EXPERIMENTAL STUDY OF ATOMIZATION PARAMETERS FROM A SINGLE-HOLE PORT FUEL INJECTOR WITH N-HEPTANE

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Abstract: The interest in studying the atomization parameters arises from the needed to better understand the behavior of the spray drops formed in several industrial processes and many other applications. To illustrate the importance of studying these spray characteristics, in internal combustion engine can be found that fuel atomization has a strong relation with the fuel consumption and pollutant emissions as well as the engine combustion efficiency. In this work, experiments are performed to investigate the atomization parameters of an automotive single-hole port fuel injector. The n-heptane is used as test fluid. The evaluations of drop sizes, drop size distributions and drop velocities are performed by Phase Doppler Particle Analyzer (PDPA) technique. Results for drop sizing are expressed in terms of Sauter Mean Diameter (SMD) and arithmetic mean diameter (D_{10}). The measurements are taken in the core of the spray into six different axial positions from the nozzle tip with 300 kPa injection pressure. Results indicate that the drop size distributions tend to have droplets with large diameter for the distances further from the nozzle tip. The same results are observed in SMD and D_{10}. For the drop velocities, the results present a slightly decreasing in the droplet velocity for the distances further from the nozzle tip.

Keywords: drop size distribution , drop velocity, n-heptane atomization, PDPA, SMD.

1. INTRODUCTION

The characteristic of the atomization process is to disintegrate a bulk liquid into small particle in a gaseous atmosphere. This process plays an important role in many different fields, such as: aerospace, agriculture, automotive, meteorology, medicine, several industrial processes and others.

For the automotive field, the liquid atomization has a key importance in combustion of liquid fuels that occurs in internal combustion engines. According to Lefebvre (1989), the combustion of liquid fuels is dependent on effective atomization to increase the specific surface area of the fuel and thereby achieve high rates of fuel mixing and evaporation. Equally important, the effective atomization leads to a reduction in mean fuel drop size and as consequence reduces the fuel consumption as well as pollutant emissions and increases engine efficiency.

As referred to above, the atomization process has a great practical importance in most applications. For this reason, researchers and engineers worldwide have started researches to better understanding the basic atomization process and improve the design of atomizers. In particular, most of the fuels used in combustion applications to obtain some type of energy are not only composed by a pure fuel but also a mixture of fuel, as mentioned by Bayvel and Orzechowski (1993). Due to this, the properties of each fuel presents variations between them affecting the performance of any given atomizer.

Many studies can be found for the atomization of fuels used in automobiles. Almost all of the works found studied the atomization process of gasoline direct injection (GDI) system which has higher injection pressure than port fuel injection (PFI) system. Most of these studies are focused on the understanding of the physical phenomena that occur in the fuel atomization, or to improve the engine efficiency, or to introduce the use of other fuels, such as the case of ethanol.

In reference to the physical phenomena of fuel atomization process and introduce the use of other fuels, Aleiferis *et al.* (2010) performed experiments varying the fuel injection temperature (20 - 120 °C) and ambient pressure (500 kPa and 1 MPa). They used gasoline and ethanol-gasoline blends as fuels. These fuels were injected by a GDI injector with constant fuel pressure of 15 MPa. The results indicate that Sauter Mean Diameter (SMD) of the fuels decreases with increasing of both fuel injection temperature and ambient pressure.

In the case of improve the engine efficiency and also introduce the use of other fuels, Anand *et al.* (2012) studied the spray characteristics of gasoline, ethanol and ethanol-gasoline blends of a multi-hole PFI injector. It was observed both spray characteristics and droplet sizes present behavior between the fuels. More recently, Fajgenbaum and Santos (2015) carried out experiments with gasoline and ethanol for two different injection temperatures (16 - 55 °C) and axial distances (25 - 100 mm) from fuel injector tip. The goal of this work was evaluate the microscopic spray characteristics of a four-hole port fuel injector, through Shadowgraphy technique, in order to improve the engine cold start. The results indicate

that SMD and velocity fields are insensitive to the range of temperature 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 higher temperatures.

Regarding to the better understanding of the physical phenomena that occur in the fuel atomization and provide data for literature, the current work presents a microscopic study of the n-heptane spray formed by a single-hole port fuel injector. The main goal of this work is to evaluate the atomization parameters (droplet sizes, drop size distribution and drop velocity) in different axial positions from the nozzle tip. The measurements of atomization parameters were done by the optical diagnostic technique called Phase Doppler Particle Analyzer (PDPA). The atomization parameters of each axial position are compared and the results are discussed.

2. EXPERIMENTAL SETUP

2.1 Experimental apparatus

In the present study, the n-heptane spray is formed by a PFI injector assembled in an experimental apparatus developed to the purpose of reproducing part of the automotive fuel injection system. Besides, a heat exchanger is integrated with the experimental apparatus in order to control and vary the test fluid temperature. A schematic diagram of experimental apparatus with the heat exchanger is shown in 1.
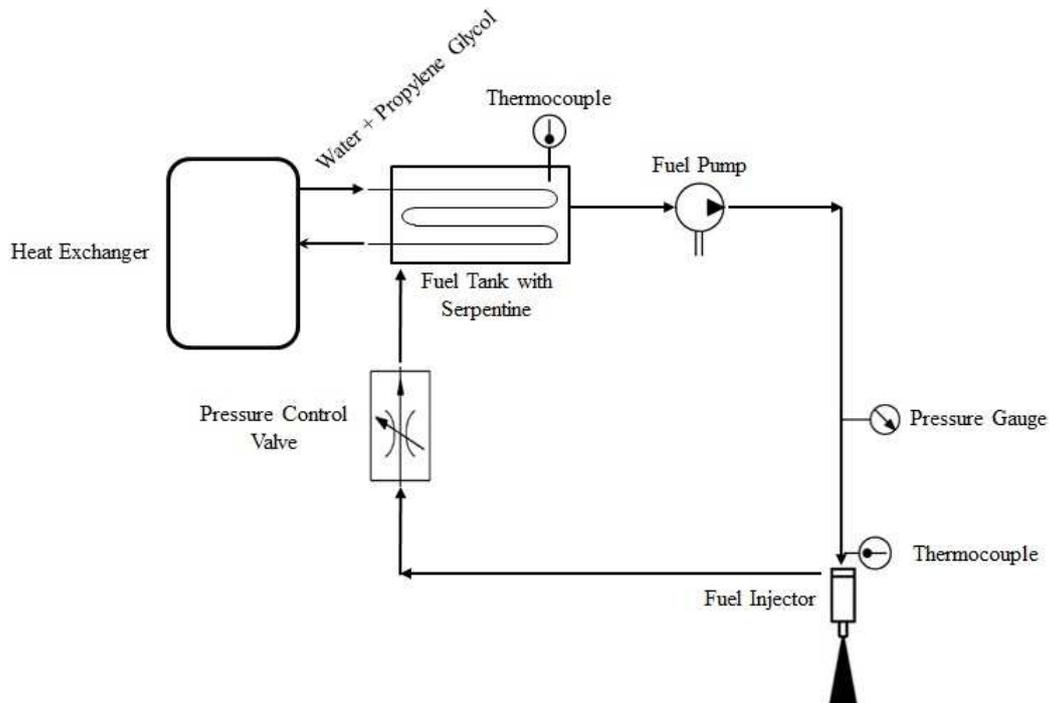

Figure 1: Schematic diagram of experimental apparatus with the heat exchanger.

The experimental apparatus consists of a fuel tank with an internal serpentine connected with a heat exchanger, model HAAKE F3. The heat exchanger uses as working fluid a mixture of 50% water with 50% propylene glycol in volume. An automotive flex fuel pump with maximum pressure of 800 kPa is used to provide fuel with desired pressure to the injector. The fuel pressure in the fuel line is controlled by a pressure control valve, model HPI SPA, and a manometer with scale from 0 to 600 kPa and measurement uncertainty of $\pm1.73\%$ to the pressure range of 0 to 400 kPa and $\pm1.27\%$ from 410 to 600 kPa. The fuel temperature is measured in two different points by two thermocouples type K with measurement uncertainty of $\pm0.75\%$ of reading. The first point determined is inside of fuel tank and second point is on the fuel injector inlet.

Atomization parameters are measured by Phase Doppler Particle Analyzer (PDPA) technique. In this work, PDPA technique is obtained through the PDI-300 equipment from Artium Inc. The PDI-300 equipment used consists of two modules (one transmitter and one receiver) laser beam. The transmitter emits two laser beams provided by technology Nd:YAG diode-pumped solid-state (DPSS) technology. The laser beams have wavelenghts of 532 nm and 473 nm with average power of 300 mJ and 180 mJ, respectively.

2.2 Fuel

The liquid n-heptane is used as test fluid in the present work. The n-heptane is recommended as standard test fluid to fuel injector in the automotive industries in order to reduce variations in the final test values that are reported for a wide variety of test protocols (Hung *et al.*,2008). In addition, it is also used because their physicochemical properties have values close to those of real fuels. For these reasons, the n-heptane was chosen as test fluid in this study.

The analysis of atomization parameters requires knowledge of some properties of the fluid to be injected. According to Lefebvre (1989), the properties that mostly affect the atomization process and spray pattern are density, surface tension and viscosity.

In the present study, the working temperature of n-heptane was 30°C. However, it is important to know how are the values of the n-heptane properties to this temperature in order to analyze the atomization process. Table 1 shows the values of physicochemical properties density, surface tension and viscosity of the n-heptane at 30°C.

Table 1: Properties of n-heptane at 30°C.

Composition	Density (kg/m^3)	Surface tension (mN.m^{-1})	Viscosity (mPa.s)
Minimum 99.5%	680.7	19.130	0.369

With the purpose of determining the n-heptane density for the temperature of 30°C, a densimeter of the manufacturer Anton Paar, model DMA 4500, supplied by CEPETRO-Unicamp was used. Regarding the surface tension and viscosity, it was not possible to measure these properties in our laboratories due to lack of available proper equipment. In this sense, the values of n-heptane surface tension and viscosity were extracted from Mohsen-Nia *et al.* (2010) and Matos *et al.* (2001), respectively.

2.3 Fuel injector

The fuel injector designated for the present study is a single-hole port fuel injector. This injector was developed specifically for the research in sprays carried out in the present study.

The single-hole port fuel injector and its technical specification are shown in Figure 2 and Table 2, respectively.

Figure 2: Single-hole port fuel injector used in the tests.

Table 2: Technical specification of single-hole port fuel injector.

Parameters	Values
Dynamic flow (g/1000 cycles of injection) @ 2.7 bar	2.4 ± 3.5%
Static flow (g/s)	1.0 ± 3.0%
Discharge orifice diameter (mm)	0.255
Discharge orifice length (mm)	0.2 ± 0.02%
Ratio orifice length/orifice diameter	0.78

2.4 Procedures and test conditions

The experimental work was carried out at the Combustion Laboratory of the Polytechnic School of University of São Paulo (USP).

The fuel injector parameters adopted in the present study were: injection pressure of 300 ± 2.7 kPa, fuel injection temperature of 30 °C and pulse width modulation (PWM) of 5 ms. The atomization parameters were measured at six different positions downstream from the injector tip along its axis: 10, 25, 50, 75, 100 e 125 mm.

The measurements of the atomization parameters occurred through PDI-300 MD equipment. For this purpose, lenses with focal length of 500 mm were used in both transmitter and receiver. The equipment modules were positioned in the forward scattering configuration with an angle of 40°.

Before starting the measurements of the atomization parameters, a settling time of at least 4 minutes was used to allow that temperature measured by the thermocouple installed at the injector inlet could stabilize.

The droplet sizes, drop size distributions and drop velocities measured experimentally consist of the values of 20,000 droplets detected and validated by the PDPA technique for various injection cycles of each n-heptane temperature. According to Refs. (Kim *et al.* (2010) and Düwel *et al.* (2007)), this strategy allows to obtain statistically significant results.

Repetition tests were performed in order to evaluate the uncertainty measurements of droplet diameters and axial velocities. As a result, the uncertainty evaluation is of ±0.55% for droplet diameters and ±0.25% for axial velocities measurements.

3. RESULTS AND DISCUSSIONS

In order to investigate the atomization parameters for six different positions downstream from the injector tip along its axis, three microscopic spray characteristics are analyzed: droplet sizes, drop size distributions and drop velocities.

3.1 Droplet sizes

Table 3 shows the variation of arithmetic mean diameter (D_{10}) and Sauter Mean Diameter (SMD) for the six different measurement positions. Each mean drop size was determined for a total of 20,000 droplets detected and validated by the PDPA technique, as explained before.

Table 3: Variation of D_{10} and SMD with different measurement positions.

Measurement positions (mm)	D_{10} (μm)	SMD (μm)
10	25.5 ± 0.1	114.9 ± 0.6
25	32.3 ± 0.2	118.8 ± 0.7
50	39.7 ± 0.2	117.7 ± 0.6
75	47.7 ± 0.3	122.2 ± 0.7
100	49.4 ± 0.3	122.8 ± 0.7
125	44.9 ± 0.3	116.7 ± 0.6

Analyzing the results presented in Table 3, it can be seen that droplet sizes tend to increase for the measurement positions further from the nozzle tip until the 100 mm position and both SMD and D_{10} decreases for measuring position 125 mm.

With the purpose of understanding the reason of distances further from the nozzle tip present the tendency of have droplets with higher diameters, the result analysis suggests that may be taking place the coalescence process of droplets as well as the smaller droplets may have evaporated.

3.2 Drop size distributions

In section 3.1 are presented two types of mean drop diameters for the n-heptane and test conditions assumed in this work. However, the mean drop diameter is a parameter that provides a qualitative information about atomization (Lefebvre,1989 and Bayvel and Orzechowski,1993). With the purpose of knowing how the drops with different sizes are distributed at the measuring point, drop size distributions are adopted.

In order to evaluate the drop size distributions of the six different measurement positions, the Probability Density Functions (PDF) of droplet diameters are presented in Figure 3.
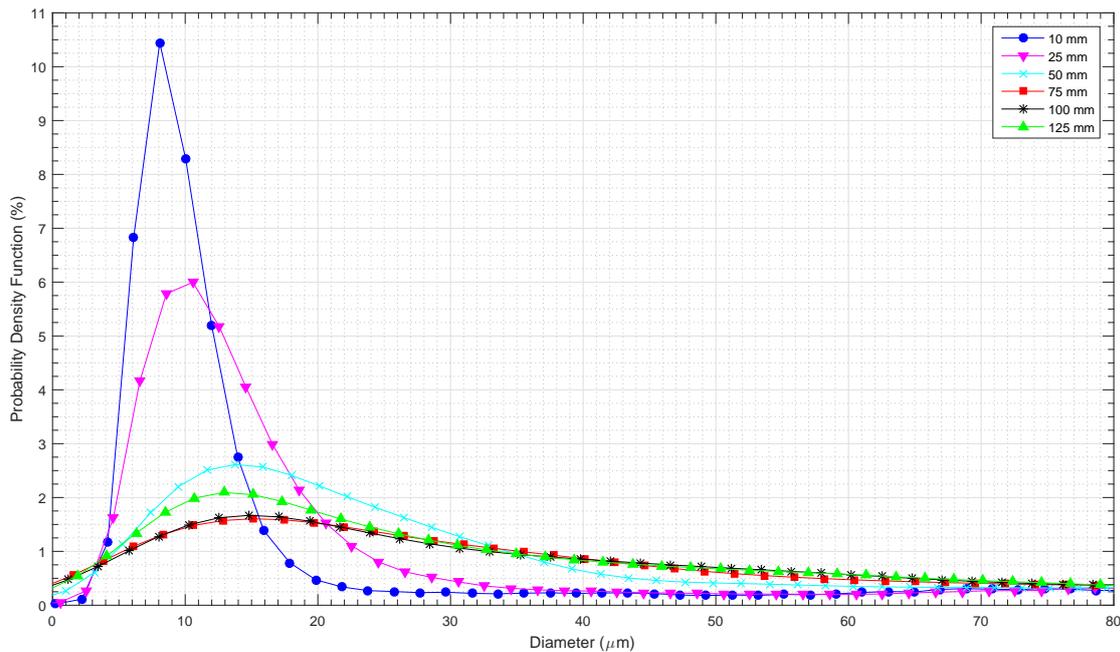

Figure 3: Probability density function of n-heptane droplet diameters.

In Figure 3, it can be observed that each measurement position has PDF with mono-modal diameter distribution. For

the position at 10 mm, the diameter distribution is centered on 8.1 μm. Also, in this position there is a higher probability of finding smaller droplets compared to the others measurement positions. Similarly to the results present in section 3.1 the maximum of PDF function of each measurement position increases up to 100 mm (14.8 μm) and decreases to 125 mm (10.7 μm).

As explained in the previous section, the coalescence and evaporation processes should be occur and influenced the results.

3.3 Drop velocities

Figure 4 shows the PDFs of droplet axial velocities for the six different measurement positions and test conditions used in the present study.
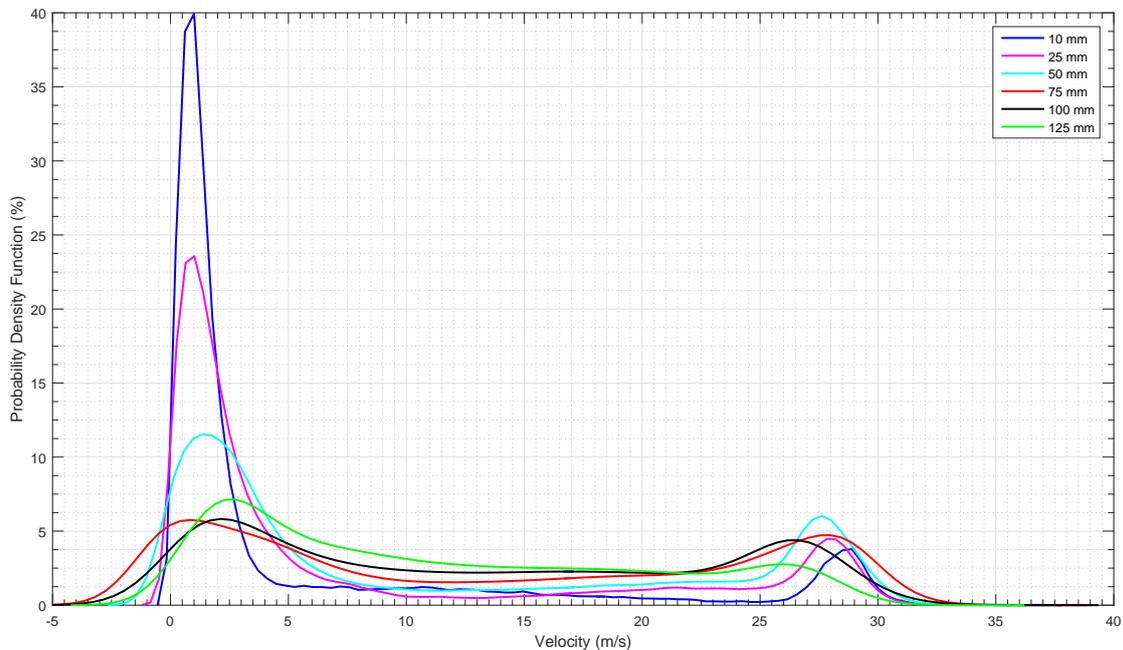

Figure 4: Probability density function of n-heptane droplet axial velocities.

Analyzing the results present in Figure 4, it can be observed that all measurement position has PDF with bi-modal velocity distribution. In the case of measuring position 10 mm, the first maximum of the PDF function is centered on 1 m/s while the second maximum is centered on 28.9 m/s. It can be noted that the first maximum of the PDF function translated from 1 m/s to 2.7 m/s between the measuring positions 10 mm and 125 mm, respectively. In reference to the second maximum of the PDF function, it can be seen the opposite behavior. For the position at 10 mm, the velocity distribution is centered on 28.9 m/s while for the position at 125 mm is centered on 26 m/s. Moreover, it can be observed that in the range of 5 m/s to 25 m/s there is an increase in the probability of finding droplets with higher velocities for the measurement positions further of the nozzle tip.

Regarding to the velocity decrease of the second maximum of function PDF when droplets move away from nozzle tip, it is important mention that this occurs due to the action of aerodynamics drag force of the droplets.

Here, it is important emphasize that the probability of finding droplets in two different velocities leads to a higher probability of collisions between them, favoring the coalescence process (Dorfner *et al.*1995).

4. CONCLUSION

In the present work, the atomization parameters of n-heptane spray from a single-hole port fuel injector have been reported. Droplet sizes, by means of representative diameter SMD (Sauter Mean Diameter) and arithmetic mean diameter (D_{10}), drop size distributions and drop velocities were measured at six different measurement positions downstream from the injector tip along its axis, 300 kPa injection pressure, pulse width modulation of 5 ms and 101 kPa ambient pressure (approximately). The measurements were carried out using a PDPA technique. According to the results presented in this study, the observation and findings can be summarized as follow:

- For the distances further from the nozzle tip of the injector, it is established that there is a higher probability of finding droplets with higher diameters as well as smaller velocities.

5. ACKNOWLEDGEMENTS

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