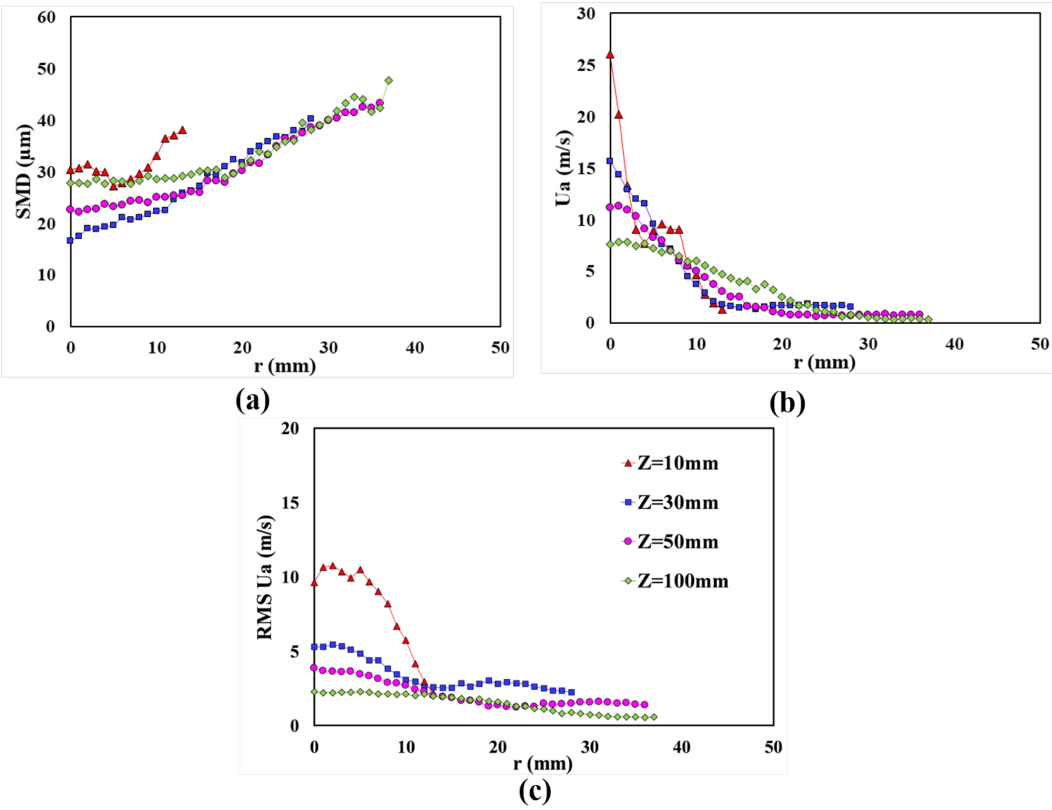


Figure 2-3 Radial variation of (a) SMD (b) Mean Axial Velocity (c) RMS Axial Velocity at ALR 2

Sauter Mean Diameter- Figure 2-3 (a) is showing the radial distribution of SMD at different Axial locations. SMD is a conventional representation of droplet diameter based on the number of droplets. Near the injector at Z=10mm, the SMD is nearly 30µm at the center, which isobserved to decrease at downstream axial location. This can be explained as the change in the regime from jet breakup in the immediate downstream location (viz. z = 10 mm) to secondary droplet breakup at downstream locations (Z ≥ 30 mm). As moving downstream of the nozzle at Z=30mm centreline, SMD decreases to 17 µm due to secondary atomization of bigger droplets into smaller droplets. As moving further downstream of injector drop size slightly increases to 22µm at Z=50mm centreline and 29µm at Z=100mm centreline. This can be attributed to droplet coalescencce. As moving radially outward, SMD increases due to centrifugal action of the swirling component of velocity pushing the bigger droplets radially outwards.

Mean Axial Velocity - Figure 2-3 (b) is showing the radial distribution of mean axial velocity at different Axial Locations. It is a conventional representation of droplet velocity based on number density. Velocity distribution is symmetric about center line, so results presented here only for half of the length of spray. Velocity is maximum at the center line and decreases radially in the outward direction resembling bell shape curve. Near the injector at Z=10 mm downstream of injector, velocity is maximum near 26 m/s at the center because near the injector axial momentum is dominant and velocity decreases as moving radially outward due to entrainment of air. As moving downstream of injector velocity decreases due to interaction with the surrounding air and so flattening of velocity profile is observed at downstream locations of the injector. The reduction in centerline velocity and radial spread at downstream location of Z = 30 mm, 50mm, 100 mm is evident from the figure 2-3.

RMS Axial Velocity - Figure 2-3 (c) is showing the radial distribution of RMS axial velocity at different axial locations. Near the injector at Z=10mm RMS axial velocity has a peak value of 10 m/s at the center and constant up to radial location of 6 mm following which monotonic decrease in RMS velocity with radial location is observed. RMS axial velocity is high near the injector, due to high turbulent intensity compared to the edge of spray. As going downstream of injector, RMS axial velocity continuously decreases to 4m/s at Z=100mm spray center and has a flatter profile.

Centre line variation of SMD, Volume weighted diameter and Mean axial velocity, Volume weighted velocity at ALR 2

Centre line variation of mean axial velocity and volume weighted velocity is shown in Figure 2-4 (a) at ALR 2. Only marginal difference along the centreline is observed for the two velocities. For downstream locations for z > 40 mm, volume weighted velocity is marginally higher indicating the mean bulk of liquid volume is moving at slightly higher speed, which would reduce the residence of the droplets in the combustor. Note that this decrease in residence time may lead to incomplete combustion of the liquid fuel. However, effect on the radial profile needs to be looked at instead of only a one point at each location, which is addressed in later part of this chapter.

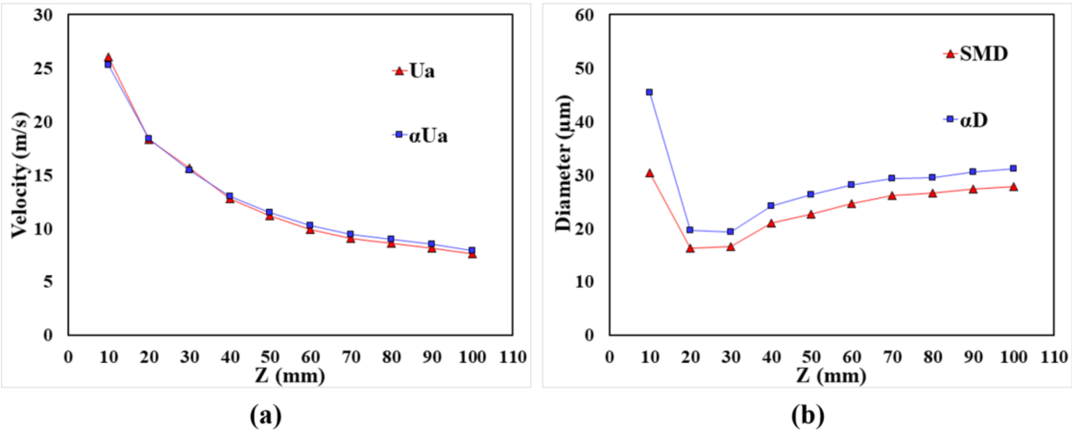


Figure 2-4 Centerline variation- (a) mean axial velocity and volume weighted velocity (in m/s) (b) SMD and volume weighted diameter (in µm)

Centreline variation of SMD and Volume weighted diameter is shown in Figure 2-4 (b) at ALR 2. Near the injector at Z=10mm spray centre, SMD and αD is maximum near 46µm and 31µm respectively. As going downstream of injector SMD and αD decreases up to Z=30mm. As moving further downstream of injector droplet diameter increases continuously due to collisions and coalescence of droplets. As going downstream of the nozzle from Z=40mm to Z=100mm, SMD changes from 20µm to 28µm but αD changes from 22µm to 32µm. So at every axial position αD is always higher than SMD, which indicates the mean representative droplet diameter for the liquid atomized at any location is larger than what SMD predicts. Note that larger droplets tend to burn in diffusion mode and would lead to inefficient combustion and higher CO, HC as well as NOx emissions.

Comparison of SMD and αD through cumulative number density and cumulative volume fraction at ALR 2

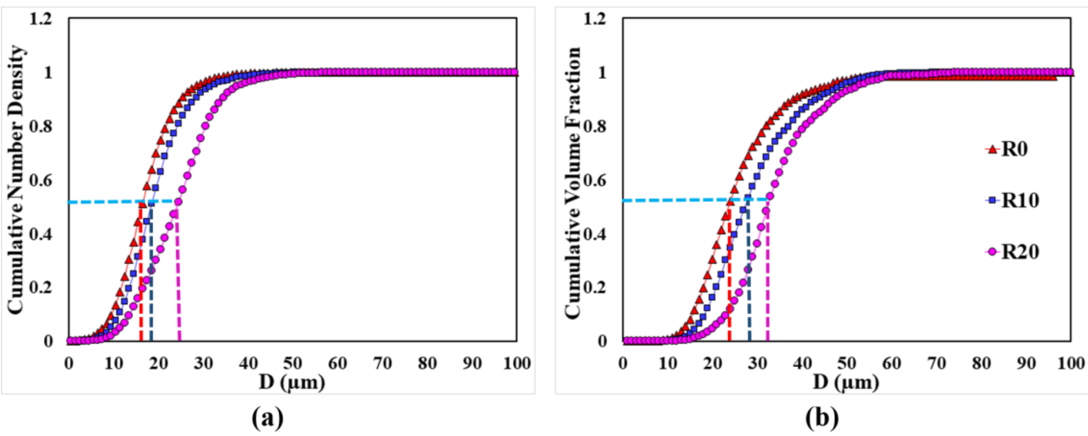


Figure 2-5 (a) Cumulative number density distribution (b) Cumulative volume fraction distribution

These statistics truly help in understanding the representative droplet diameter for the bulk of liquid atomized.

From CND plots

At radial positions R0, R10, R20, 50 % of the number of droplets are below 15µm, 18µm, 25µm respectively but 50% of the number of droplets still larger than this. Additionally, it is evident that droplet number density for larger droplets increases at outer radial location. At Z=50mm, R0, R10, R20 radial positions, SMD values are 23µm, 25µm, 30µm respectively, which comprises less than 83%, 82%, 78% based on number density.

At R0, R10, R20 radial positions αD values are 26µm, 28µm,33µm respectively, which comprises less than 91%, 89%, 88% based on number density. It is clear that αD value gives more close representation of bulk of liquid atomized for all radial positions compared to SMD.

From CVF plot

At Z=50mm R0, R10, R20 radial positions, SMD values are 23µm, 25µm, 30µm respectively, which are showing 48%, 47.5%,47% of total droplet volume fraction for all diameters lower than these mentioned diameters.

At these same axial radial positions, αD values are 26µm, 28µm, 33µm respectively, which are showing 62%, 61%, 61% of total droplet volume fraction for all diameters lower than these mentioned diameters. Volume weighted diameter comprises more amount of droplets than Sauter Mean diameter. In fact, cumulative volume fraction indicates that at downstream location of z = 50 mm also, SMD cannot be considered true representative for bulk of liquid atomized as it represents less than 50% of the volume only.

Table 2-3 Spray quality prediction through SMD

Axial Position	Radial Position	SMD (in μm)	% Prediction in CVF	% Prediction in CDF
Z10	L0	30.44	41.8	93.2
	L5	27.14	41	91.5
	L10	33.05	44.2	89.1
Z30	L0	16.48	47.8	86.5
	L10	22.38	51.8	88.2
	L20	31.81	52.2	85.9
Z50	L0	22.65	47.8	98.1
	L10	25.09	48.5	96.2
	L20	30.26	46.6	95.2

Table 2-4 Spray quality prediction through αD

Axial Position	Radial Position	αD (in μm)	% Prediction in CVF	% Prediction in CDF
Z10	L0	45.44	63.8	98.1
	L5	35.14	59.8	96.4
	L10	41.15	60.4	95.5
Z30	L0	19.35	64.2	93.7
	L10	27.31	69.8	95.2
	L20	36.34	62.8	90.8
Z50	L0	26.23	64.8	92.2
	L10	28.22	60.5	89.9
	L20	32.99	57.4	88.2

Based on the above results, we can conclude that

(i) αD predicting more number density compared to SMD.

(ii) The Volume weighted diameter is always larger than SMD; i.e., the actual size of the droplet diameter is under predicted using SMD statistics.

(iii) From the above results, the number density is very high for all axial & radial location, but the actual volume fraction is less.

(iv) Volume weighted statistics such as αD and CVF truly gives picture of spray quality

2.4.3 Self Similarity of Spray

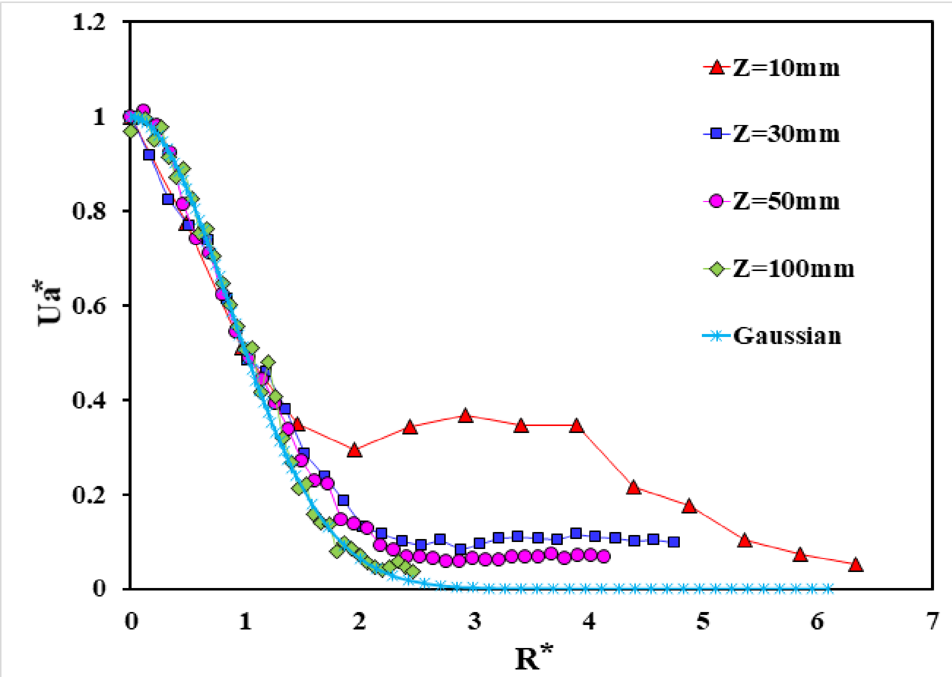


Figure 2-6 Self-Similarity of Spray

Self-similar behavior of spray has been shown in Figure 2-6 for ALR2. It has been drawn between centre line normalized velocity Ua^* and normalized half radial location R^*. Centre line normalized velocity is obtained when axial velocity is normalized by centreline velocity. The radial location is normalized by radial location distance where axial velocity is 50% value of centreline velocity. This radial profiles of normalized axial velocity have been shown at different Z (axial) locations. Near central zone R*<1 velocity profile follows Gaussian distribution at the different axial locations. Near the injector location Z=10mm, as going radially outward normalized velocity indicates heavy tailed distribution instead of Gaussian velocity distribution.

The Ua* profile does not become self-similar until the distance from injector reached 50mm. Clearly, the presence of dispersed droplet has delayed the development of self-similar velocity distribution. Because of secondary break up of droplets, the spray becomes self-similar at downstream locations.

There are following conclusions from self-similarity plot-

1) We can find the axial location after which self-similar behavior is achieved.
2) This plot shows the extent in the downstream direction up to which experimental measurements we have to take because after that turbulent behavior of the spray can be modeled in terms of few constants.

2.4.4 Effect of ALR-

Radial Variation of Sauter mean diameter & Volume weighted diameter At Z=10mm

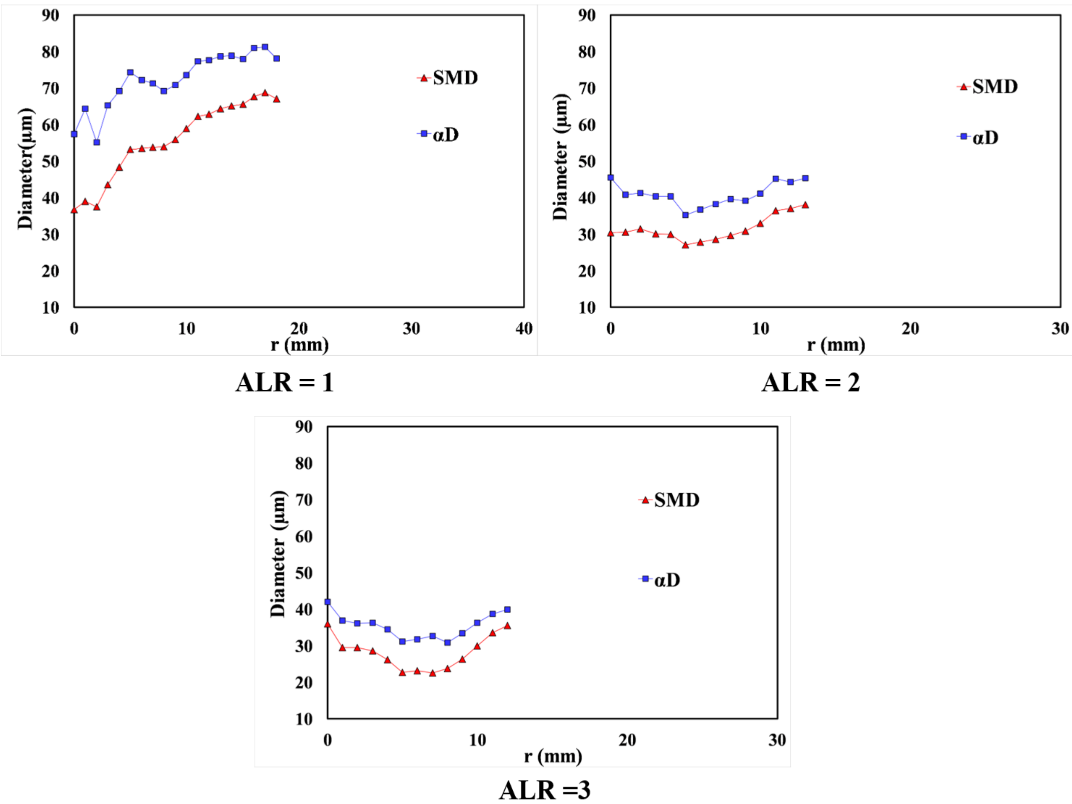


Figure 2-7 Effect of ALR on SMD and Volume weighted diameter at Z=10mm

Radial variation of Sauter Mean diameter and volume weighted diameter for different ALR at Z=10mm axial location is shown in Figure 2-7. At Z=10mm for smallest ALR 1, SMD and αD is nearly showing similar profile and at centreline droplet size is minimum and increases as going radially outward. For high ALR 2-3 diameter profile show insignificant variation in mean diameter with radial location. Fine atomization is depicted by the SMD and αD variation with range of sauter mean diameter observed over the radial extent is 28-35µm for ALR 3.

For ALR1, at the centerline of spray SMD is nearly 38 microns, and volume weighted diameter is almost 60 microns, at every radial position for all ALRs, volume weighted diameter is significantly larger compared to SMD. However, with increase in ALR, difference in SMD and αD is reducing due to fine spray.

At Z=50mm

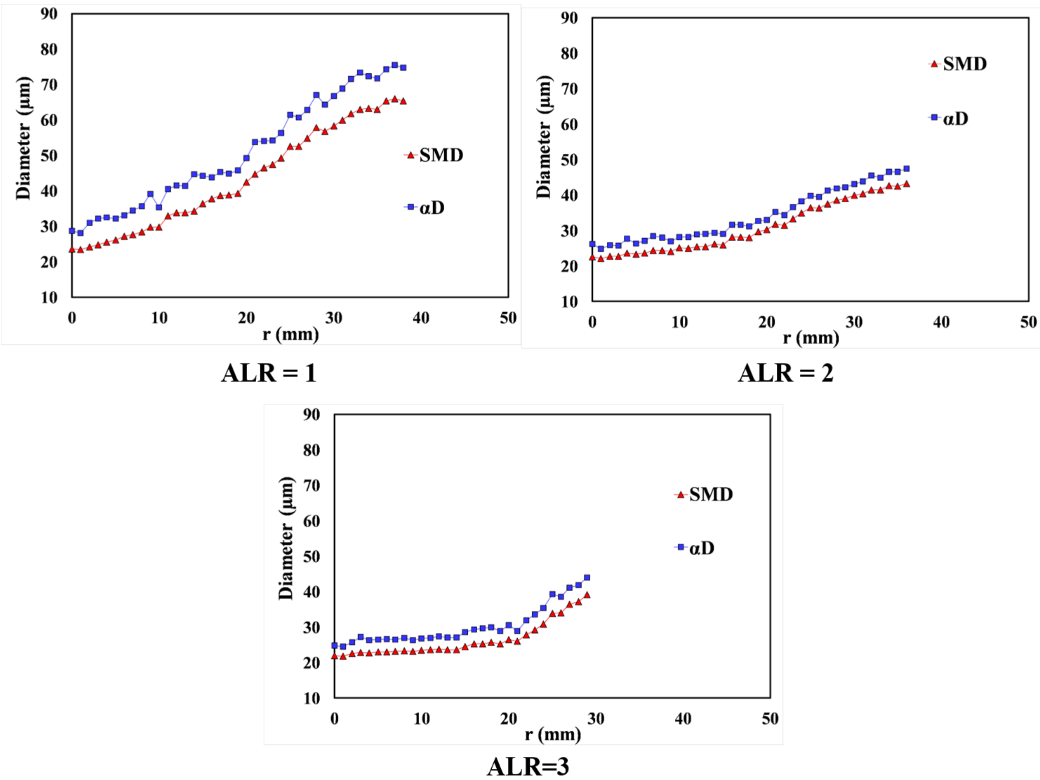


Figure 2-8 Effect of ALR on SMD and Volume weighted diameter at Z=50mm

Radial Variation of Sauter Mean Diameter and Volume weighted diameter for different ALRs at Z=50mm downstream of the injector is shown in Figure 2-8. As moving radially outward droplet diameter increases due to centrifugal action, the swirling component of velocity pushing the bigger droplets radially outward. The smaller droplets are entrained to pull towards spray centre region by the high-velocity core air stream. At low ALR of 1, SMD is minimum 21µm at the centre of spray and continuously increases to 60µm at the periphery of spray. For high ALR 2, SMD ranges nearly from 21µm at the centre to 44µm.at the periphery of spray. At high ALRs, due to the high relative velocity between the liquid jet and air, drop size reduction is observed an aerodynamic strain exerted is more. At this axial location also volume weighted diameter is always larger than SMD. Clearly, αD is better representative of bulk of liquid atomized compared to SMD from combustion persepctive.

Radial Variation of Volume weighted velocity & Mean Axial Velocity

At Z=10mm

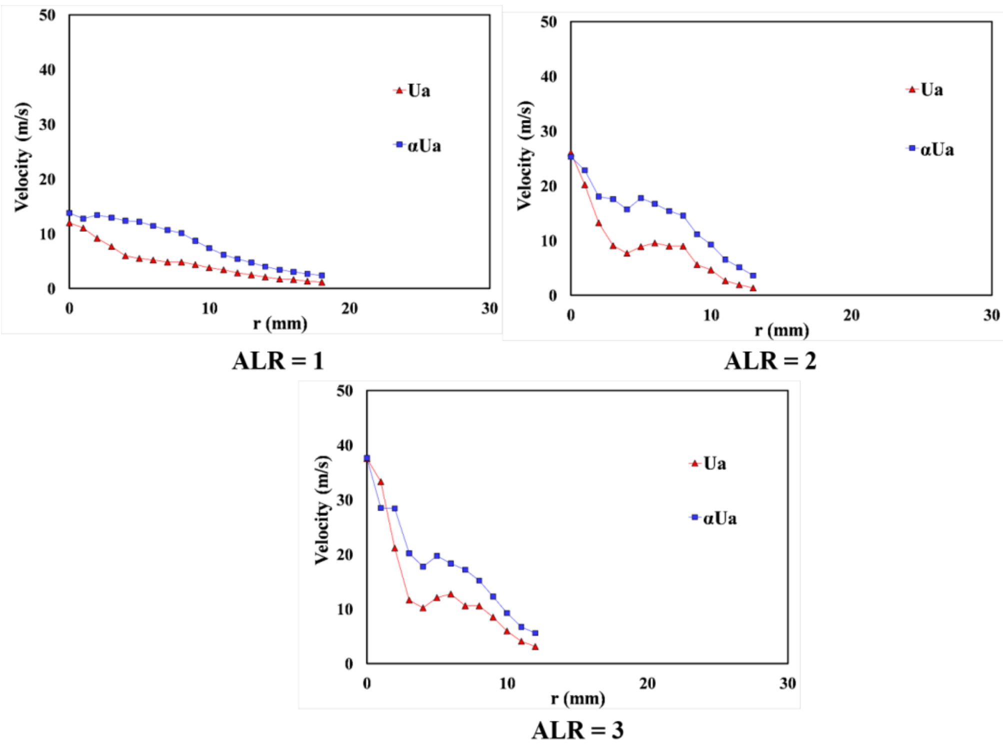


Figure 2-9 Effect of ALR on Mean Axial velocity and Volume weighted velocity at Z=10mm

Radial variation of volume weighted velocity and mean axial velocity at different ALRs are shown in Figure 2-9. Velocity distribution is symmetric about the centre line, so the results are presented for the half radial length of spray. Velocity reaches a maximum at the centre line and decreases towards the periphery in the outward direction. Velocity is high because the axial momentum is dominant near the injector. The velocity of droplets decreases towards the periphery of spray due to air entrainment phenomenon. At ALR 1 mean axial velocity at the centreline is 11m/s. As ALR increases mean axial velocity also increases, this is because of increase in pressure drop at high ALRs. Larger energy provided by the high momentum airflow translates into the higher velocity of droplets. At ALR 2 & ALR 3 centre line mean axial velocity is 28m/s and 39 m/s respectively.

Both mean and weighted volume axial velocity distribution indicate larger discrepancy in shear layer and away from the centre of the spray. Volume weighted velocity is higher than mean axial velocity as moving radially except at centre line. This difference is significant from the combustion perspective as bulk of atomized liquid is moving at higher velocity than predicted by mean axial velocity, which would change the residence time and cause distributed flame instead of intense short reaction zone.

At Z=50mm

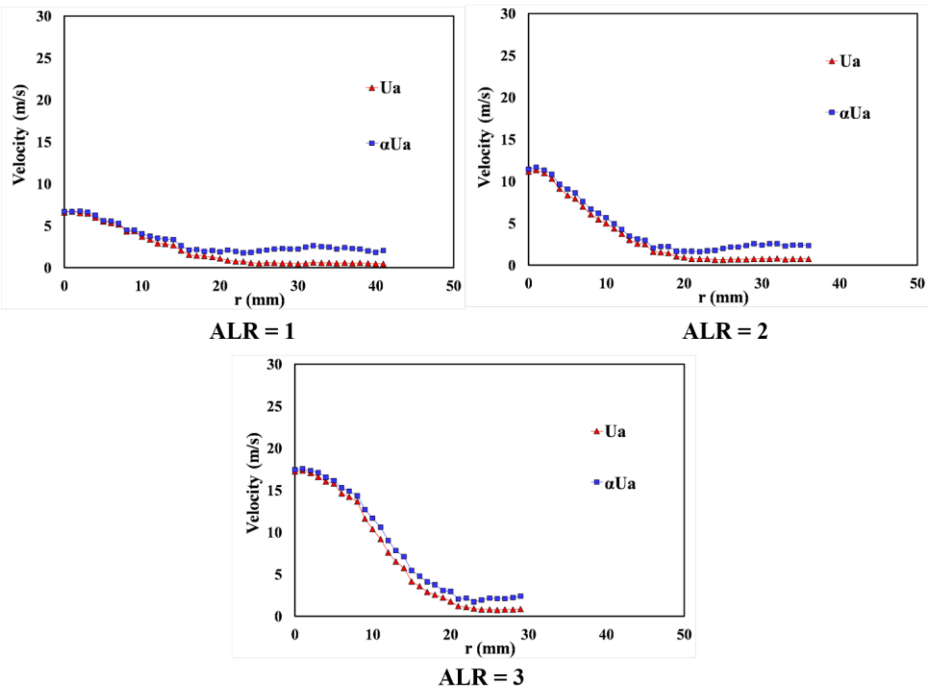


Figure 2-10 Effect of ALR on Mean Axial velocity and Volume weighted velocity at Z=50mm

Figure 2-10 shows the radial variation of volume weighted velocity and mean axial velocity at Z=50mm downstream of injector. The velocity of droplets decreases as going downstream of the nozzle because the momentum of droplet exchange with surrounding air reduces the droplet velocity. Here also, as ALR increases, the velocity of droplets increases because of an increase in pressure drop. The further energy provided by the high momentum airflow result into the higher velocity of droplets. Radial distribution for both mean axial velocity and volume weighted velocity resemble the bell curve shape. Difference in both mean and volume weighted axial velocity can be observed only at outer radial location for z = 50 mm. Note that for swirl flow these outer radial locations would indicate larger droplets having higher velocity than mean axial velocity. ty.

2.4.5 Spray Cone Angle-

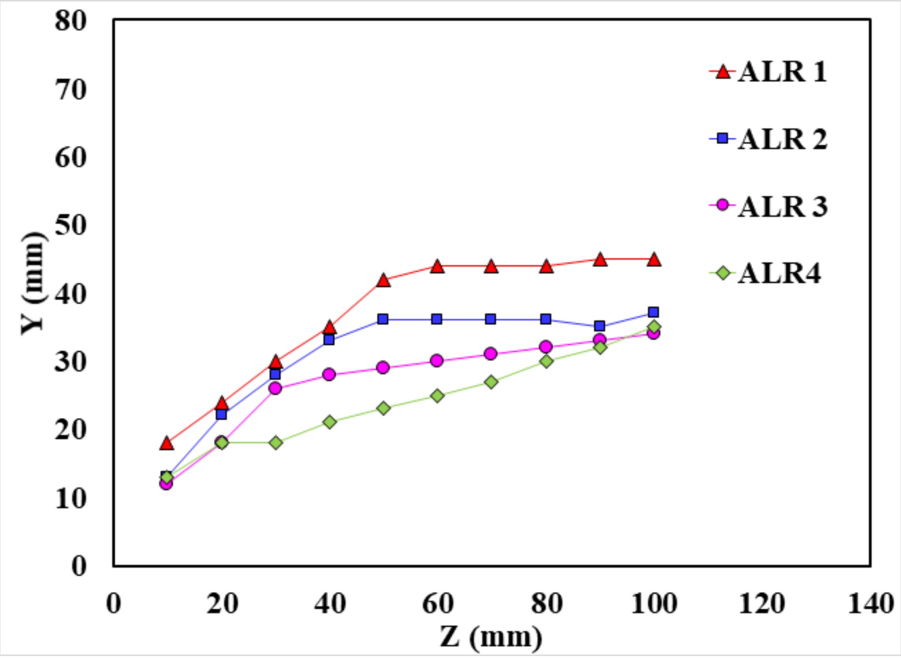


Figure 2-11 Radial extent of Spray at different ALRs

Spray cone angle tells about the maximum radial span of spray, which is a fundamental requirement of combustor geometry. Half Spray cone angle can be found by extent of the spray acquired from PDPA experiment. The data rate was usually high at the centre and decreased moving towards the end of spray. At the edge of the spray, the data rate is negligible. The radial extent of the spray is shown in Figure 2-11 for ALR 1 to 4. Here Z represents the axial locations (10-100mm) downstream of injector, and Y represents the radial span of spray at various axial locations, which enables to estimate spray half cone angle. As going downstream of injector, a radial span of spray increases. For ALR 1 radial span of spray is more and wider spray cone angle. With increasing ALR, the radial span of spray decreases, so the spray cone angle is less for high ALR, which can be explained through increase axial momentum.

2.5 Conclusions

Spray characterization of commercially available Air-blast atomizer is discussed using water as a liquid fuel. AB atomization happens only the expense of air energy because of pressure drop in a liquid line is negligible. The velocity of droplets is maximum at the centre and gradually decreasing towards the periphery of the spray. SMD is minimum at the centreline of the spray and increasing towards the periphery of the spray, which is attributed to the centrifugal action generated by swirler, which pulling the bigger droplet towards the outer side. With increasing ALR, the velocity of droplet increases, and droplet diameter decreases. The volume weighted diameter and velocity is more important powerful statistical tool compared to conventional statistics SMD and mean axial velocity because it predicts more realistic picture of spray quality. Self-similar plot shows the spray development and axial extent up to which it needs to be characterized through experiments.

Chapter 3

Spray Characterization of Flow-Blurring Atomizer

3.1 Background

In this chapter, the spray characteristics of Flow-blurring Injector is discussed. In 2005 Ganan Calvo [9] introduced an internal-external mixing type atomizer based on geometric constrained called as Flow Blurring (FB) atomizer. FB atomizer offers greater advantage in terms of combustion efficiency, low pollutant emission, through better atomization [9], [12], [11], [17], [18]. Spray characterization of water spray using conventional statistics, and alternate statistics are discussed in this chapter.

3.2 Geometry of Flow-blurring injector

In the present study, Flow-blurring injector is manufactured after some changes in Delavan model-30609 Air-blast injector. We have done the following hardware changes in AB injector to get Flow-Blurring concept as shown in Figure 3-1 Schematic Geometry of Flow-Blurring Injector.

i) The swirler of AB injector from screw pin is replaced by plain fuel tube in FB injector. In the top of the fuel tube, the step is provided to provide the mixing zone and fulfilling the requirement for FB atomizer criteria. The gap between the tip of fuel to the exit of an orifice is 0.1125mm.

ii) The exit orifice is flipped. The angular grooved face side is provided on the outer side.

The geometrical configuration criteria to be fulfilled by flow blurring injector is

i) The fuel tube diameter is equal to the exit orifice diameter.

ii) The axial distance between the orifice and the nozzle exit is less than 0.25d ($h<0.25d$).

Flow blurring injector used in this study is shown in the figure. In which atomizing air coming from an annular path interact with the incoming slow moving liquid jet. At the tip of the fuel tip and before the exit orifice, the vigorous turbulent mixing of air and fuel taking place. Based on the literature [10] [19] In flow-blurring injector, primary atomization happens inside the injector only. While leaving from the injector, only secondary atomization is taking place.

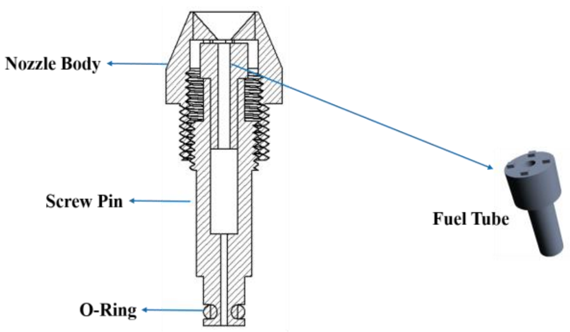


Figure 3-1 Schematic Geometry of Flow-Blurring Injector

3.3 Operating parameters-

Experiments were carried out for stand-alone Flow-Blurring injector. In this study, the air is used as gas and water is taken as a liquid fuel, and, the flow rate of liquid is kept constant at 12mlpm with help of a peristaltic pump. Airflow rate is kept on changing by the mass flow controller to obtain different ALRs. and operating parameters are shown in below Table 3-1.

Table 3-1 Operating Parameters for FB Atomizer

Air to Liquid mass ratio (ALR)	Mass of Water in (MLPM)	Mass of Water in (kg/s)	Mass of Air in (SLPM)	Mass of Air in (kg/s)
1	12	0.0002	10	0.0002
2	12	0.0002	20	0.0004
3	12	0.0002	30	0.0006
4	12	0.0002	40	0.0008

3.4 Results and Discussion

3.4.1 Pressure Drop Measurement

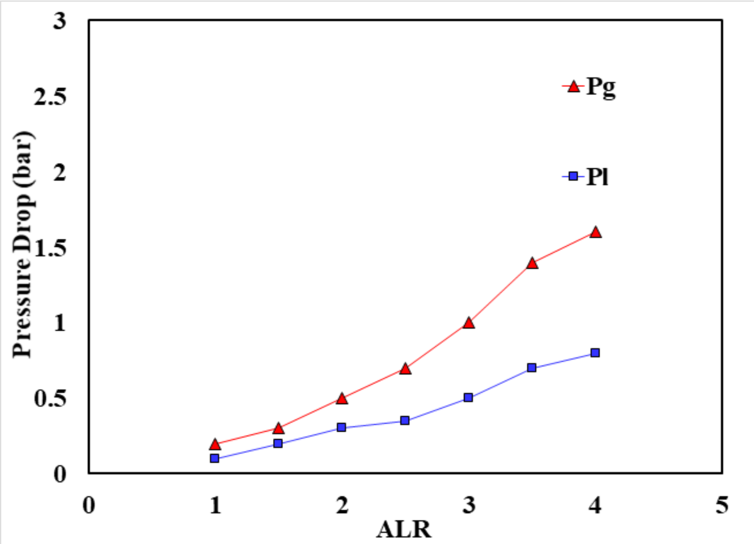


Figure 3-2 Pressure drop in air and liquid line

Figure 3-2 shows the pressure drop in the atomizing air and fuel line of the injector. For that, the two pressure gauge having least count 0.1 bar have been installed very close to the injector. Pressure drop calculation is essential in various aspect because pressure drop across the nozzle is used for the calculation of atomization efficiency. The liquid fuel atomization is happening at the expense of pressure energy. At ALR 1 pressure drop in the airline is 0.2 bar and in liquid line is 0.1 bar. As the atomizing air mass flow rate or ALR was increased, the FB injector experienced more pressure drop in both the airline & fuel line. So at ALR 4 pressure drop in air and liquid line are 1.6 bar & 0.8 bar respectively. Note that to achieve the spray, peristaltic pump has to develop the required pressure to push the liquid and protocol followed to initiate measurement was to let the spray develop and pressure drop settle down to fixed value.

3.4.2 Droplet size and velocity distribution

Radial & Axial distribution at ALR 2

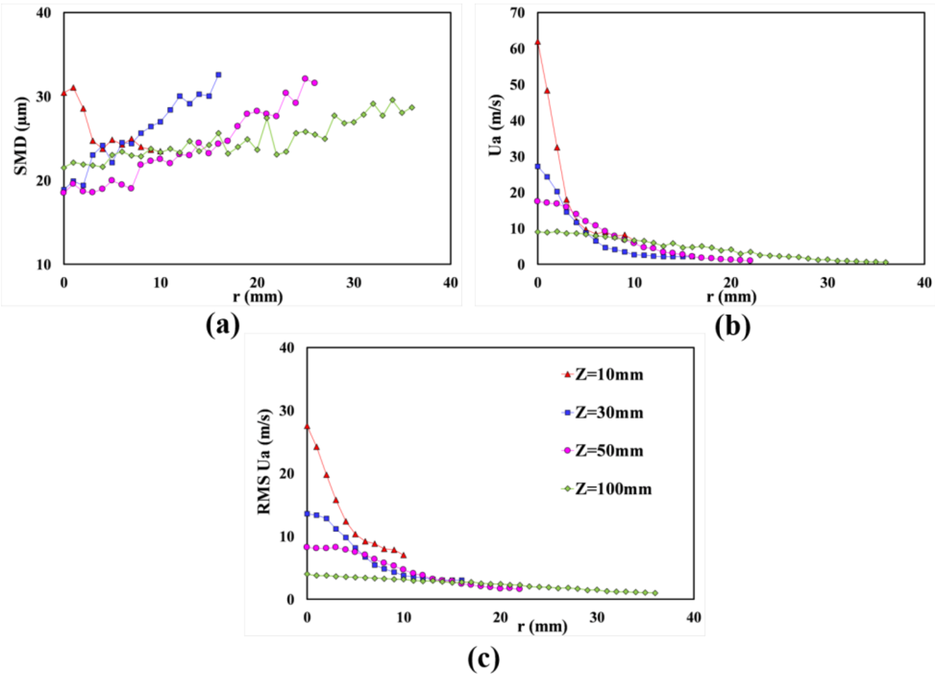


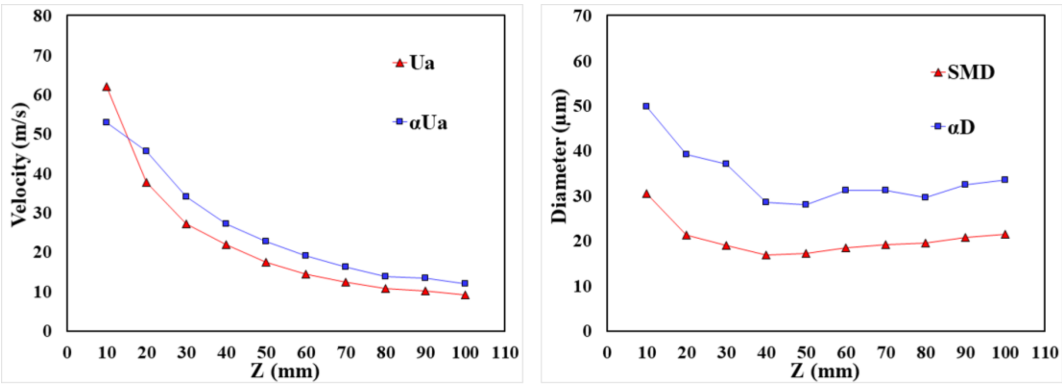
Figure 3-3 Radial & Axial Distribution at ALR 2 of- (a) Mean Axial Velocity (b) Sauter Mean Diameter (c) RMS Axial Velocity

Sauter Mean Diameter- Figure 3-3 (a) is showing the radial distribution of SMD at different Axial locations. SMD is a conventional representation of droplet diameter based on the number of droplets. Near the injector at Z=10mm, the SMD is nearly 30µm at the center and has a peak of 32µm (2mm from center) and decreases as moving radially outward. Drop size is large near the nozzle because of primary atomization process occurs near the injector. As moving downstream of the nozzle at Z=30mm centreline, SMD decreases to 17µm due to secondary atomization of bigger droplets occurs below injector. As moving further downstream of injector drop size slightly increases to 18µm at Z=50mm centreline and 22µm at Z=100mm centreline. This may be due to collisions and coalescence of droplets as moving downstream of injector.

Mean axial Velocity- Figure 3-3 (b) is showing the radial variation of mean axial velocity at different axial locations. It is a conventional representation of droplet velocity based on number density. Velocity distribution is symmetric about center line, so results presented here only for half of the length of spray, velocity is maximum at the center line and decreases radially in the outward direction. Near the injector at Z=10mm downstream of the nozzle, velocity is maximum near 62 m/s at the center because near the injector axial momentum is dominant and velocity decreases as moving radially outward due to entrainment of air. At Z=30mm centerline mean axial velocity suddenly drop to 29 m/s. As moving further downstream of injector velocity decreases due to interaction with the surrounding air and so flattening of velocity profile was observed at downstream locations. So at Z=100mm downstream of injector velocity at centreline is around 9 m/s. As going downstream of injector radial span also increases.

RMS Axial Velocity- Figure 3-3 (c) is showing the radial distribution of RMS axial velocity at different axial locations. Near the injector at Z=10mm RMS axial velocity has a peak value of 28µm at the center, and it is decreasing as going radially outward. High RMS axial velocity caused by high turbulent fluctuation near the center compared to the edge of spray. As going downstream of injector, RMS axial velocity continuously decreases to 3m/s at Z=100mm spray center and has a flatter profile.

Centre line variation of SMD, Volume weighted diameter and Mean axial velocity, Volume weighted velocity at ALR 2



(a) (b)

Figure 3-4 Centerline variation- (a) mean axial velocity and volume weighted velocity (in m/s) (b) SMD and volume weighted diameter (in µm)

Centre line variation of mean axial velocity and volume weighted velocity is shown in Figure 3-4 (a) at ALR 2. Near the injector at Z=10 mm centre of spray, mean axial velocity and volume weighted velocities are maximum near 62m/s and 52m/s respectively. As going downstream of injector axial velocity and volume weighted velocity both decreased because of entrainment and radial spreading. At Z=10mm mean axial velocity is higher than volume weighted velocity, but all other axial positions, Volume weighted velocity is higher than mean axial velocity. So it can be concluded that mean axial velocity is under predicting droplet velocity for the bulk of liquid atomized.

Centreline variation of SMD and Volume weighted diameter is shown in Figure 3-4 (b) at ALR 2. Near the injector at Z=10mm, SMD and αD are maxima near 51µm and 31µm respectively. As going downstream of injector SMD and αD decreases up to Z=40mm but after this SMD and αD increases as going downstream of injector. This is because small droplets merge and produce bigger droplets. As going downstream of the nozzle from Z=40mm to Z=100mm, SMD ranges from 20µm to 24µm but αD ranges from 30µm to 35µm. So at every axial position αD is always higher than SMD.

3.4.3 Self-Similarity of Spray

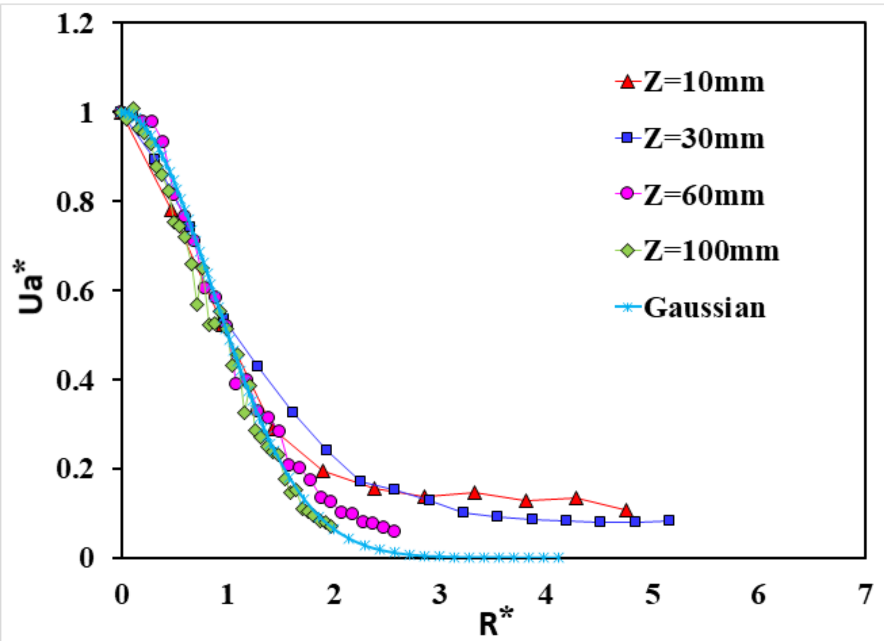


Figure 3-5 Self-Similarity of Spray

Self-similar behavior of spray has been shown in Figure 3-5 for ALR2. It has been drawn between centre line normalized velocity Ua^* and normalized half radial location R^*. Centre line normalized velocity is obtained by when axial velocity is normalized by centreline velocity. The radial location is normalized by radial location distance where axial velocity is 50% value of centreline velocity. This radial profile of normalized axial velocity has been shown at different Z (axial) locations. Near central zone $R^*<1$ velocity profile follows Gaussian distribution at the different axial locations. Near the injector location Z=10mm and Z=30mm. As going radially outward normalized velocity is higher than reference Gaussian velocity distribution.

The Ua* profile does not become self-similar until the distance from injector reached 50mm. Clearly, the presence of dispersed droplet has delayed the development of self-similar velocity distribution. Because of secondary break up of droplets, the spray becomes self-similar as going downstream of injector.

There are following conclusions from self-similarity plot-

1) We can find the axial location after which self-similar behaviour is achieved.
2) This plot shows the extent in the downstream direction up to which experimental measurements we have to take because after that turbulent behaviour of the spray can be modeled in terms of few constants.

It is clear from the above results there is no use to study the spray once self-similarity of spray is attained.

3.4.4 Effect of ALR

Radial Distribution of Sauter Mean Diameter (SMD) and volume weighted diameter (αD)

At Z=10mm

Radial variation of SMD and volume weighted diameter at different Air to liquid mass ratio (ALR 1-3) is shown in Figure 3-6. At Z=10 mm downstream of injector. For low ALR 1 SMD ranges from 38µm at the centre to 60 µm at the periphery of spray but αD ranges from 50 µm at the centre to 80 µm at the boundary. With increasing ALR droplet diameter decreases, At ALR 2 SMD reduces to 30 µm at the centre and 20 µm at the edge of spray. With increasing atomizing air flow rate interaction between jet and air shorten the optimum wavelength of jet break up, which results in smaller droplets and spray become atomized with increasing ALR. At high ALR 3 SMD is near 21μm and has a peak of 37μm at 3mm radial from the centre and then SMD decreases as moving further radially outward. At ALR 3 peak of SMD is due to less interaction of fuel and air. SMD and αD profiles are similar at all ALRs, but the magnitude is different. We can observe from the figure that at all radial positions for all ALRs, αD is always higher than SMD.

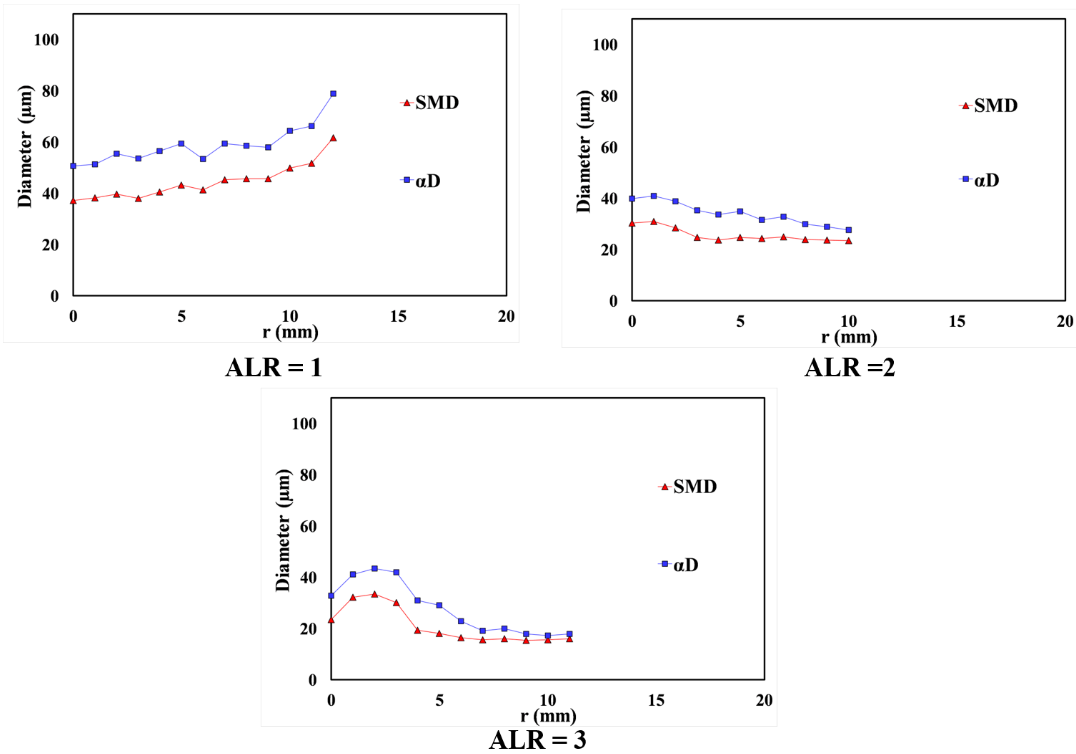
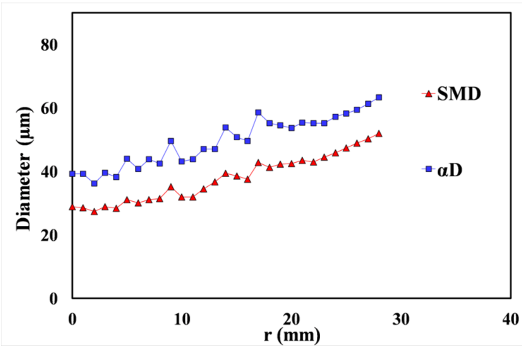
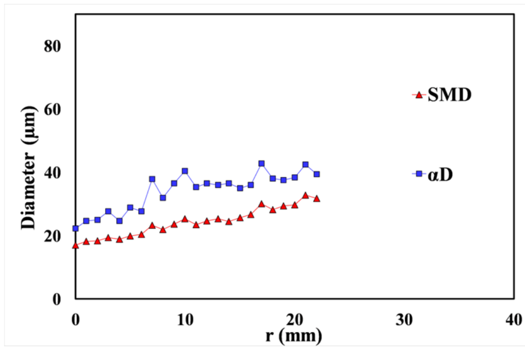


Figure 3-6 Effect of ALR on (a) SMD (b) Volume weighted diameter at Z=10mm

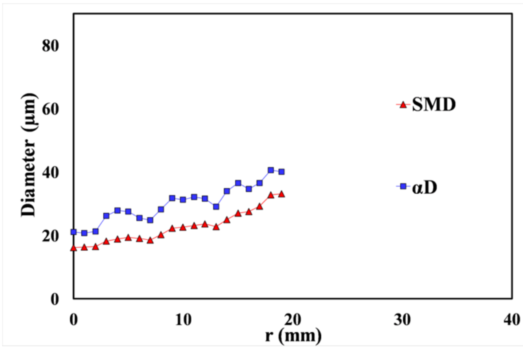
At Z=50mm



ALR = 1



ALR = 2



ALR = 3

Figure 3-7 Effect of ALR on (a) SMD (b) Volume weighted diameter at Z=50mm

Radial variation of SMD and αD at different ALRs are shown in Figure 3-7. These results are represented here at fixed axial location 50mm downstream of injector. For low ALR 1, SMD is nearly 27µm at the center. With increasing air flow rate, SMD decreases to nearly 19µm at the center of spray for high ALRs. For all ALRs and radial positions, αD is always higher than SMD indicating that the actual size of the droplets is large, which is underpredicted by SMD. Note that larger droplets are undesired results into the pollutant, emission problem. we can conclude that the conventional representation of diameter SMD is not enough to represent droplet diameter in a spray.

Radial Distribution of Mean Axial Velocity (Ua) and Volume weighted velocity (αUa)

At Z=10mm

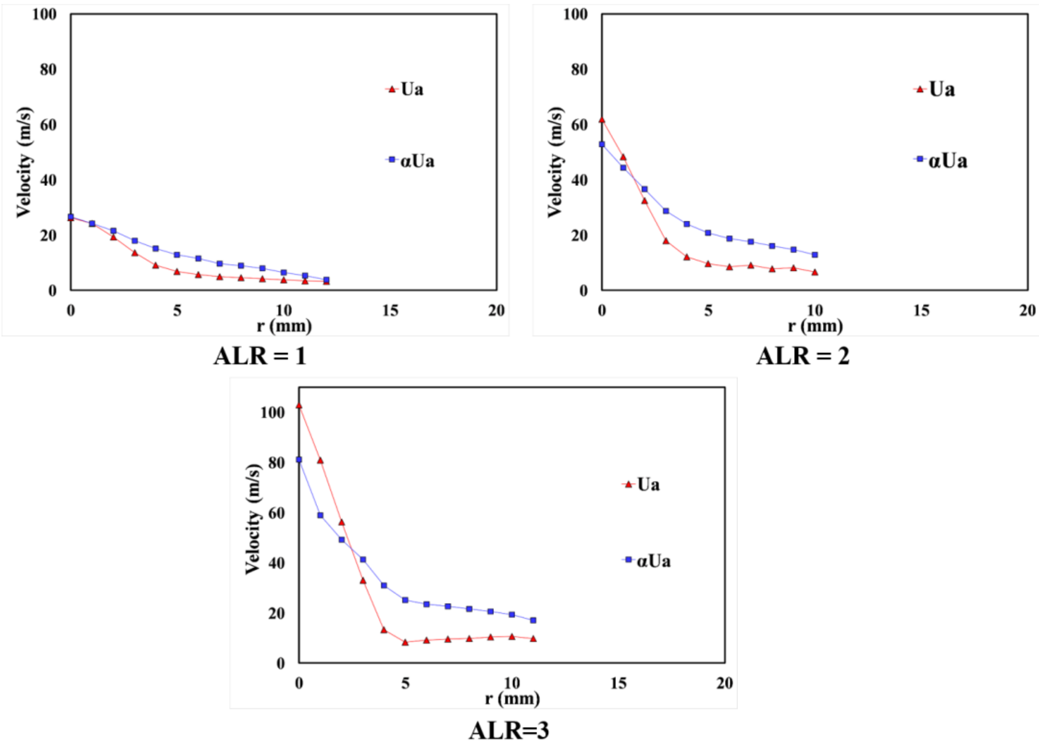


Figure 3-8 Effect of ALR on (a) Axial velocity (b) Volume weighted velocity at Z=10mm

Radial variation of mean axial velocity and volume weighted velocity at different ALRs are shown in Figure 3-8. At Z = 10 mm downstream of injector, velocity distribution is symmetric about the centre line, so the result represented for the half radial length of spray. Radial distribution of velocity shows bell shape curve variation wherein velocity reaches the maximum at the centre line and decreases towards the periphery in the outward direction. The lower velocity of droplet towards the edge of spray due to air entrainment phenomenon. At ALR 1 mean axial velocity at the centreline is 22 m/s. As ALR increases, droplet mean axial velocity also increases because of increased pressure drop at high ALR. The additional energy provided by the high momentum airflow translates into the higher velocity of droplets. Both mean axial velocity distribution and volume weighted velocity distribution are the same in behavior, but the magnitude is different. At ALR 1 Mean axial velocity is 110 m/s, but volume weighted velocity is 88 m/s at the centreline of spray. We can observe from the figure that near the centreline, mean axial velocity is higher than volume weighted velocity but at the periphery of spray volume weighted velocity is higher than Mean axial velocity. So mean axial velocity over predict droplet velocity near the centreline and under predicts at the periphery of the spray.

.

At Z=50mm

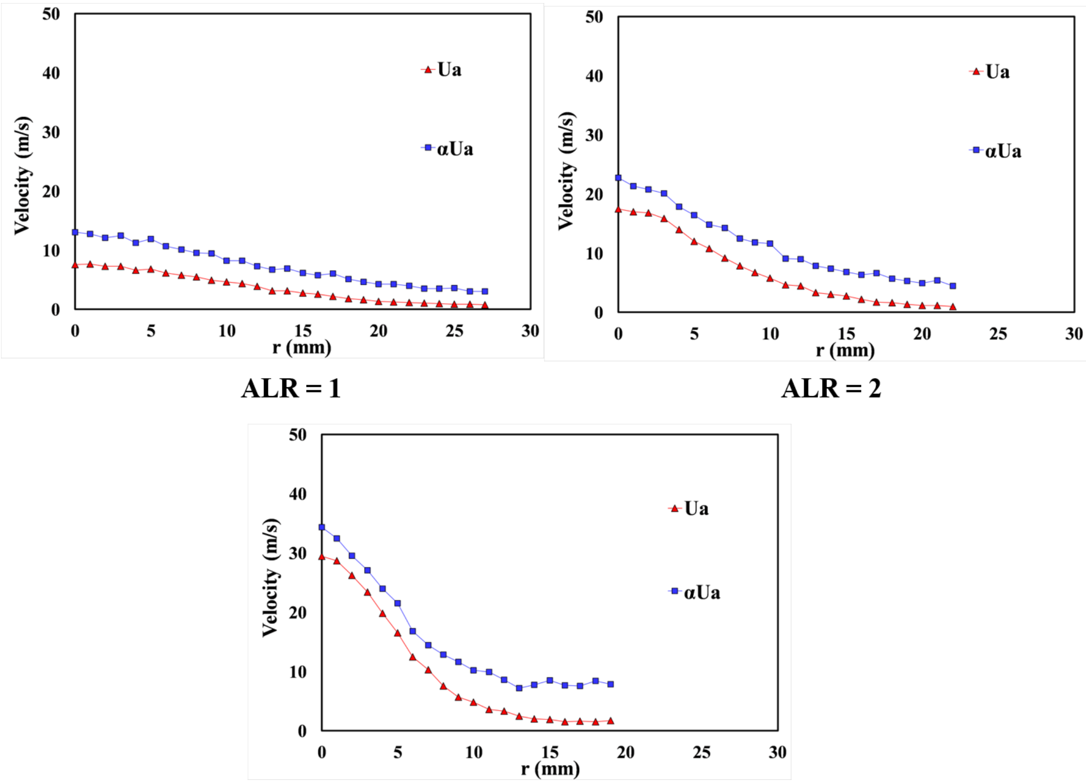


Figure 3-9 Effect of ALR on (a) Axial velocity (b) Volume weighted velocity at Z=50mm

Figure 3-9 shows the radial distribution of the velocity of droplets at Z = 50 mm downstream of the injector at different ALRs. Mean axial velocity of droplets is less compared to Z = 10 mm because of radial spread and ambient air entrainment. With increase in ALR, the velocity of droplets increases because of increase axial momentum of atomizing air as well as liquid due to larger pressure drop. The additional energy provided by the high momentum airflow translates into the higher velocity of droplets.

Radial distribution for both Mean axial velocity and volume weighted velocity looking like Gaussian distribution that is the peak value of the velocity at the centre and radially decreases due to the interaction of lower momentum air.

Both axial velocity distribution and volume weighted distribution is similar, but the magnitude is different. At Z=50mm, there is less difference of magnitude between volume weighted velocity and mean axial velocity compared to Z=10mm. As going radially outward difference of magnitude between mean axial velocity and volume weighted velocity increases. Volume weighted velocity is higher than mean axial velocity. So conventional representation by mean axial velocity under predicting the droplet velocity.

3.4.5 Spray Cone Angle

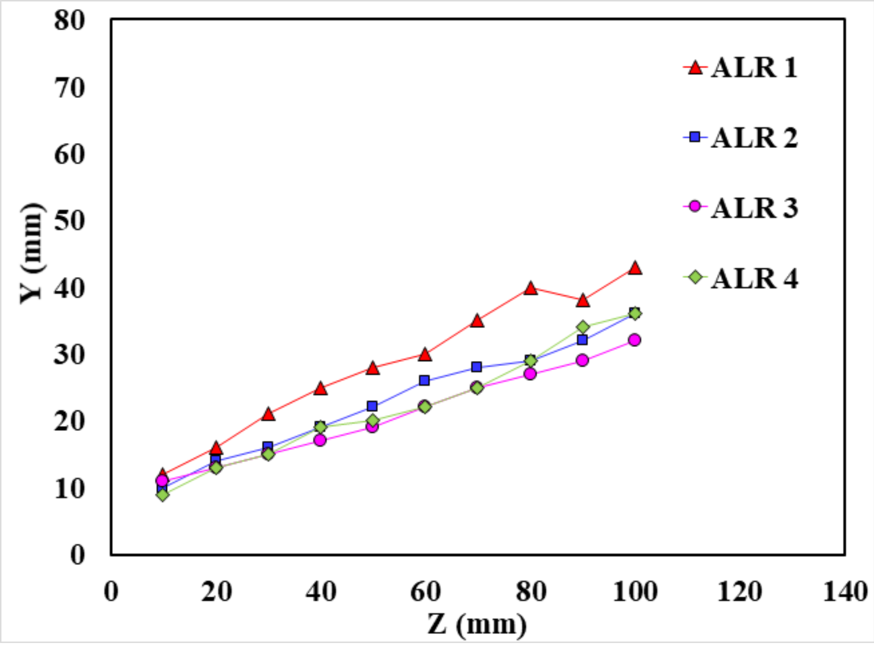


Figure 3-10 Trajectory of Spray at different ALRs for FB injector

Spray cone angle tells about the maximum radial span of spray, which is a fundamental requirement of combustor geometry. So the spray cone angle is essential characteristics. Half Spray cone angle can be found by trajectory information acquired from PDPA experiment. The data rate was usually high at the centre and decreased moving towards the end of spray. So maximum radial distance points where negligible data rate, considered as the edge of spray. The radial exent of spray is shown in Figure 3-10 for ALR 1-4. Here X represents the axial locations (10-100mm) downstream of injector, Y represents the radial span of spray at various axial locations. We can find spray half cone angle by the trajectory of spray. As going downstream of injector, a radial span of spray increases. For ALR 1 radial span of spray is more and hence the wide spray cone angle. With increasing ALR, spray become narrow but for high ALRs 2- 4, the variation in the spray radial extent is not significant. Spray images are independent for high ALRs. There is no significant difference in spray cone angle with ALRs for FB atomizer is noticed.

3.5 Conclusions-

Spray characterization of novel Flow-blurring atomizer is discussed using water as a liquid fuel. FB atomization happens expense of both air energy and liquid energy. With increasing ALR, the pressure drop in a liquid line and gas line increases. The velocity of droplets is maximum at the centre and gradually decreasing towards the periphery of the spray. With increasing ALR, the velocity of droplet increases, and droplet diameter decreases. The volume weighted diameter and velocity is more important powerful statistical tool compared to conventional statistics SMD and mean axial velocity because it predicts more realistic about the droplet data sampling. With increasing ALR, Spray cone angle increases, but at high ALRs, there is no significant difference in spray cone angle of FB injector.

Chapter 4

Effect of Viscosity on Injector Performance

4.1 Background

Atomization of liquid fuel is affected by physical properties like viscosity and surface tension. In atomization, the aerodynamic force should be large enough to exceed viscosity force and surface tension force. The air-blast atomizer, as discussed in chapter 2, delivers air at high velocity to break up fuel jet. AB atomizer requires high energy to produce finer droplets. The geometry of Flow-blurring atomizer provides higher mixing of fuel and air at the tip of a liquid tube. Due to the different flow dynamics in injectors, they provide different mixing zone for fuel and air. In this chapter effect of fuel properties on Air-Blast and Flow-Blurring injector is discussed using water and Soya oil (VO) as liquid fuels. Even though the viscosity of VO is 50 times that of the water. The result shows that FB atomizer is less affected by the viscosity of fuels compared to AB atomizer.

4.2 Operating Parameter

Table 4-1 Compares Properties for VO (fully refined Soya bean- oil) with Water at room temperature. The viscosity of vegetable oil is nearly 50 times than water. The surface tension and density of VO are less than water. ALR 1.5 is considered for a fixed fuel flow rate 12mlpm for both VO and water spray. Effect of viscosity is studied on both Air-Blast atomizer and Flow-Blurring injector.

Table 4-1 Properties of Fuels and Air

Properties	VO	Water	Air
Density (kg/m3)	925	997	1.2
Kinematic Viscosity (m2/sec)	53.74 *1e-6	1.0034 * 1e-6	1..516* 1e-5
Dynamic Viscosity (Nsec/m2)	0.0497	0.001	1.825* 1e-5
Surface Tension (N/m)	0.03	0.072	
Refractive Index	1.47	1.33	1

4.3 Results and Discussion

4.3.1 Effect of Viscosity on characteristics of AB spray

SMD Distribution-

At Z=10mm

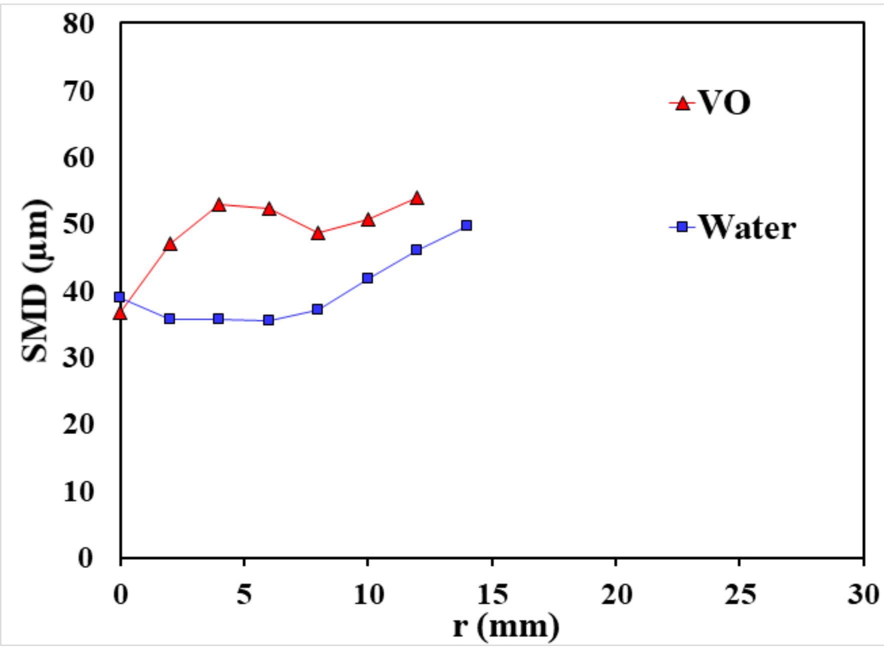


Figure 4-1 AB Atomizer -SMD variation for VO and Water spray at Z=10mm

Radial variation of Sauter Mean diameter for both vegetable oil and water sprays is shown in Figure 4-1at Z = 10 mm downstream of injector. At spray centre, SMD for VO spray is near 38µm and SMD for water spray is 40 µm. For VO spray, as going radially outward, SMD ranges from 39 µm to 57 µm. For water spray, as going radially outward, SMD decreases to nearly 37 µm is constant up to 6 mm from the centre and radially increases and reaches maximum up to 50 µm at the periphery of spray. It can be seen that SMD for VO spray is higher than water spray for every radial position except at centre. For fix ALR, there is a huge difference in SMD between sprays. This is due to the high viscous force which resists and delay droplet deformation in VO spray.

At Z=50mm

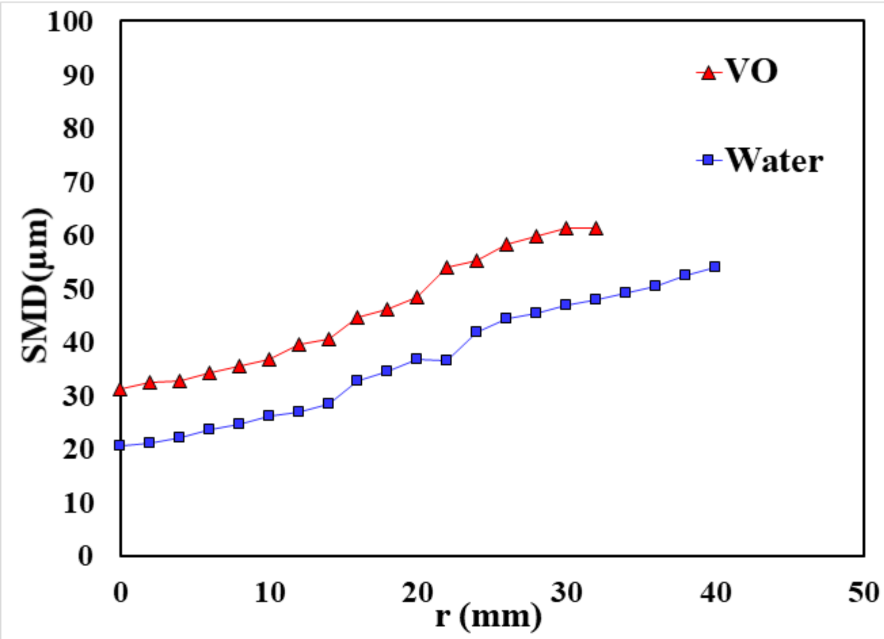


Figure 4-2 AB Atomizer -SMD variation for VO and Water sprays at Z=50mm

Radial variation of Sauter Mean diameter for both vegetable oil and water sprays at Z = 50 mm is shown in Figure 4-2. At Z = 50 mm spray centre, SMD for VO and water sprays are 30 µm and 20 µm respectively. As moving radially outward, SMD increases for both sprays due to centrifugal action, the swirling component of velocity pulling the bigger droplets radially outward. For VO spray, SMD is near 61µm maximum at the periphery of spray (32mm from the centre of spray), but for water spray, SMD is 53µm maximum at the edge of spray (40mm from the centre of spray). As we can see the radial span for water spray is more than VO spray. SMD for VO spray is always higher than water spray. This is due to the high viscous force which resists and delay droplet deformation in VO spray.

Centre line variation of SMD

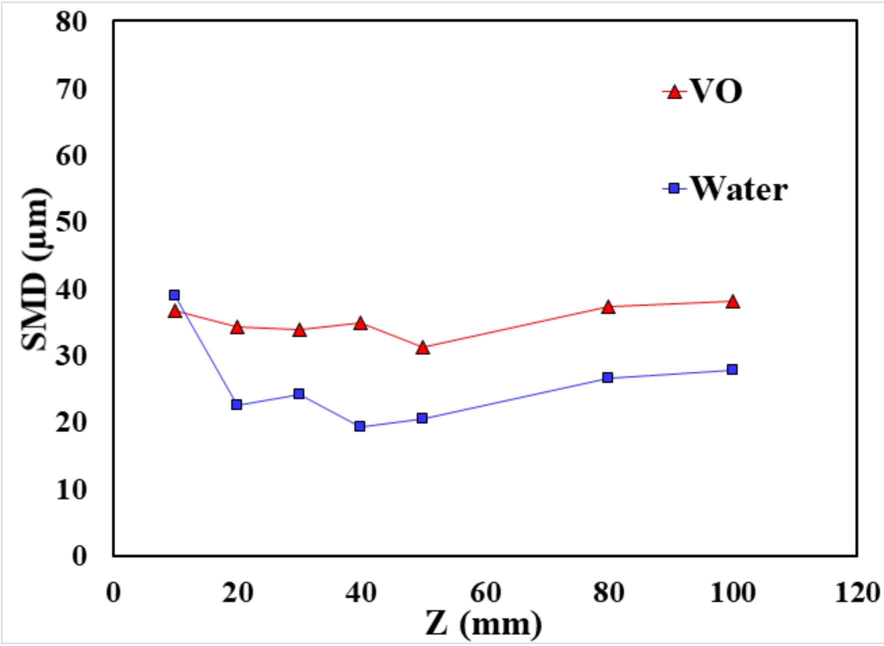


Figure 4-3 AB Atomizer - Centre line variation of SMD for VO and Water Sprays

Centre line variation of Sauter Mean Diameter for VO and water sprays are shown in Figure 4-3 at ALR 1.5. This variation showed at different axial locations, which is represented by Z in the figure. Near the injector at Z=10mm SMD is nearly 40µm for water spray and 37µm for VO spray. There is no significant difference in SMD for both sprays near the injector at Z=10mm. As moving downstream of the nozzle at Z=20mm, SMD decreases to 22µm for water spray and 34µm for VO spray. As going downstream of the injector from Z=50mm to Z=100mm SMD of droplets for both sprays increases, this may be due to collisions and coalescence of droplets. At every axial location, SMD for VO spray is much higher than water spray even though the same air flow rate is supplied; This is due to the high viscous force which resists and delay droplet deformation in VO spray.

Mean Axial Velocity Distribution

At Z=10mm

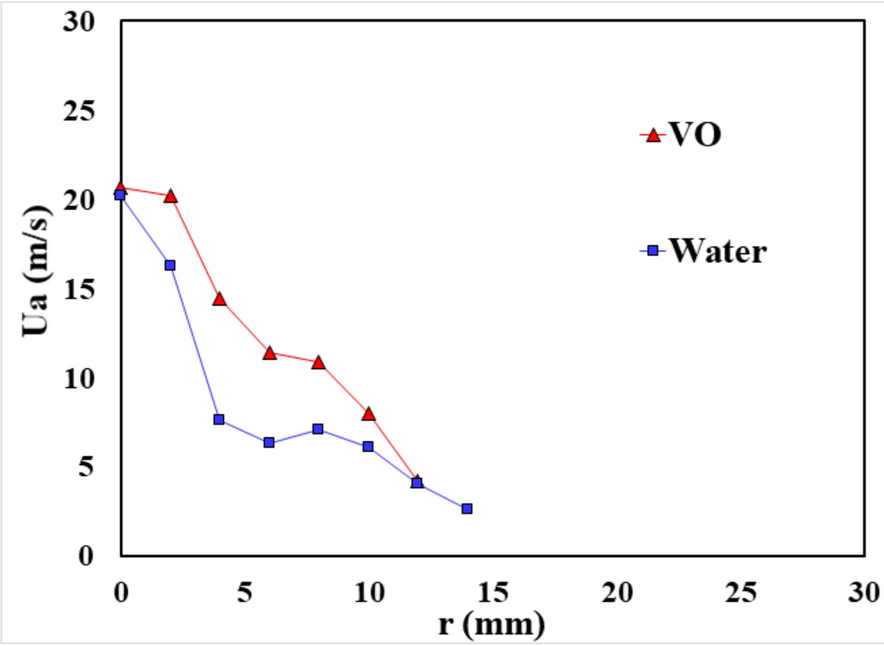


Figure 4-4 AB Atomizer- Mean Axial Velocity variation for VO and water Sprays at Z=10mm

Radial variation of mean axial velocity for both water and vegetable oil sprays is shown in Figure 4-4 at fixed ALR 1.5. Velocity is maximum at the centre and decreases continuously. At Z=10mm spray centre, mean axial velocity is maximum 21m/s for both water and VO sprays. Near the spray, axial momentum is dominant so mean axial velocity is higher. As going radial outward velocity of droplets decreases due to ambient air entrainment. Mean axial velocity of droplets for VO spray is higher than water spray except at centre. The radial span of VO spray is less than water spray So surface area of droplets in VO spray is less than water spray. To maintain the same mass flow rate, the velocity of droplets is higher in VO spray compared to water spray.

At Z=50mm

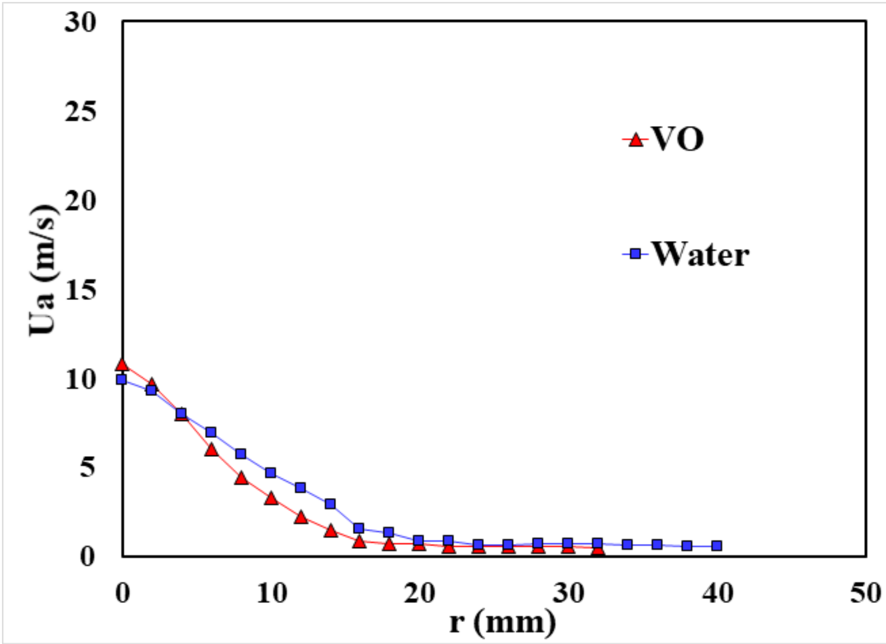


Figure 4-5 AB atomizer- Mean Axial Velocity variation for VO and water Sprays at Z=50mm

Figure 4-5 shows the radial distribution of the mean axial velocity of droplets at Z = 50 mm downstream of injector for both water and VO sprays. At Z = 50 mm centre of spray, mean axial velocity is 11 m/s and 10 m/s for VO and water spray respectively. Radial distribution of mean axial velocity looking like bell shape curve that peaks at the centre and radially decreases due to the interaction of lower momentum air. As moving radial outward mean axial velocity of water spray is more than VO spray up to Z = 18 mm, but the difference is not as much as like Z = 10 mm. At the periphery of sprays, there is no significant difference in mean axial velocity, and the radial spread of water spray is more than VO spray.

Centre line variation of Mean Axial Velocity

Centre line variation of Mean axial velocity for VO and water sprays are shown in Figure 4-6 at ALR 1.5. This variation showed at different axial locations, which is represented by Z in the figure. Near the injector at Z = 10 mm mean axial velocity is maximum near 21 m/s for water and VO sprays. As going downstream of the nozzle, mean axial velocity of both fuels sprays decreases continuously because the high momentum of droplets exchange with surrounding air reduces the droplets velocity. So Z = 100 mm Mean axial velocity reduces to 7m/s for both sprays. At Z = 20 mm downstream of injector, mean axial velocity is 17 m/s for VO spray and but for water spray mean axial velocity is 14 m/s which is less than VO spray. At axial locations, Z = 20 mm and Z = 30 mm mean axial velocity for VO spray is more than water spray. As moving further downstream of injector, there is no significant difference in mean axial velocity between water and VO sprays.

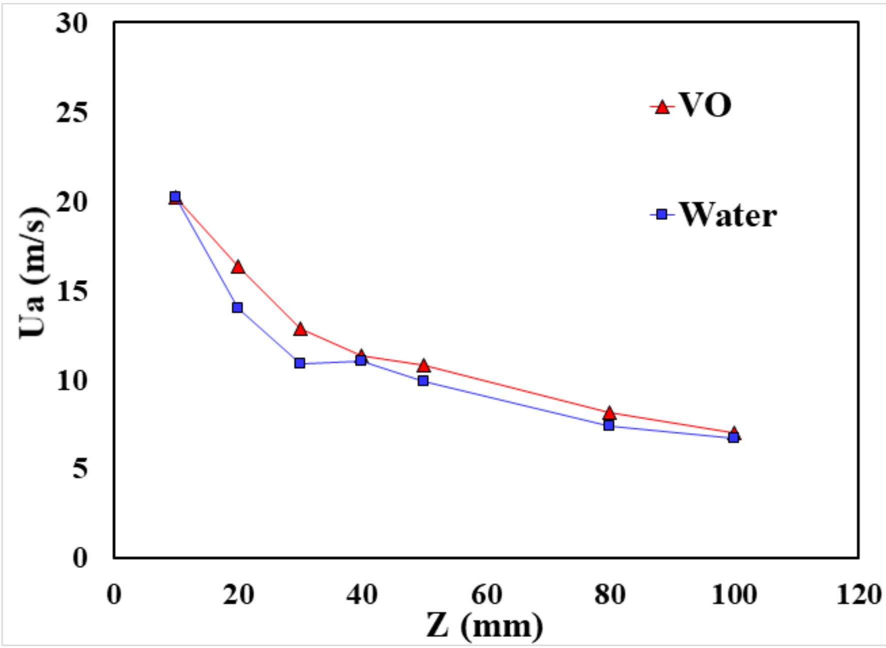


Figure 4-6 AB Atomizer - Centre line variation of Mean Axial Velocity for VO and Water Sprays

4.3.2 Effect of viscosity on characteristics of FB injector

Diameter Distribution

At Z=10mm

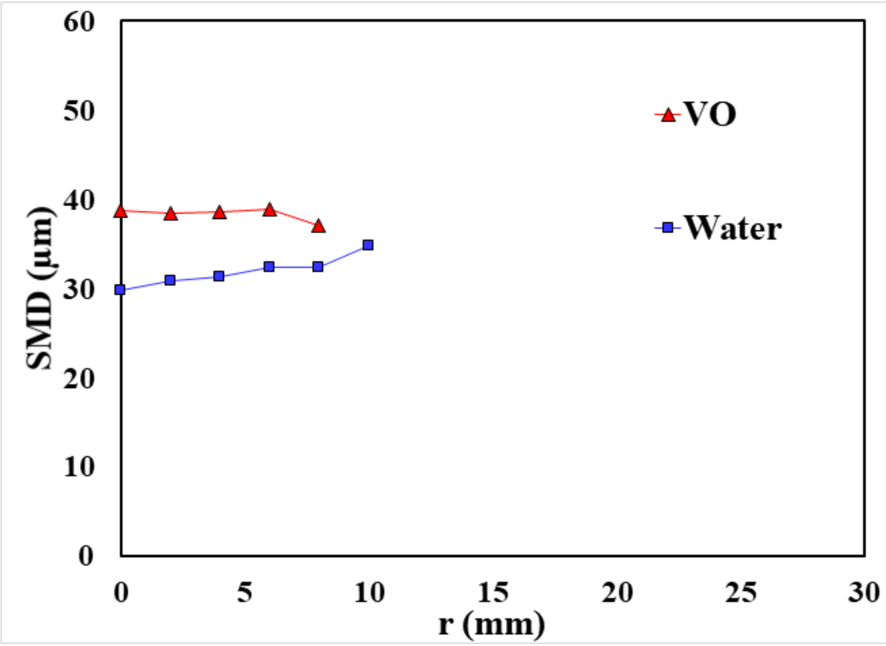


Figure 4-7 FB Atomizer - SMD variation for VO and Water Spray at Z=10mm

Radial variation of Sauter Mean diameter for both vegetable oil and water sprays is shown in Figure 4-7. Diameter distribution is shown at Z = 10 mm downstream of injector. At spray centre, SMD for VO and water spray is 39 µm and 30 µm, respectively. For VO spray, as going radially outward there is no significant difference in SMD of droplets. So at the periphery of spray SMD decreases to 37 µm. But for water spray as going radially outward, SMD increases to 34 µm at the edge of spray. Ranges of SMD for water spray is from 30 µm to 35 µm, and ranges for VO spray is from 39 µm to 37 µm. We can see SMD of droplets for VO spray is higher than water spray for every radial position. As going radially outward, SMD does not change FB injector. The difference in SMD is less compared. The difference in SMD between VO and water sprays is less in FB atomizer compared to AB atomizer.

At Z=50mm

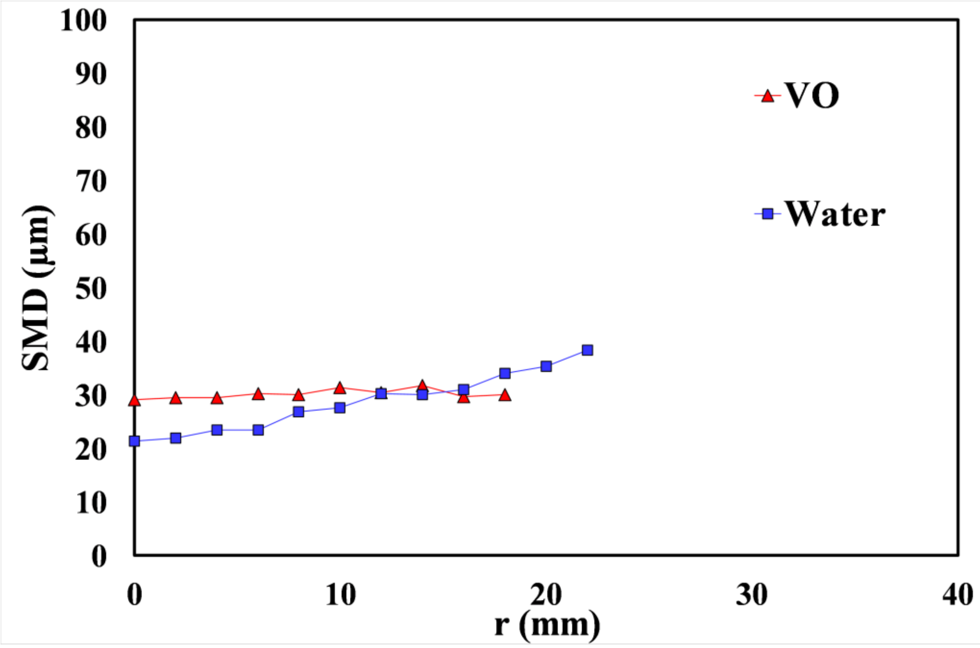


Figure 4-8 FB Atomizer - SMD variation for VO and Water spray at Z=50mm

Radial variation of Sauter Mean diameter for both vegetable oil and water sprays is shown in Figure 4-8. This diameter distribution is shown at Z = 50 mm downstream of injector. At spray centre, SMD for VO and water sprays are nearly 29µm and 21µm respectively, which is less than Z=10mm spray centre. SMD is observed to decrease as going downstream of injector. For VO spray, as going radially outward there is no significant difference in SMD of droplets. For water spray as going radially outward, SMD continuously increases and reaches to 38 µm at the periphery of spray. Near the injector SMD for VO spray is higher than water spray. As going radially outward, the difference in SMD decreases. The difference in SMD between VO and water sprays is less than in FB atomizer compared to AB atomizer, we can conclude this after comparing Figure 4-5 and Figure 4-8. Due to the proper mixing of fuel and air, FB produces small droplets in both VO and water spray. FB atomization is not affected by higher viscosity of VO fuel. Due to less viscosity of water, the radial span of water spray is more than VO spray.

Centre line variation of SMD

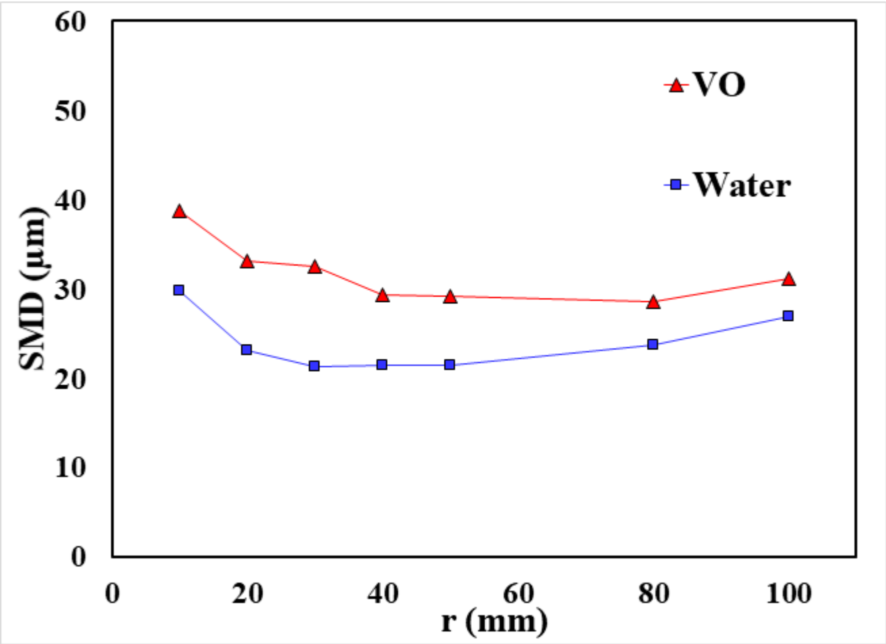


Figure 4-9 FB Atomizer - Centre line variation of SMD for VO and Water Sprays

Centre line variation of Sauter Mean Diameter for VO and water sprays are shown in Figure 4-9 at ALR 1.5. This variation showed at different axial locations, which represent by Z in the figure. Near the injector at Z=10mm SMD is near 39 µm for VO spray and 30 µm for water spray. As moving downstream of the nozzle at Z = 20 mm, SMD decreases to 33 µm for VO spray and 23 µm for water spray. As going downstream of the injector from Z = 50 mm to Z = 100 mm, SMD of droplets for both sprays increases, this may be due to collisions and coalescence of droplets, and small droplets merge and produce bigger droplets. At every axial location, SMD for VO spray is much higher than water spray even though the same air flow rate is supplied. This is because high viscosity force in VO opposes break up of droplets. So bigger droplets produced in VO spray compared to water spray. The difference in SMD of droplets of both fuel sprays is less at 80 mm and 100 mm downstream of the injector.

Mean Axial Velocity Distribution-

At Z=10mm

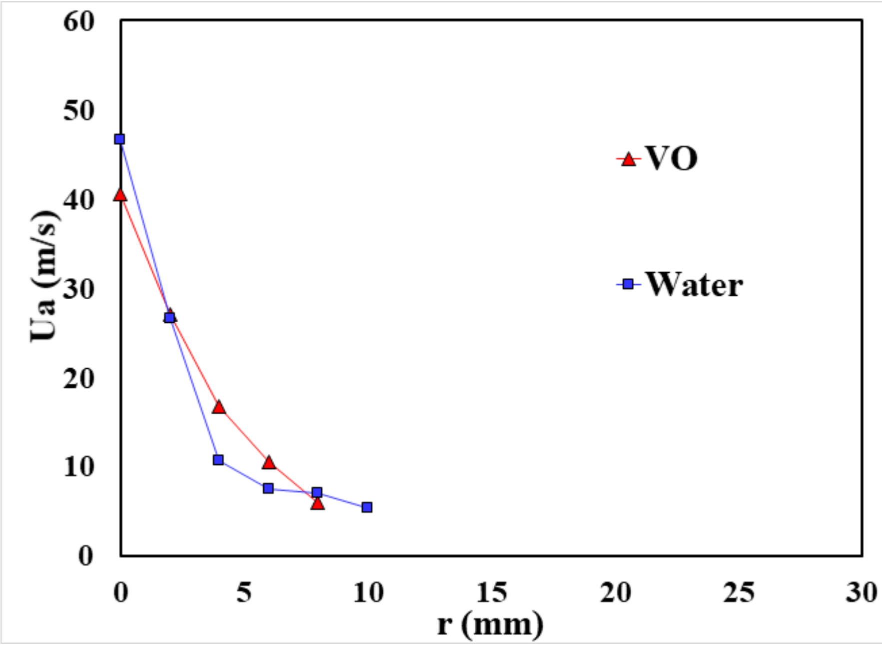


Figure 4-10 FB Atomizer - Mean Axial Velocity variation for VO and Water Sprays at Z=10mm

Radial variation of mean axial velocity for both vegetable oil and water sprays is shown in Figure 4-10. This diameter distribution is shown at Z = 10 mm downstream of injector. Velocity is maximum near 48 m/s and 41 m/s for water spray and VO spray respectively at spray centre. As going radial outward, velocity of droplets decreases due to the interaction of low momentum surrounding air. Near the spray centre, mean axial velocity of water spray is more than VO spray. As moving radially outward, mean axial velocity for VO spray is more than water spray. At radial location of 4 mm, mean axial velocity is 15 m/s and 11 m/s for VO spray and water spray respectively. The radial span of VO spray is less than water spray So surface area of droplets in VO spray is less than water spray. To maintain the same mass flow rate, the velocity of droplets is higher in VO spray compared to water spray, but the difference is not significant at the periphery of spray.

At Z=50mm

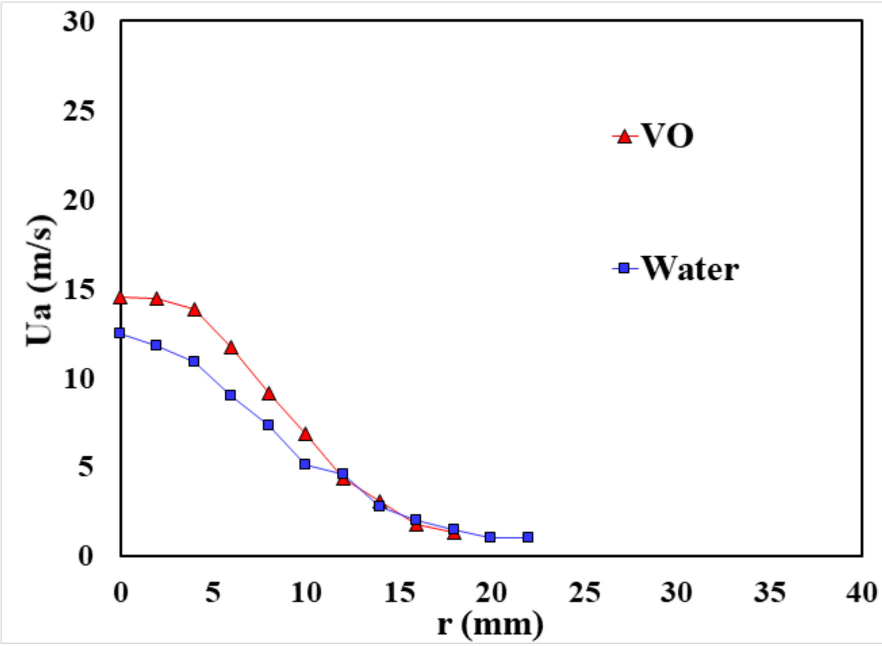


Figure 4-11 FB Atomizer - Mean Axial Velocity variation for VO and Water Sprays at Z=50mm

Radial variation of mean axial velocity for both vegetable oil and water sprays is shown in Figure 4-11. This diameter distribution is shown at Z = 50 mm downstream of injector. At spray centre, mean axial velocity is maximum near 14 m/s and 12 m/s for VO and water spray respectively. Mean axial velocity decreases at radilly outward locations due to entrainment of ambient air. Mean axial velocity of VO spray is more than water spray. The radial span of VO spray is less than water spray. So surface area of droplets in VO spray is less than water spray. To maintain the same mass flow rate, the velocity of droplets is higher in VO spray compared to water spray. The difference in mean axial velocity decreases at outer radial locations.

Centre line variation of Mean axial velocity

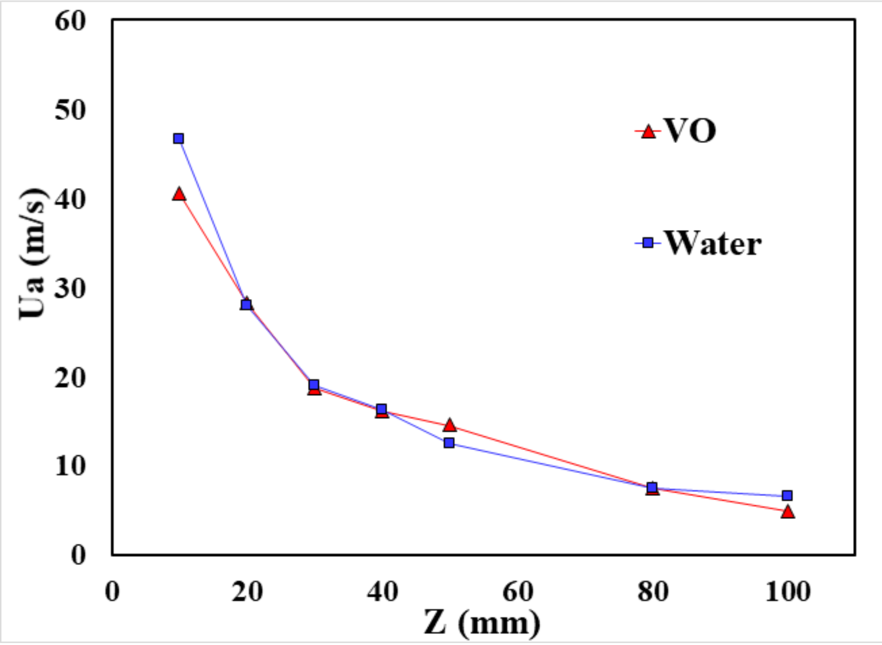


Figure 4-12 FB Atomizer - Centre line variation of Mean Axial Velocity for VO and Water Sprays

Centre line variation of Mean axial velocity for VO and water sprays are shown in Figure 4-12 at ALR 1.5. This variation showed at different axial locations, which represent by Z in the figure. Near the injector at Z = 10 mm mean axial velocity is maximum near 40 m/s for water spray and 46 m/s for VO sprays. As going downstream of the nozzle, Mean axial velocity of both fuels sprays decreases continuously because the high momentum of droplets exchange with surrounding air reduces the droplets velocity. So Z = 100 mm mean axial velocity reduces to 5 m/s for VO spray and 6 m/s for water spray. At Z=10mm downstream of injector, Mean axial velocity for water spray is more than VO spray As moving further downstream of the nozzle there is no significant difference in mean axial velocity between water and VO sprays. So viscosity of fuels does not affect the mean axial velocity of droplets in the flow-blurring injector.

4.4 Conclusions

In this chapter, non-reacting VO and water spray are compared for Air-blast and Flow-blurring atomizers. The viscosity of VO is around 50 times than water, but the surface tension of VO is less than water. Larger range of drop size is observed for high viscosity fuel compared to water. SMD difference between VO spray and water spray is far more in AB atomizer compared to FB atomizer. The radial span of high viscous fuel is less than water. Mean axial velocity is higher for high viscous fuel near the injector, but the difference is not observed at the periphery of sprays. FB atomization is less affected by the viscosity of fuels compared to AB atomization.

Chapter 5

Comparison of Air-Blast and Flow-Blurring Atomizer

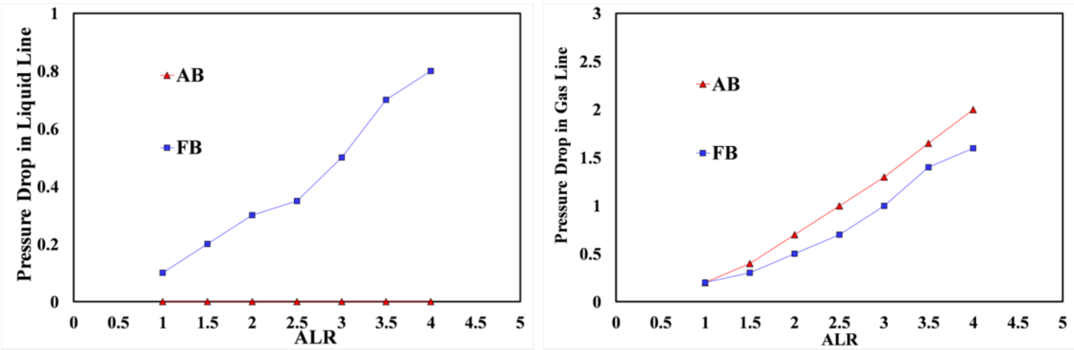
5.1 Background

In this section, spray characteristics like SMD and Mean axial velocity is compared using two different mechanics Air- Blast injector and Flow- Blurring injector. Simmons et al. [21] compared Air-blast and Flow-blurring injector for water spray using spray characteristics SMD, Mean axial velocity and RMS axial velocity. In this study Air-blast and Flow-blurring atomizer is compared for water spray and VO spray. Previous researches [11][18][19][24] claimed that FB atomizer creates 5 to 50 times more surface area than AB atomizer. Air-blast injector and Flow-blurring injector are compared for water spray and VO spray. Liquid flow rate and Air flow rate is taken constantly for maintaining fix ALR 1.5. Properties of fuels are given in Table 4-1. Operating Parameters are given in Table 2-2.

5.2 Water Spray

5.2.1 Pressure Drop Comparison

Figure 5-1 shows pressure drop comparison between Air-Blast injector and Flow-Blurring injector in the liquid line and gas line. As ALR increases, the Pressure drop in the gas line increases for both AB and FB injector. Pressure drop in the airline is always higher in AB atomizer compared to FB. Pressure drop in a liquid line is negligible in AB injector, the liquid flow rate in AB injector also contributed to increment in pressure drop in the gas line. So atomization happens in AB atomizer at expense of only atomizing air energy. In FB injector, As air flow rate increases pressure drop in the liquid line and airline continuously increases. So the interaction of air and liquid are different in both atomizers. In FB injector spray starts coming out when required supply pressure is reached in the liquid line, so proper mixing of air and liquid takes place inside the injector.



Liquid Line **Air Line**

Figure 5-1 Pressure drop comparison in liquid and airline

5.2.2 SMD Distribution

At Z=10mm

Figure 5-2 shows the SMD variation of Air-Blast and Flow-Blurring injectors at Z = 10 mm downstream of the nozzle. For AB injector SMD is near 39 µm at centreline and SMD decreased to 35 µm (6 mm from centre) then SMD uniformly increased to near 50 µm at the periphery of spray (14 mm from centre). For FB injector SMD is near 30 µm minimum at the centre of spray and radially increases to a 35 µm maximum at the periphery of spray (10 mm from centre). FB atomizer produces droplets within a narrow range of 5 µm. At every radial location, SMD is higher for AB atomizer than FB atomizer. AB atomizer has wider spray and higher range of droplet diameter compared to FB atomizer. This is because in AB atomizer primary atomization occurs near the injector so bigger droplets are there near the AB atomizer., But in FB atomizer, vigorous mixing of fuel and air takes place at the tip of liquid fuel tip, so primary atomization takes place inside the nozzle only; secondary atomization takes place after leaving the injector, So FB atomizer produces smaller droplets compared to AB.

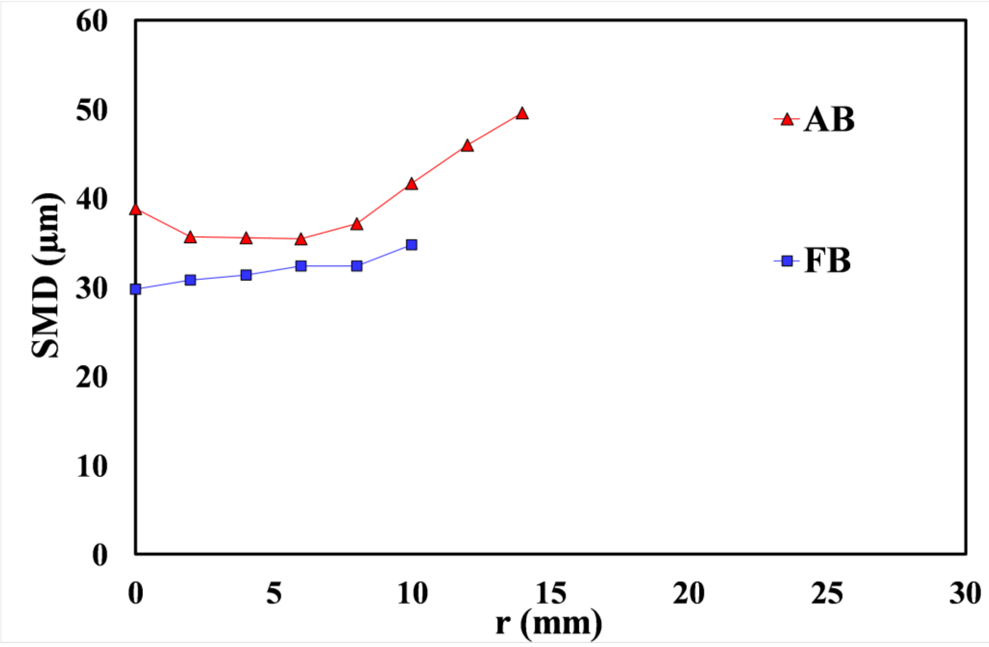


Figure 5-2 Water Spray - SMD variation for AB and FB atomizers at Z=10mm

At Z=50mm

Figure 5-3 shows the SMD variation of Air-Blast and Flow-Blurring injectors at Z=50mm downstream of the nozzle. For AB and FB injector SMD is 20 µm and 21 µm respectively at centreline of spray. SMD radially increases monotonically to 40 µm for FB atomizer and 48 µm for AB atomizer at the periphery of sprays. AB atomizer has wider spray than FB atomizer. At this axial location, there is no significant difference in SMD between atomizers. However, for AB injector larger droplets at the radially outer locations are observed, where FB spray is not detected as its radial extent is smaller than than AB injector. Similar values of SMD at common radial locations can be attributed to significant secondary atomization prior to this axial location at downstream region.

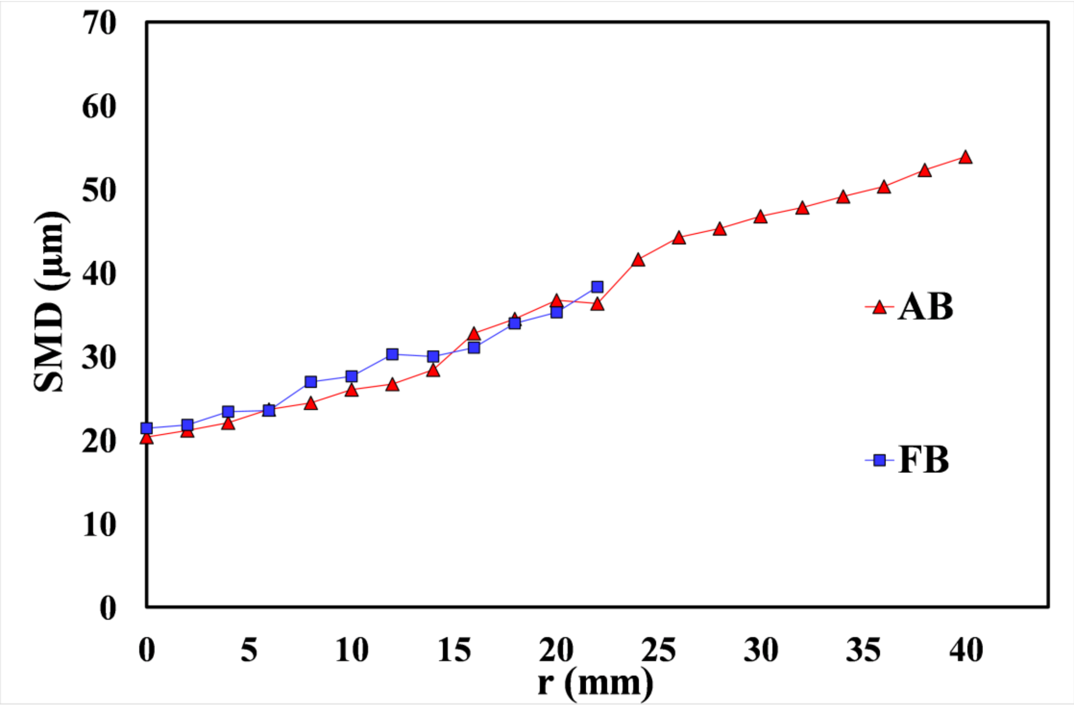


Figure 5-3 Water Spray - SMD variation for AB and FB atomizers at Z=50mm

5.2.3 Mean Axial Velocity Distribution

At Z=10mm

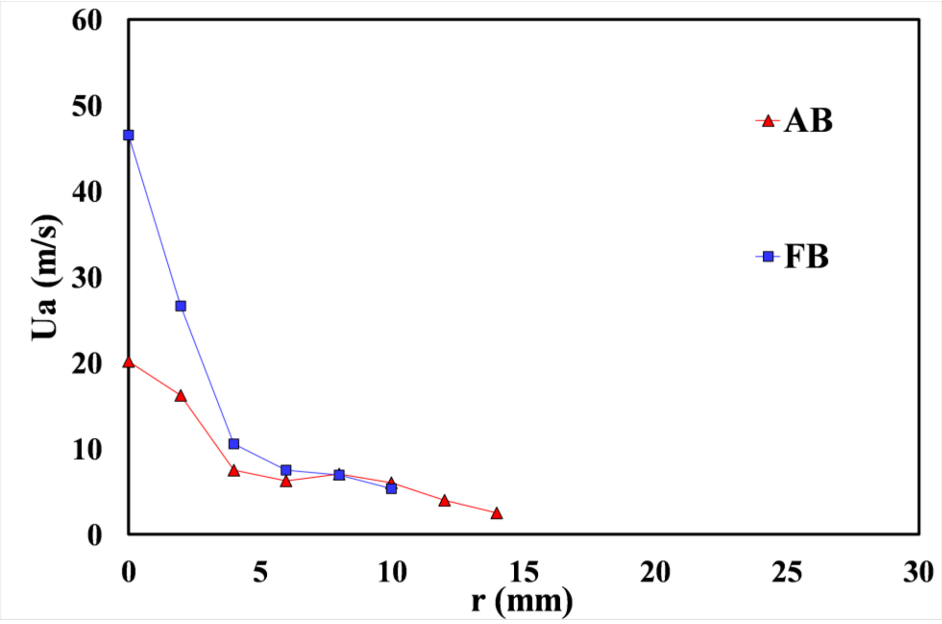


Figure 5-4 Water Spray- Mean Axial Velocity variation for AB and FB atomizers at Z=10mm

Figure 5-4 shows the radial variation of mean axial velocity for AB and FB atomizers at 10mm axial location (near the injector). Radial variation looks like Gaussian distribution in which velocity is maximum at the centre of spray and radially decreases. For FB injector there is a sudden drop in mean axial velocity due to high turbulent mixing near the nozzle (up to 4 mm from centre). At the centre of spray mean axial velocity is near 48 µm and 20 µm respectively for FB and AB injectors. Near the nozzle, there is a considerable difference in mean axial velocity, but as moving radially outward; the difference in mean axial velocity decreases. Mean axial velocity for FB injector is higher than for AB injector. Because of FB atomizer working mechanics, shorter mixing area available in the atomizer. FB atomizer produces a dominant axial flow while AB atomizer transfer liquid momentum in radial and tangential direction due to swirler in AB atomizer. So FB atomizer produces a high axial velocity of droplets compared to AB atomizer.

At Z=50mm

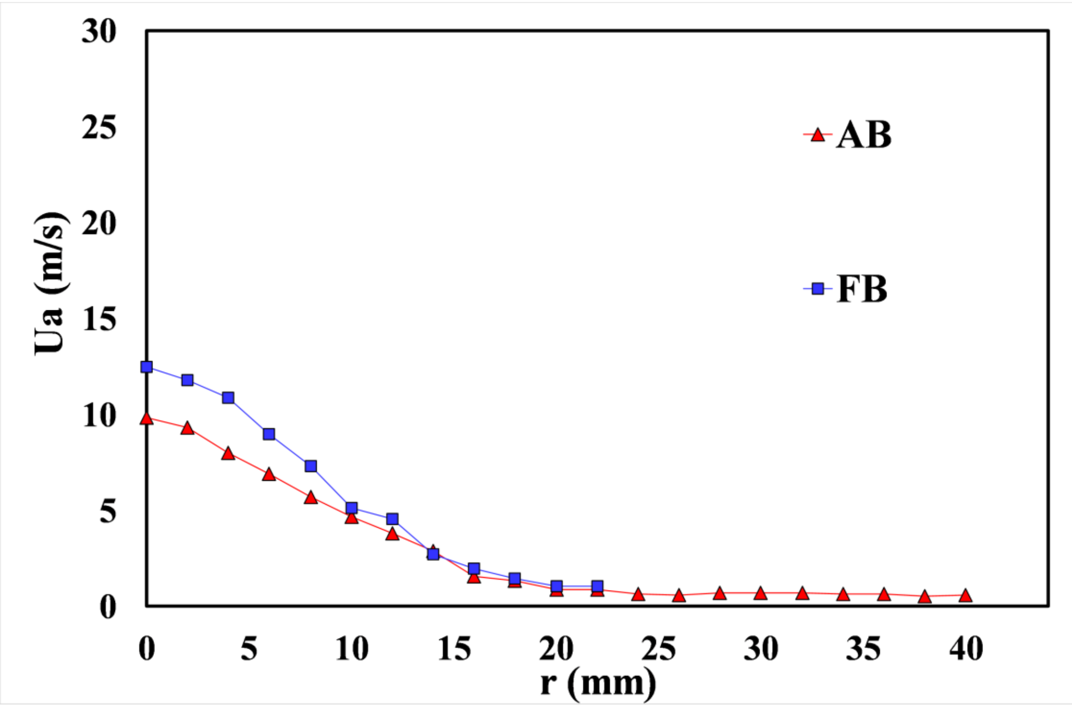


Figure 5-5 Water Spray- Mean Axial Velocity variation for AB and FB atomizers at Z=50mm

Figure 5-5 shows the radial variation of mean axial velocity for AB and FB atomizers at Z = 50mm downstream of injector. Radial variation is like Gaussian distribution in which velocity is maximum at the centre of spray and radially decreases as going radially outward.

At the centre of spray mean axial velocity is near 13 m/s and 9 m/s respectively for FB and AB injector. Near the centre of spray, there is still a huge difference in mean axial velocity, but difference decreases as going radially outward, so there is no difference in mean axial velocity at the periphery of sprays. Mean axial velocity is higher for FB atomizer compared to AB atomizer. Due to dominant axial flow in FB atomizer while AB atomizer transfer liquid momentum in the tangential and radial direction due to swirler. The difference in mean axial velocity is not much as we observed at Z = 10mm downstream of injector.

5.2.4 RMS Axial Velocity Distribution

At Z=10mm

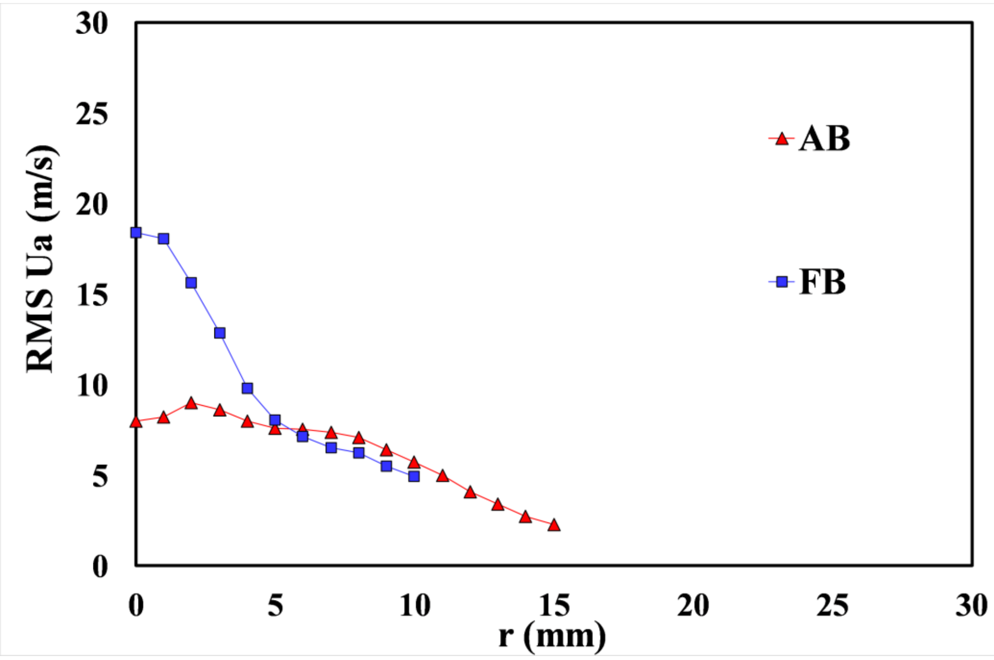


Figure 5-6 Water Spray- RMS Axial Velocity variation for AB and FB atomizers at Z=10mm

Figure 5-6 shows the radial variation of RMS axial velocity for AB and FB atomizers at Z=10mm downstream of injector. RMS axial velocity has a peak of 18 m/s at the centre for FB atomizer and 10 m/s at the 3mm from centre of spray and decreases as going radially outward. High RMS axial velocity in FB atomizer can be caused by vigorous turbulent mixing inside the atomizer. So FB atomizer has high turbulent mixing near the injector compared to AB atomizer. At the periphery of spray difference in RMS axial velocity decreases.

At Z=50mm

Figure 5-7 shows the radial variation of RMS axial velocity for AB and FB atomizers. As going downstream of the injector at Z=50mm RMS axial velocity decreases to 6m/s at the centre for FB atomizer and 3m/s at the centre for AB atomizer. There is less turbulent mixing downstream of injector compared to near the injector as going radially outward mean axial velocity decreases. FB atomizer has high RMS axial velocity at all radial location compared to AB atomizer. This is due to high turbulent mixing available inside the FB atomizer. AB atomizer has a peak of 3m/s at the centre and decreases to 1m/s at the periphery. So RMS axial velocity has a flatter profile at this axial location.

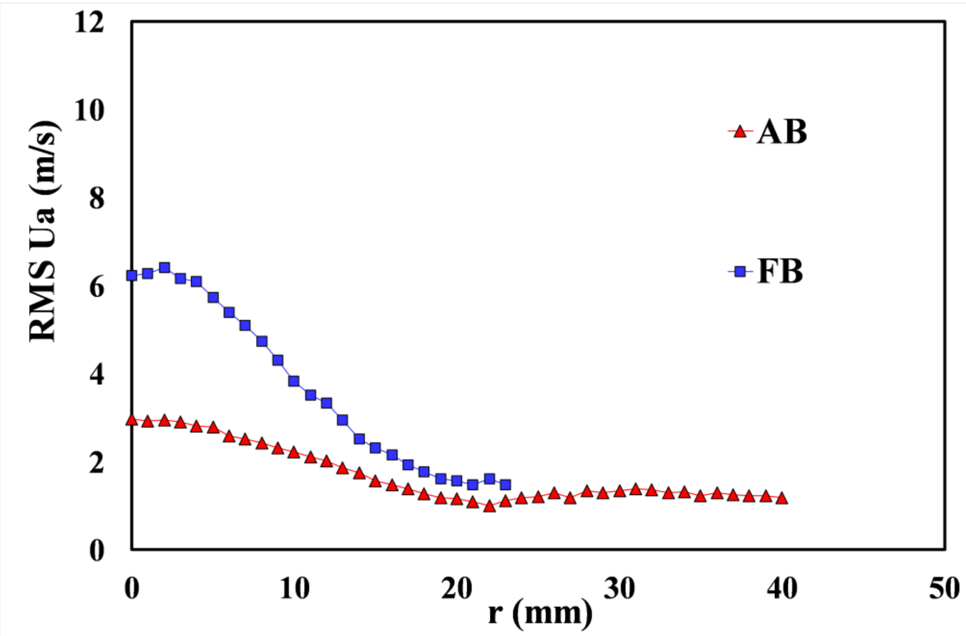


Figure 5-7 Water Spray- RMS Axial Velocity variation for AB and FB atomizers at Z=50mm

5.3 For VO Spray

5.3.1 SMD Distribution

At Z=10mm

Figure 5-8 shows the SMD variation of VO spray for Air-Blast and Flow-Blurring injectors at Z=10 mm downstream of the nozzle for VO fuel spray. At the centre of sprays, SMD is nearly 37 µm and 39 µm respectively for AB and FB injector. As going radially outward, SMD increases to 54 µm at the periphery of spray for AB atomizer, but there is variation in SMD at the edge of spray due to ongoing secondary atomization process. This is due to swirler in AB atomizer. But FB atomizer produces droplets within narrow range 39 µm to 37 µm. So FB atomizer produces smaller droplets compared to AB atomizer. FB atomizer is more useful to atomize highly viscous fuel VO compared to AB atomizer.

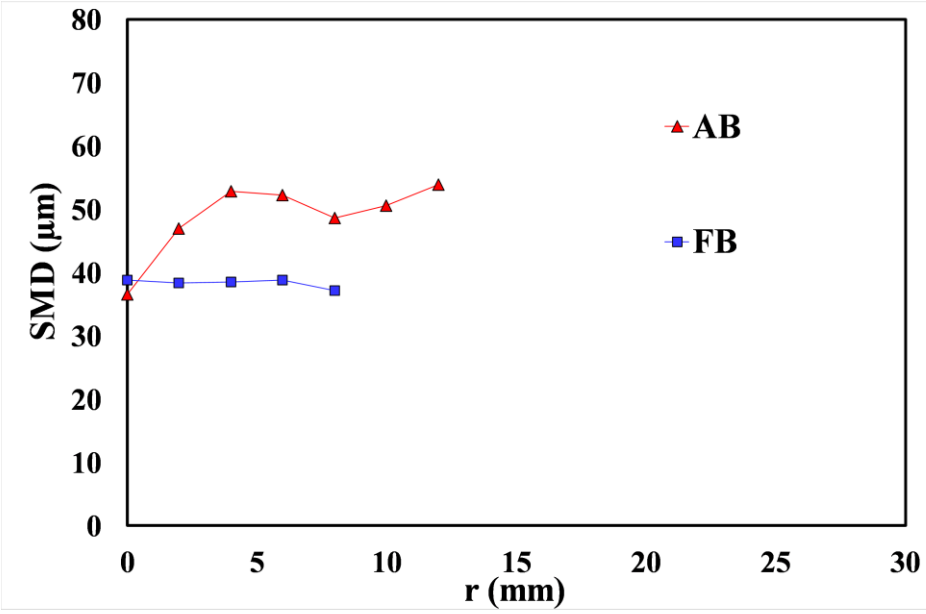


Figure 5-8 VO Spray - SMD variation for AB and FB Atomizers at Z=10mm

At Z=50mm

Figure 5-9 shows the SMD variation of VO spray for Air-Blast and Flow-Blurring injectors at Z=50mm downstream of the nozzle for VO fuel spray. At this axial location, SMD is less compared to 10mm downstream of injector. At Z=50mm centre of sprays, SMD is nearly 29 µm and 30 µm respectively for FB and AB injector. For AB injector, minimum diameter is at the centre of spray, as going radially outward SMD increases monotonically to 61 µm at the periphery of spray (32 mm from centre) because centrifugal force throwing the bigger droplets radially outward. FB injector produces droplets still in a very narrow range from 29 µm to 31 µm, as going radially outward no significant variation is observed in SMD. At every radial position, FB atomizer produces a larger number of smaller droplets compared to AB atomizer. FB atomizer is more useful to atomize highly viscous fuel compared to AB atomizer. This is due to the mechanics of FB atomizer, in which high mixing of liquid and air is available, which atomize spray more effectively compared to AB atomizer.

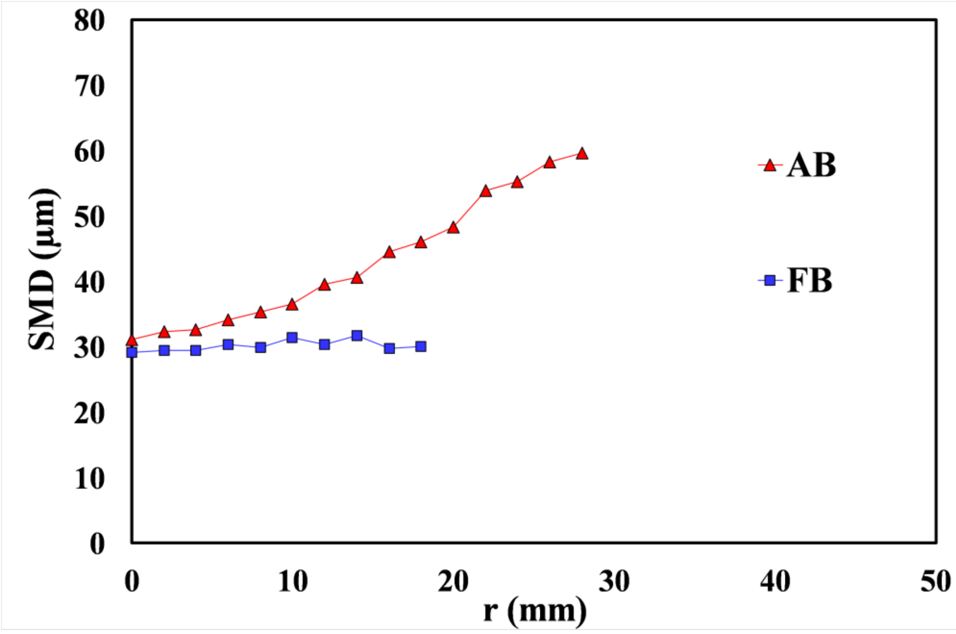


Figure 5-9 VO Spray - SMD variation for AB and FB Atomizers at Z=50mm

5.3.2 Mean Axial Velocity Distribution

At Z=10mm

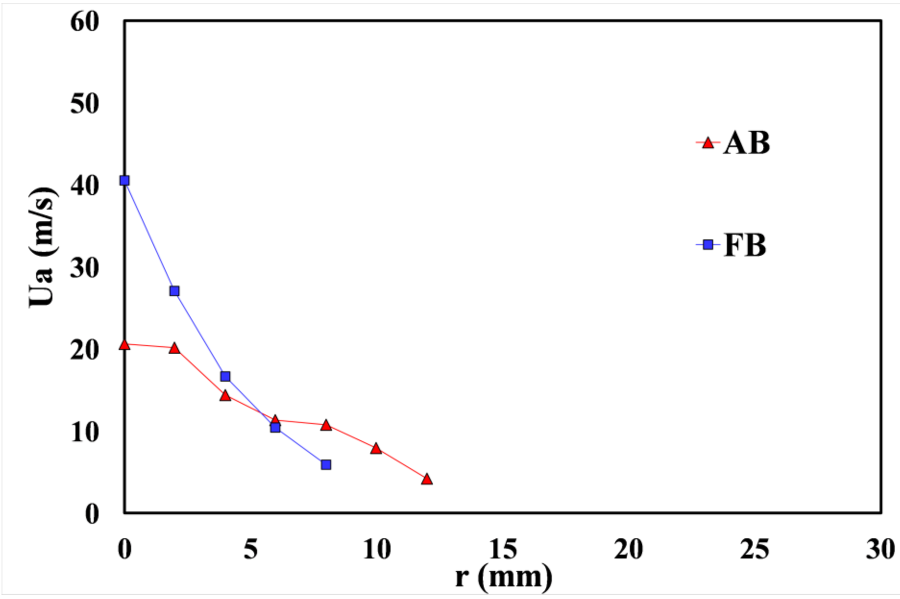


Figure 5-10 VO Spray - Mean Axial Velocity variation for AB and FB Atomizers at 10mm

Figure 5-10 shows the radial variation of mean axial velocity of VO sprays for AB and FB atomizers at 10 mm axial location (near the injector). Velocity distribution is like Gaussian distribution. Mean axial velocity is maximum near 41 m/s and 20 m/s respectively for FB and AB injectors at the centre of spray. As going radially outward Mean axial velocity decreases. In FB injector there is a sudden drop in mean axial velocity near the spray. Mean axial velocity is higher for FB injector compared to AB injector, which could be attributed to higher momentum exchange between atomizing air and liquid during internal two phase flow creation for FB atomizer.

At Z=50mm

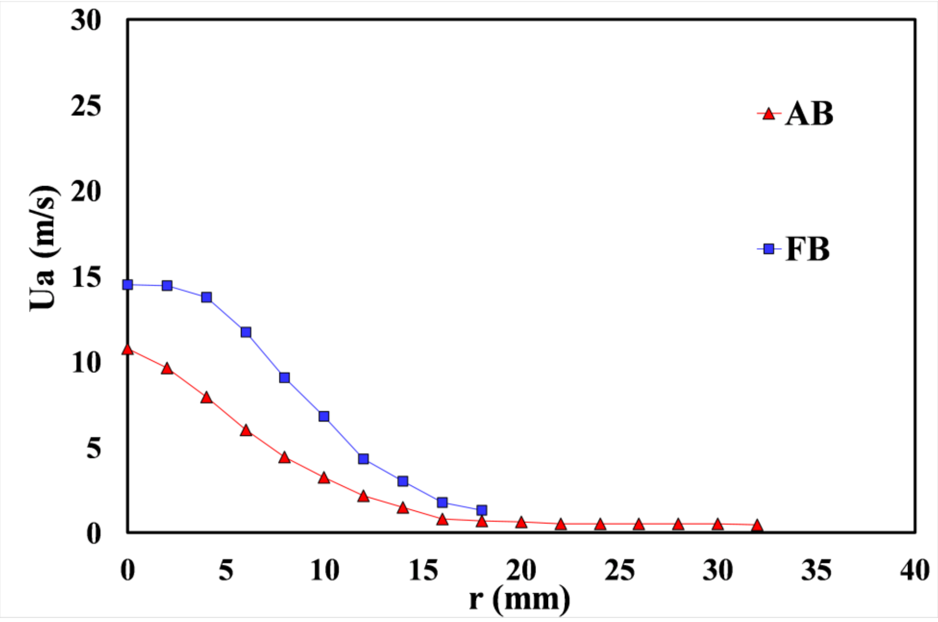


Figure 5-11 VO Spray - Mean Axial Velocity variation for AB and FB Atomizers at Z=50mm

Figure 5-11 shows the radial variation of mean axial velocity of VO sprays for AB and FB atomizers at 50 mm downstream of injector. At the centre of spray velocity of droplets are maximum near 14 m/s and 11 m/s respectively for FB and AB atomizers. Mean axial velocity decreases as going radially outward. Mean axial velocity of droplets is higher for FB atomizer compared to AB atomizer. The difference in velocity is higher near the centre of spray, and the difference in Mean axial velocity decreases as going radially outward. Note that the pressure drop in liquid line is larger for the FB atomizer and would contribute to the higher axial velocities with additional momentum gain in the internal two phase flow mixing.

5.4 Conclusions

Spray characteristics of Air-blast atomizer and Flow-blurring atomizer are compared using water and VO as liquid fuels. The results show that Flow-blurring atomizer produces sprays with a smaller range of droplets compared to Air-blast atomizer. FB atomizer produces sprays with a narrower range of droplet sizes compared to AB atomizer. So FB atomizer creates more surface area to volume ratio compared to AB. FB atomizer produces sprays having a high mean axial velocity of droplets compared to AB atomizer, but the difference is negligible at the periphery of spray. Due to swirling action, the radial span of AB spray is more compared to FB spray.

Chapter 6

Conclusions and Future Scope

This study characterizes the spray of Air-blast and Flow-blurring injector using conventional statistics as well as exploring alternate statistics for diameter and velocity of droplets. Effect of viscosity on AB and FB atomization is studied using non-reacting VO and Water Sprays. Air-blast and Flow-blurring atomizers are compared with each other using water and VO as the working fluids. From the present work, the following conclusions can be drawn.

1) The volume weighted diameter and velocity provide better description of bulk of liquid atomized.
2) In Air-blast atomizer, SMD value is minimum at the centreline of the spray and increasing towards the edge of the spray. Larger droplets are observed towards the periphery of the spray. This is due to the centrifugal action generated due to swirler pulling the bigger droplet towards the outer side. The centreline SMD value decreasing to its minimum and then start increasing continuously towards downstream from the exit of injector.
3) The axial velocity profile shows the heacy tailed bell shape curve distribution along the radius. Its value is maximum at the centre of the spray and gradually decreasing towards the periphery of the spray. The centreline axial velocity is also gradually decreasing having a maximum value near the exit of the injector.
4) With increasing ALR, droplet diameter decreases due to high aerodynamic force. So Atomization improves by increasing the ALR.
5) With increasing ALR, the mean axial velocity of droplets increases due to high-pressure drop in the injector.
6) In Air-blast atomizer, as ALR increases the pressure drop in airline increases but pressure drop in liquid line is negligible, so atomization happens only the expense of air energy.

7) In FB atomizer, Atomization happens expense of both liquid energy and air energy. With increasing ALR, pressure drop in the airline and liquid line both increases
8) The self-similar plot gives a suggestion that up to what extent the experiment needs to be carried out.
9) Less viscous fuel has more radial span compared to highly viscous fuel.
10) Larger range of drop sizes is observed for high viscosity fuel compared to water.
11) Mean axial velocity is higher for high viscous fuel near the injector, but the difference is not observed at the periphery of sprays.
12) Due to the vigorous mixing of fuel and air at the tip of the liquid tube in FB atomizer, so it is capable of atomizing high viscous fuel more effectively.
13) SMD difference between VO spray and water spray is far more in AB atomizer compared to FB atomizer. So FB atomization is less affected by the viscosity of fuels compared to AB atomization.
14) Flow-blurring atomizer produces sprays with a limited range of droplet sizes compared to Air-blast atomizer.
15) FB atomizer produces sprays having high mean axial velocity compared to AB atomizer, but the difference is negligible at the periphery of spray.
16) The pressure drop in the airline is more in AB atomizer compared to FB atomizer.
17) The spray cone angle is relatively insensitive to ALR in FB atomizer compared to AB atomizer.
18) Due to swirling action, the radial span for AB spray is more compared to FB spray.

Future Scope

1) Preheating of Fuel can be done for effective atomization in AB and FB atomizer.
2) Planar measurement of droplet size and velocity using Particle Imaging Velocimetry (PIV) and Interferometric Laser Imaging Droplet Sizing (ILIDS) technique.

References

[1] Rizk, N. K., & Lefebvre, A. H. (1984). Spray characteristics of plain-jet airblast atomizers. Journal of engineering for gas turbines and power, 106(3), 634-638.A. J. Bard and L. R. Faulkner. Electrochemical Methods Fundamentals and Applications. 2nd edition. John Wiley & Sons, 2001.

[2] Chong, C. T., & Hochgreb, S. (2014). Spray characteristics of an internal-mix airblast atomizer. In Applied Mechanics and Materials (Vol. 629, pp. 125-130). Trans Tech Publications.

[3] Bachalo, W. D., & Houser, M. J. (1984). Phase/Doppler spray analyzer for simultaneous measurements of drop size and velocity distributions. Optical Engineering, 23(5), 235583.

[4] Lorenzetto, G. E., & Lefebvre, A. H. (1977). Measurements of drop size on a plain-jet airblast atomizer. AIAA journal, 15(7), 1006-1010..

[5] Santolaya, J. L., Aisa, L. A., Calvo, E., García, I., & Cerecedo, L. M. (2007). Experimental study of near-field flow structure in hollow cone pressure swirl sprays. Journal of propulsion and power, 23(2), 382-389.

[6] Roudini, M., & Wozniak, G. (2018). Experimental Investigation of Spray Characteristics of Pre-filming Air-blast Atomizers. Journal of Applied Fluid Mechanics, 11(6), 1455-1469.

[7] Liu, H. F., Gong, X., Li, W. F., Wang, F. C., & Yu, Z. H. (2006). Prediction of droplet size distribution in sprays of prefilming air-blast atomizers. Chemical engineering science, 61(6), 1741-1747.

[8] Kumara Gurubaran, R., Sujith, R. I., & Chakravarthy, S. R. (2008). Characterization of a prefilming airblast atomizer in a strong swirl flow field. Journal of Propulsion and Power, 24(5), 1124-1132.

[9] Kulkarni, A. P., & Deshmukh, D. (2017). Spatial drop-sizing in airblast atomization−an experimental study. Atomization and Sprays, 27(11).

[10] Lefebvre, A. H. (1998). Gas turbine combustion. CRC press.

[11] Gañán-Calvo, A. M. (2005). Enhanced liquid atomization: From flow-focusing to flow-blurring. Applied Physics Letters, 86(21), 214101.

[12] Panchasara, H. V., Sequera, D. E., Schreiber, W. C., & Agrawal, A. K. (2009). Emissions reductions in diesel and kerosene flames using a novel fuel injector. Journal of Propulsion and Power, 25(4), 984-987.

[13] Fisher, B. T., Weismiller, M. R., Tuttle, S. G., & Hinnant, K. M. (2018). Effects of fluid properties on spray characteristics of a flow-blurring atomizer. Journal of Engineering for Gas Turbines and Power, 140(4), 041511.

[14] de Azevedo, C. G., de Souza Costa, F., & da Silva Couto, H. (2011). Initial Study of a Blurry Injector for Biofuel. Bibdigital. Sid. Inpe. Br, 1-10.

[15] Pilch, M., & Erdman, C. A. (1987). Use of breakup time data and velocity history data to predict the maximum size of stable fragments for the acceleration-induced breakup of a liquid drop. International journal of multiphase flow, 13(6), 741-757.

[16] Guildenbecher, D. R., López-Rivera, C., & Sojka, P. E. (2009). Secondary atomization. Experiments in Fluids, 46(3), 371.

[17] Dumouchel, C., (2008). On the experimental investigation on primary atomization of liquid streams. Experiments in fluids, 45(3), 371-422.

[18] de Azevedo, C. G., de Souza Costa, F., & da Silva Couto, H. (2010). Initial development of a blurry injector for biofuels.

[19] Jiang, L., & Agrawal, A. K. (2015). Spray features in the near field of a flow-blurring injector investigated by high-speed visualization and time-resolved PIV. *Experiments in Fluids*, *56*(5), 103.

[20] Panchasara, H. V., Sequera, D. E., Schreiber, W. C., & Agrawal, A. K. (2009). Emissions reductions in diesel and kerosene flames using a novel fuel injector. Journal of Propulsion and Power, 25(4), 984-987.

[21] Simmons, B. M., Panchasara, H. V., & Agrawal, A. K. (2009, January). A comparison of air-blast and flow-blurring injectors using phase Doppler particle analyzer technique. In ASME Turbo Expo 2009: Power for Land, Sea, and Air (pp. 981-992). American Society of Mechanical Engineers.'

[22] Jedelsky, J., & Jicha, M. (2013). Energy conversion during effervescent atomization. Fuel, 111, 836-844.

[23] Pozarlik, A. K., Bouma, W., Ratering, M., & Brem, G. (2017, October). Flow blurring atomization for combustion of viscous (bio) fuels. In Combura Symposium 2017.

[24] Jiang, L., Agrawal, A. K., & Taylor, R. P. (2014). Clean combustion of different liquid fuels using a novel injector. Experimental Thermal and Fluid Science, 57, 275-284.

[25] Akinyemi, Oladapo & Jiang, Lulin. (2018). Effect of Fuel Properties and Atomizing Air to Liquid Ratio on Combustion Performance of a Novel Twin-Fluid Injector.

[26] Araneo, L., Soare, V., Payri, R., & Shakal, J. (2006). Setting up a PDPA system for measurements in a Diesel spray. In Journal of Physics: Conference Series (Vol. 45, No. 1, p. 85). IOP Publishing.

[27] Gad, H. M., Ibrahim, I. A., Abdel-Baky, M. E., El-samed, A. A., & Farag, T. M. (2018). Experimental study of diesel fuel atomization performance of air blast atomizer. Experimental Thermal and Fluid Science, 99, 211-218.