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MICROSCOPIC SPRAY CHARACTERISTICS FROM A MULTI-HOLE PORT FUEL INJECTOR USING OPTICAL DIAGNOSTIC TECHNIQUE

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Abstract. *The spray structure of the fuel injectors of internal combustion engine have been widely studied by researchers around the world in order to reduce the greenhouse gases and introduce the use of environmentally friendly fuels, such as the case of ethanol. In the present work, experiments were performed with the purpose of investigating the atomization process of an internal combustion engine pressure-swirl atomizer. The bio-fuel ethanol, Brazilian standard gasoline type C and E50 (50% ethanol, 50% gasoline in volume) were used as test fluids. Phase Doppler Anemometry was used to measure the atomization parameters, such as: droplets mean diameter, droplet size distributions and droplet velocities. The measurements were taken 25 mm downstream from the injector tip along the axis with 0.3 MPa injection pressure and pulse-width of 5.9 ms. The droplets mean diameter were expressed in terms of Sauter Mean Diameter (SMD). The results showed that SMD remained insensitive to the different tested fuels. On the other hand, the droplet spray distributions and droplet velocities have had a slight variation.*

Keywords: *atomization, ethanol, ethanol-gasoline blend, gasoline, multi-hole port fuel injector.*

1. INTRODUCTION

Nowadays, the increasing use of renewable and environmentally friendly fuels has occurred around the world in order to replace the fossil fuels. One of these renewable fuels is ethanol, which has been widely used as blends with conventional fuels in various proportions. In some countries, such as Brazil, ethanol is used in the internal combustion engine (ICE) of vehicles both as an alternative fuel and in blends with gasoline.

Currently, there are two different types of injection systems used in the ICE: the port fuel injection (PFI) and the gasoline direct injection (GDI). Focusing on the world automotive scene, the vast majority fuel injectors used in the ICE is the PFI injector (Anand *et al.*, 2012). The spray structure from PFI injectors is completely different from that of GDI injectors because the injection pressures and injector geometries are very different. In the PFI systems, the injection pressure is low (0.2-0.6 MPa), its fuel injection happens outside of combustion chamber and typically involve plate type injectors. On the other hand, the GDI systems work with high injection pressure (up to 2 MPa), the fuel is injected into the combustion chamber and usually involve hollow cone sprays, as Anand *et al.* (2012) pointed out.

In order to characterize and improve the atomization process of automotive injection systems, researches have been carried out to understand the physics of macroscopic and microscopic sprays. The main goal of these researches is to reduce the fuel consumption and pollutant emissions and increase engine efficiency. The macroscopic and microscopic sprays characteristics are composed by important parameters such as: droplet size distributions, droplets mean diameter, droplet velocity, spray tip penetration and spray cone angle. These parameters influence the air-fuel mixture and the combustion process and thus the engine combustion efficiency.

A great amount of researchers have studied the macroscopic and microscopic sprays characteristics of both GDI and PFI systems. Researches in GDI systems include, for instance, Aleiferis *et al.* (2010), which varied the injection temperature (20-120 ^oC) and pressure (0.05-0.1 MPa) of gasoline and ethanol-gasoline blends, found out that SMD decreases with increasing temperature. Another study example using GDI injectors can be seen in Zeng *et al.* (2012), that quantified the macroscopic spray characteristics using dimensionless analysis through examining of the forces associated with the liquid-jet breakup.

The GDI systems, as Anand *et al.* (2012) and Fajgenbaum and Santos (2013) argue, is the injection system most studied in the world in order to predict and improve the atomization process. Moreover, they complement that there is no reference in the literature of studies involving ethanol and its blends in PFI systems. In this sense, they decided study the subject and the present work aims the same argument. Anand *et al.* (2012), performed the spray characterization of gasoline-ethanol blends, investigating the fuel mass injected, spray structure and tip penetration, droplet spray distributions and SMD, for two different injection pressures for a multi-hole port fuel injector. Fajgenbaum (2013) studied the microscopic spray characteristics through Shadowgraph technique of a four-hole port fuel injector for two different injection temperatures and axial distances from fuel injector. It was observed that SMD and velocity fields are insensitive to the range of temperature (16 - 55 ^oC) tested because it provided an insignificant variation in the fuel properties. On the other hand, droplet size distributions were influenced by the temperature, which provided a higher amount of smaller droplets to the higher temperatures than that for lower temperatures. Another study using PFI injectors can be observed in Padala *et al.* (2013), that rated the ethanol spray of PFI through the imaging diagnostics using Mie-Scattering and Shadowgraphy technique. More recently, Fukumasu *et al.* (2015) investigated the influence of three different fuel injection frequency on droplet dispersion in ethanol pulsed spray flame. They found out that density spray patterns are influenced by the fuel injection frequency, impacting the combustion process of the droplets.

The current work presents a microscopic study of spray structure of a four-hole port fuel injector in order to evaluate the droplets mean diameter, droplet size distributions and droplet velocities. In this study, two Brazilian fuels, termed Brazilian standard gasoline type C and hydrous ethanol, as well as a multi-component fuel, called E50 (50% ethanol mixture with 50% gasoline in volume) were used as test fluids. The tests were carried out in an experimental apparatus with an injection system using the optical diagnostic technique called Phase Doppler Anemometry (PDA). A comparative analysis between the droplets mean diameter, droplet size distributions and droplet velocities for the three different fuels obtained by the PDA is shown.

2. EXPERIMENTAL SETUP

In the next sections will be presented the relevant properties of fuels used in the tests, the technical specifications of fuel injector, the description of the experimental apparatus, and finally the procedures and test conditions used to perform the tests.

2.1 Fuels

Hydrous ethanol, Brazilian standard commercial gasoline type C and E50 (50% hydrous ethanol mixture with 50% Brazilian standard commercial gasoline type C in volume) were used in the present work. This type of gasoline and ethanol are used as vehicle fuels in Brazil. Table 1 shows the relevant fuels properties to the analysis of atomization process.

Table 1. Fuels properties.

Fuel Properties	Gasoline (Type C)	Hydrous Ethanol
Composition	Hydrocarbons (75-87%)	Ethanol (92.6-93.8%)
	Anhydrous alcohol (13-25%)	Water (6.2-7.4%)
Density (kg/m^3)$^{(1)}$	751.5	809.9
Surface tension (mN/m)$^{(2)}$	21.922	23.516
Viscosity (mPa.s)$^{(2)}$	0.79	1.77

$^{(1)}$ measured at 25 ^oC
$^{(2)}$ measured at 20 ^oC

In order to obtain the properties of each fuel shown in Tab. 1, specific tests with a given volume fraction of fuels were conducted in the Laboratory of Fuels and Combustion of the Mechanical Engineering Department at Federal University of Minas Gerais (UFMG). The viscosity test was performed in a rheometer of the manufacturer Brookfield, model DV-III Ultra. The surface tension and density were measured using a tensiometer, model DCAT 11, of the manufacturer Dataphysics.

2.2 Fuel injector

The injector designated for the present study is a four-hole port fuel injector. This type of injector contains a pressure-swirl atomizer and produces a conical spray. The injector mass flow is 4.4 mg/pulse, the diameter (*do*) and the length (*lo*) of discharge orifice are 0.225 mm and 0.2 mm, respectively. The four-hole port fuel injector used in the tests is shown in Fig. 1.

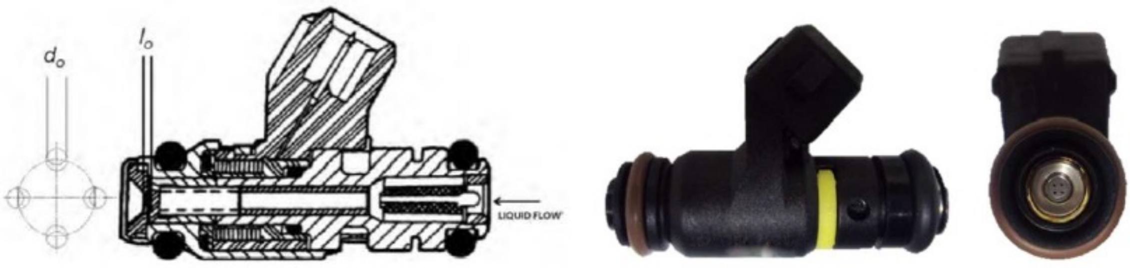

Figure 1. Four-hole port fuel injector used in the tests.

A characteristic image obtained by back illumination of fuel injection of the PFI injector used in the present study is shown in Fig. 2.

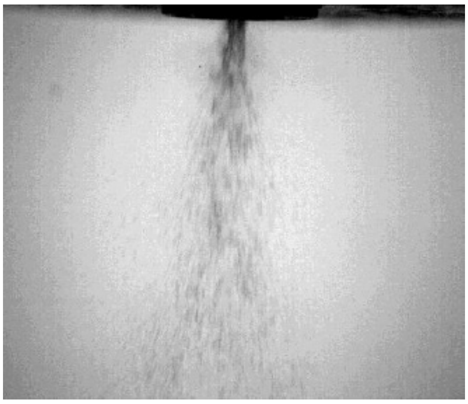

Figure 2. Characteristic image of a fuel injection of the four-hole PFI injector.

2.3 Experimental apparatus

The experimental apparatus used in the present work was developed by the Department of Mechanical Engineering at Federal University of Minas Gerais (UFMG). It is composed of a fuel injection system and a laser system.

The fuel injection system contains two subsystems: hydraulic and electronic system. The hydraulic system includes a compressed air line, a rigid tank and an ambient-pressure chamber. It is responsible to drive the fuel from the rigid tank to the fuel injector. The electronic system houses an engine control unit (ECU) called MoTec. In the ECU, the injector parameters are programmed and it is accountable for controlling the fuel injection.

The laser system consists of a PDA device (HiDense PDA from Dantec Dynamics A/S). The PDA light source is composed by an Argon-Ion laser with an output power of up to 120 mW. The laser beam enters the Bragg cell and the separator unit, where the beam is split into two beams. The Bragg cell is responsible to shift the frequency of one of the beams by 80 MHz in order to avoid directional ambiguity. A lens of the transmitting optics focuses the two beams, which form the measurement volume at a focal length of 300 mm. The detected light signals pass through optical fibers and reach the signal processing unit where photomultiplier transform the light signals into voltage signals, which can be processed. Additional information related to the PDA setting is described in Tab. 2.

A schematic diagram of experimental apparatus with PDA system is shown in Fig. 3.

2.4 Procedure and test conditions

In the present study, a simulated engine speed rotation of 5040 rpm and a duty cycle of 24.8% were used as injection parameters. These parameters were set up in the MoTec ECU with the purpose of simulating an engine working at high rotation and low load. Due to this configuration, a total period (the time interval of two simulated engine rotations - duty cycle of 100%) of 23.8 ms with the pulse width modulation (PWM) of 5.9 ms were obtained.

Table 2. Details of PDA system settings.

Wavelengths transmitter	660 nm/785 nm
Beam diameter	2.5 mm
Focal length transmitter	300 mm
Focal length receiver	310 mm
Fringe direction	positive
Scattering mode	refraction

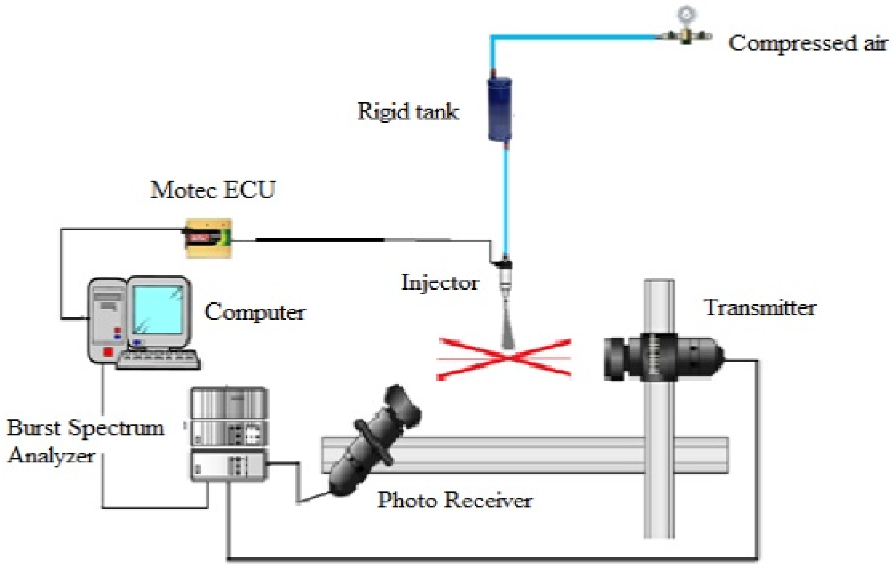

Figure 3. Schematic diagram of experimental apparatus with PDA system.

Compressed air was used for pressurizing a rigid tank containing the test fuels in order to supply the desired injection pressure of 0.3 MPa. For a better control of the injection conditions, a digital thermometer with a thermocouple type K of the manufacturer ICEL, model TD-965, with scale from -64^{o}C to 1400^{o}C, 0.1^{o}C resolution and reading accuracy of $\pm 1.0\%$ was embedded into the rigid tank to read the fuel temperature.

The PDA system was used in order to measure the droplets mean diameter, droplet size distributions and droplet velocities of sprays of the test fuels. The measurements point using the PDA was taken 25 mm downstream from the injector tip along the axis. This position was chosen because it represents primary breakup of the liquid jet into ligaments and droplets which has significant influence on the spray, as Zeng *et al.* (2012) pointed out. The measurement volume was set to the smallest possible size in order to minimize the risk of burst splitting and other multiple particle events. A front lens with a focal length of 300 mm was mounted on the receiving optics to focus the scattered light from the measuring volume on the detectors. The receiving probe was placed at 310 mm from the measuring volume at an angle of 56°.

The droplets mean diameter, droplet size distributions and droplet velocities measured experimentally consist of the values of 5,000 droplets detected by the PDA for various injection cycles of each fuel. According to Cenedese *et al.* (1994), this strategy allows to obtain statistically significant results. In order to provide the uncertainty evaluation for droplet diameters and droplet velocities measurements, repetition tests were performed. As a result, the uncertainty evaluation is $\pm 1.8\%$ for droplet diameters and $\pm 1.7\%$ for droplet velocities.

3. RESULTS AND DISCUSSION

3.1 Sauter mean diameter (SMD)

Table 3 shows SMD results for the three different fuels in the position of 25 mm downstream from the injector nozzle tip, 0.3 MPa injection pressure, $\sim$0.1 MPa ambient pressure and 5.9 ms PWM.

In Tab. 3, a comparison between the SMD of the three different fuels can be done. It reveals that the SMD of the fuels do not present significant variations among them. The fuels SMD results are close to each other and therefore, it is not possible to stablish a pattern, for instance, ensure that the gasoline has a smaller SMD compared to ethanol and E50 for the parameters of the injection and the measurement point in relation of injector presented in item 2.4.

Table 3. SMD results for the three different fuels.

Fuel	Fuel Temperature (°C)	SMD (μm)
Gasoline (Type C)	24.3	35.0
E50	28.1	35.7
Hydrous Ethanol	21.2	35.6

3.2 Droplet velocities

Figure 4 presents the scatter plot of droplet velocities for position of 25 mm downstream from the injector tip along the axis. It was used the total number of 5,000 particles detected by the PDA to plot these graphs.

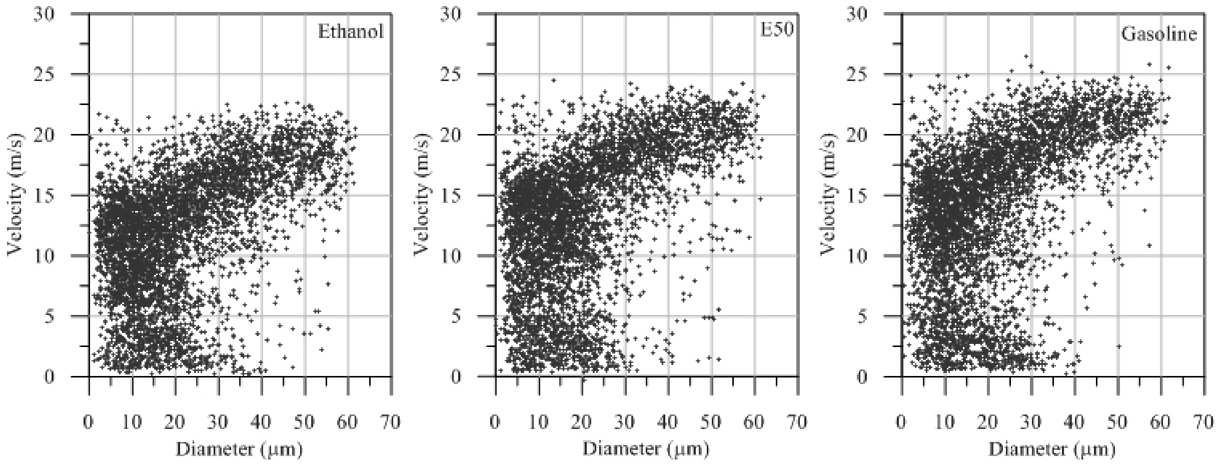

Figure 4. Ethanol, E50 and gasoline droplet velocities versus diameter.

Analysing the Fig. 4, it can be observed that velocities patterns have a slightly difference. A comparison between the graphs of gasoline and ethanol shows that gasoline velocities pattern has larger droplets with higher velocities than ethanol larger droplets. Through the results of E50 velocities pattern, it can be seen that the behavior of E50 larger droplets tend to closer to ethanol than gasoline.

Regarding the droplet velocities patterns, the velocities of the smaller droplets of ethanol (less than 20 μm) are primarily concentrated in the range of 0 to 16.0 m/s while the larger droplet (bigger than 20 μm) are between 12.5 and 22.5 m/s. In the E50 graph, the velocities of the smaller and larger droplets are condensed from 0 to 17.5 m/s and 15 to 22.5 m/s, respectively. In reference to gasoline graph, the both smaller and larger droplets presented the maximum velocity around 20 m/s and 25 m/s, respectively.

With the purpose of understanding the reason of gasoline has higher velocities of both smaller and larger droplets, it can be found in the literature, such as Fajgenbaum (2013), which the smaller density of the gasoline compared to the other fuels used in the present study (see Tab. 1) provides the higher velocity of the droplets. More information can be seen in Fajgenbaum (2013). Even more, it is important to emphasize that the higher velocity of gasoline larger droplets will provide smaller droplets in the second atomization.

3.3 Droplet size distributions

In order to assess the droplet size distributions of the three different fuels, the counts cumulative percent of droplet diameters and the modified log-normal (frequency) of the droplet diameters are presented in Figs. 5 and 6, respectively.

The analysis of droplet distributions reveals some characteristics of the droplet sizes of each fuel. It can be observed that the counts cumulative distribution and the modified log-normal of the diameters of gasoline droplets are displaced to the left compared to E50 and Ethanol. This behavior can indicate a reduction in the mean diameter of the gasoline droplets.

Figure 5 also presents that the behavior of E50 has tendency towards droplet diameters close to gasoline than ethanol between 3 μm to 10 μm. In contrast, in the range of droplet diameters between 19 μm to 55 μm the E50 tends to be close to ethanol than gasoline.

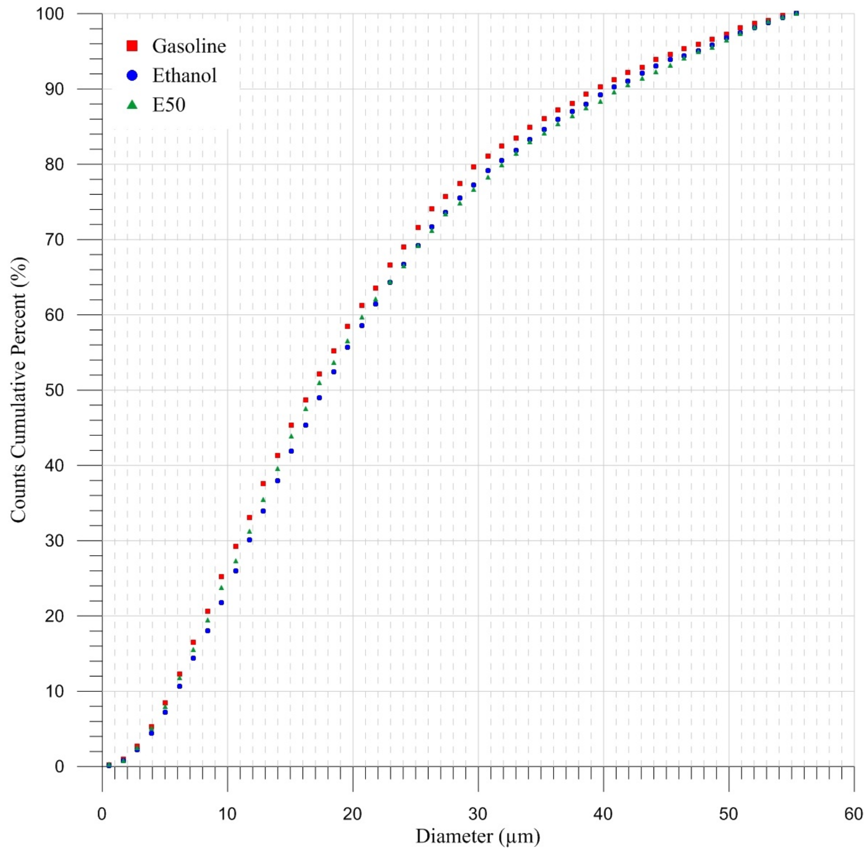

Figure 5. Counts cumulative percent of the droplet diameters of ethanol, E50 and gasoline.

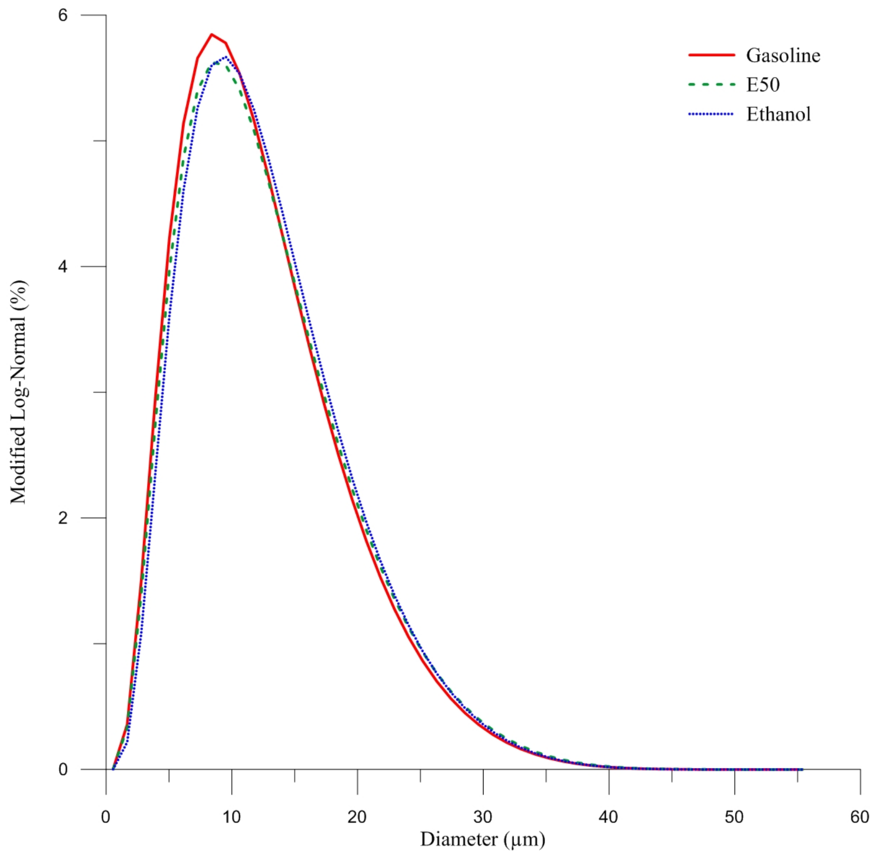

Figure 6. Frequency curves of the droplet diameters of ethanol, E50 and gasoline.

4. CONCLUSIONS

The microscopic spray characteristics of hydrous ethanol, E50 (50% hydrous ethanol mixture 50% gasoline type C in volume) and Brazilian standard gasoline type C from a four-hole port fuel injector have been reported. Experiments were carried out in an experimental apparatus using a PDA system. Droplet sizes, by means of representative diameter SMD (Sauter mean diameter), droplet velocities and droplet size distributions of each fuel were measured at 25 mm from the discharge orifice (axial position) with 0.3 MPa injection pressure, pulse width modulation of 5.9 ms and approximately 0.1 MPa ambient pressure. The observation and findings can be summarized as follow:

1. Although there is considerable difference in the properties of fuels, SMD did not present significant variations for the tested fuels in order to establish a relationship between them.

2. The fuel velocity patterns presented that both smaller and larger gasoline droplets have higher velocities compared to ethanol and E50. This result implies that the gasoline tends to have smaller droplets in the second atomization.

3. The droplet size distributions of the gasoline showed that the counts cumulative distribution and the modified log-normal (frequency) of the droplet diameters are displaced to the left compared to the other fuels, indicating a reduction in the mean diameter of droplets.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE