Proceedings of ENCIT 2012
Copyright © 2012 by ABCM

14th Brazilian Congress of Thermal Sciences and Engineering
November 18-22, 2012, Rio de Janeiro, RJ, Brazil

# CHARACTERIZATION OF A BLURRY INJECTOR FOR BURNING BIOFUELS IN A COMPACT FLAMELESS COMBUSTION CHAMBER

**Claudia Gonçalves de Azevedo, claudia@lcp.inpe.br**
**José Carlos Andrade, andrade@lcp.inpe.br**
**Fernando de Souza Costa, fernando@lcp.inpe.br**

Instituto Nacional de Pesquisas Espaciais, Laboratório Associado de Combustão e Propulsão, Rod. Presidente Dutra, km 40, Cachoeira Paulista, SP, CEP 12630-000

***Abstract.*** *In recent years there has been a great interest in the use of biofuels in order to reduce the environmental impact of combustion processes and replacement of fossil fuels. New combustion technologies are also under development, aiming to reduce costs, increase operating efficiency and reduce pollutants emissions. This work describes the spray characteristics of hydrous ethanol and B100 soy biodiesel in a blurry injector for applications in a flameless compact combustion chamber. The experimental results are obtained over a range of relatively low flow rates and injection pressures, with different air-to-liquid mass flow ratios (ALR). The main parameters that have been selected in the experimental characterization are average drop diameter, drop size distribution and discharge coefficient.*

**Keywords**: Blurry injector, Biofuels, Hydrous Ethanol, Soy Biodiesel, Drop Size

## 1. INTRODUCTION

The atomization of a liquid into small droplets in the form of a spray is an important process in industrial, combustion and propulsion system. A larger surface area is produced by forming droplets, thus reducing the liquid vaporization time. In liquid fuel combustion application this results in better mixing and an increase in the time available for complete combustion (Lefebvre, 1983).

According (Lefebvre, 1989) a efficient combustion requires optimal droplet size distribution within the spray for a range of operating conditions to include droplets both large enough to penetrate into the combustion chamber and small enough to vaporize within the short residence time upstream of the reaction zone.

Gañan-Calvo, 2005, reported a new class of twin fluid injector, the flow-blurring injector (FB), which presents several advantages over other injectors, such as formation of a relatively uniform spray, better atomization, a simple and reproducible configuration, and robust flow pattern which gives rise to a gas-liquid interaction with a high efficiency. For given values of liquid flow and total energy input, (Gañan-Calvo, 2005) claims that the FB configuration is capable of creating about 5 and 50 times more droplet surface area than other pneumatic injector of the plain-jet airblast type.

Figure 1 illustrates the working principle of the FB injector consisting of a fuel tube of inside diameter *d* separated by distance *H* from the injector orifice, also of diameter *d*.

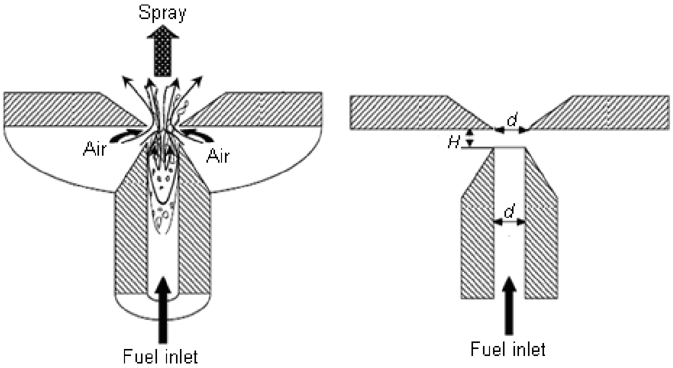


Figure 1. Schematic of a flow-blurring injector: flow structure and geometric details.
Source: Adapted from Panchasara, H.V. *et al.* (2009)

When $H/d < 0.25$, the atomizing air flow penetrates a short distance upstream into the fuel tube to create a two-phase mixture at the tip of the fuel tube. This two-phase mixture undergoes sudden decrease in pressure while exiting through the injector orifice. Consequently, air bubbles in the flow expand and eventually collapse to breakdown the surrounding fuel into a spray of fine droplets. The FB atomization is similar to the EA process, but the two-phase mixing occurs at the tip of the fuel tube, which requires a lower supply pressure for the atomizing air flow and prevents two-phase flow instabilities. The FB injector produces internal and external mixing of the two phases simultaneously, producing gas-liquid interaction with a high efficiency, and therefore, superiority over the other injectors. Compared to air blast atomizer, previous studies show that FB can gain finer spray with lower energy input since it incurs a lower pressure drop in the atomizing air line (Simmons and Agrawal, 2010), and also, liquid fuel atomized by FB can mainly burn under lean premixed mode and thus yield much lower emissions of CO and $NO_x$ (Panchasara *et al,* 2009).

A blurry injector with a cylindrical-divergent exit was developed by Azevedo *et al.* (2011) for injection of biofuels. The liquid flow rate was measured experimentally and air flow rate in the injector was theoretically calculated from pressure data, and relatively high pressures and high flow rates were considered. The present work shows the characterization of biofuel sprays formed by a blurry injector with a divergent exit. The liquid and air mass flow rates were measured experimentally and, since lower flow rates and pressures were adopted, the injector will be considered for applications in a flameless compact combustion chamber. Flameless combustion is a homogeneous low temperature burning process leading to strongly reduced pollutant emissions and higher efficiency compared to traditional combustion processes (Wünning *et al.*, 1997). Experiments are conducted for different atomizing air-to-liquid mass ratios (ALRs) at ambient conditions of temperature and pressure.

## 2. EXPERIMENTS

### 2.1. Blurry injector

Figure 2 shows the injector developed that will be possibly used in a flameless compact combustor. The blurry injector consisted of a central liquid tube ($d$ = 0.5 mm) and a coaxial atomizing air passage with inner diameter 6 mm. The two-phase mixture exits through the orifice of diameter $d$ = 0.5 mm in the discharge plate located such that $H$ = 0.125 mm.

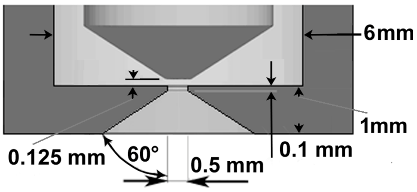


Figure 2. Schematic representation of the blurry injector.

### 2.2. Experimental setup

The experimental setup is shown schematically in Fig. 3.

The biofuels tanks were pressurized using nitrogen gas from a high-pressure commercial nitrogen cylinder.

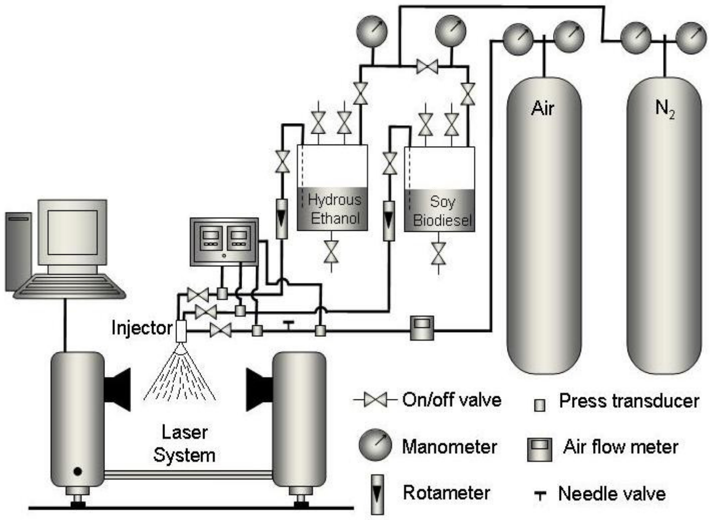


Figure 3. Experimental setup.

Compressed air was used as the atomizing gas and was supplied from a high-pressure cylinder, controlled by a needle valve, and measured by a calibrated flow meter with an uncertainty of ± 1.5 standard liters per minute (slpm).

The flow rates of biofuels were measured by rotameters, with the uncertainty in the measurements being ± 2%. Supply pressure in the fuel and atomizing air lines was measured using pressure transducers at locations depicted in Fig. 3. The laser diffraction system Spraytec/Malvern® was used to determine the drop sizes and their distributions in the spray. The accuracy of the instrument was ±1% of full scale (specified by the manufacturer) and it could measure the droplet size and distribution of sprays with obscurations up to 95%. Drop size measurements were carried out at an axial distance of 50 mm from the discharge orifice of the injector.

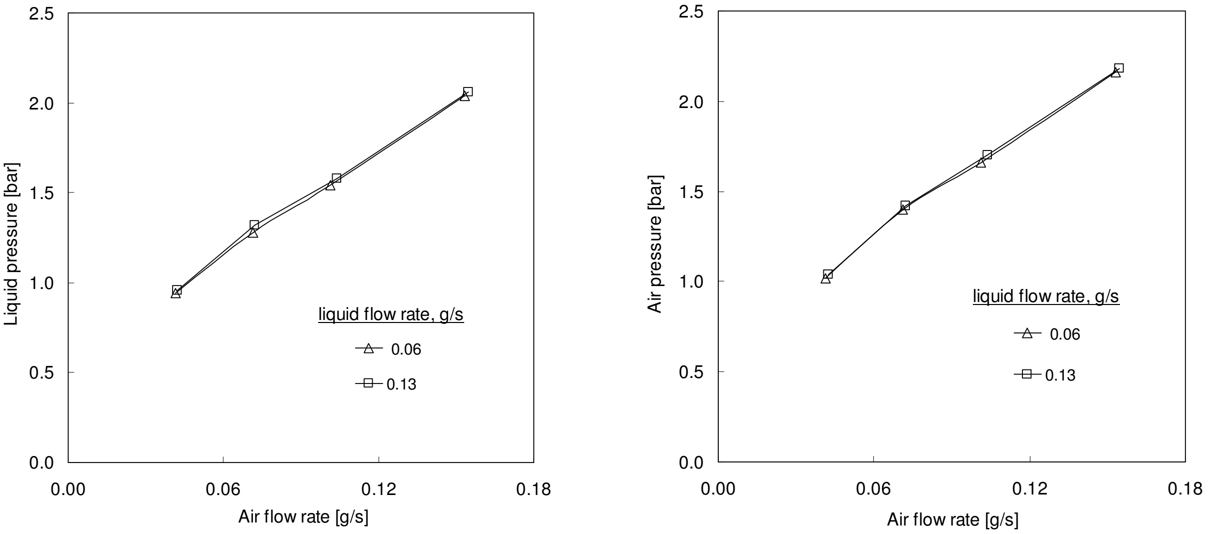
## 3. RESULTS AND DISCUSSION

Initially, the liquid flow rate was kept constant and the air flow rate was varied to obtain the variation in air-to-liquid mass ratio (ALR) in the injector. Then, the liquid flow rate was varied for different values of air flow rate. Air density was calculated, considering the supply pressure and temperature of the atomizing air.

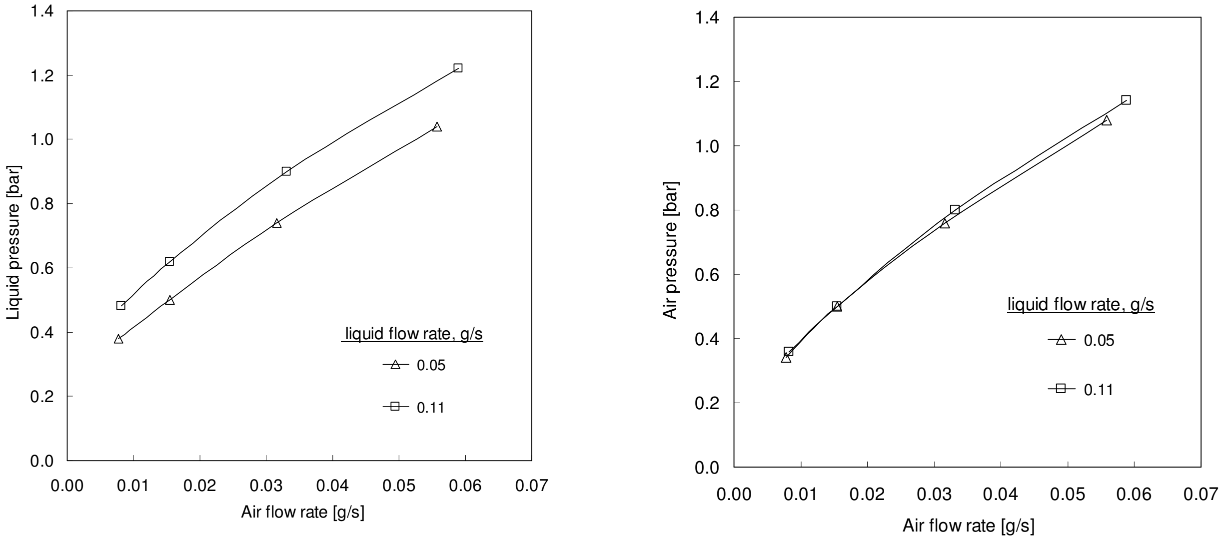
### 3.1. Pressure Measurements

Pressure drop in the atomizing air and fuel supply lines is important for practical operation of the injector.

Figure 4 shows the pressure drop in the fuel and atomizing air lines. The measured pressure was effectively the pressure drop in the air line because the atomizer was open to the ambient.



a) Hydrous ethanol



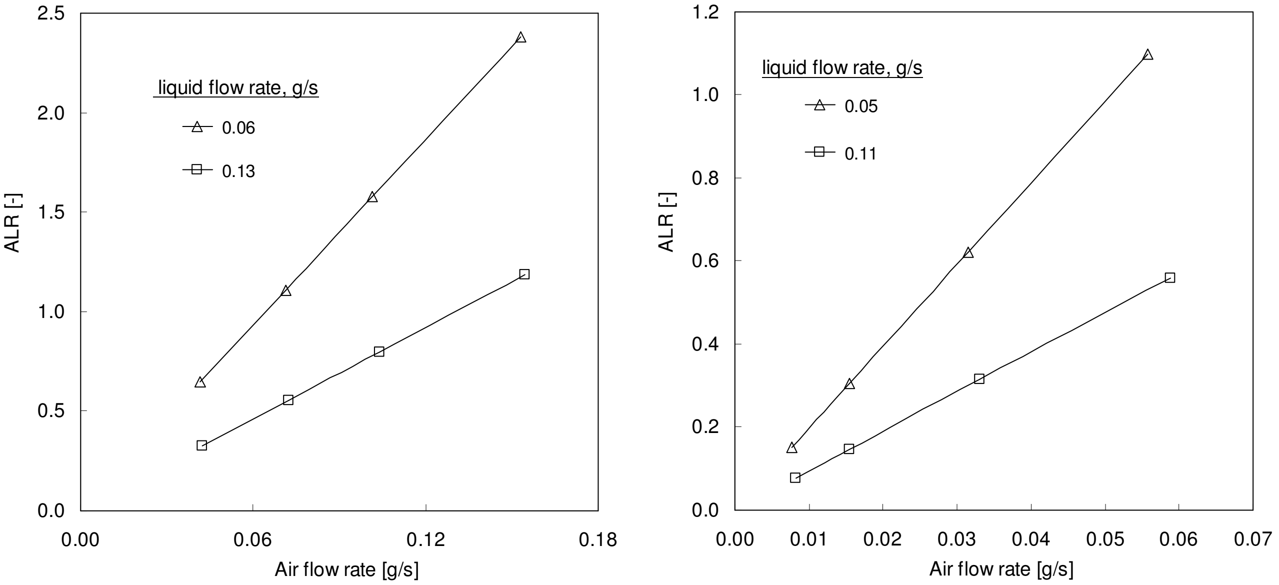
b) B100 soy biodiesel

Figure 4. Liquid and air pressure.

An increase in the atomizing air flow rate increases the pressure drop in fuel and atomizing air lines, as expected. Increasing the atomizing air flow rate increases the flow resistance in the fuel-air mixing process at the tip of the fuel tube. Evidently, the pressure drop in the two-phase mixing region is much greater than the frictional loss in the fuel supply tube since the total pressure drop is independent of the physical properties of the fuel.

### 3.2. Air-to-liquid mass flow ratios

The air-to-liquid mass flow ratios for the operational conditions are depicted in Fig. 5.



a) Hydrous ethanol
b) B100 soy biodiesel

Figure 5. Air-to-liquid mass flow ratio.

For a given liquid flow rate an increase in the air flow rate leads to an increase in ALR. The data in Fig. 5 also show an increase in ALR with a decrease in the liquid flow rate. The reason for the increase in ALR can be attributed to the fact that with the decrease in the area occupied by the liquid due to the decrease in its flow rate the area available for air flow increases, and thus, increasing the air flow rate. Furthermore, the liquid flow rate is seen to decrease with an increase in air flow rate, which is expected due to the increase in incoming air velocity with the increase in supply pressure. For the liquid flow rates analyzed it is verified that for the hydrous ethanol the air flow rate vary between 0.04 and 0.16 g/s and the ALR is seen to vary between 0.33 and 2.38, for soy biodiesel the air flow rate vary between 0.008 and 0.06g/s and the ALR vary between 0.08 and 1.10.

### 3.3. Discharge coefficient

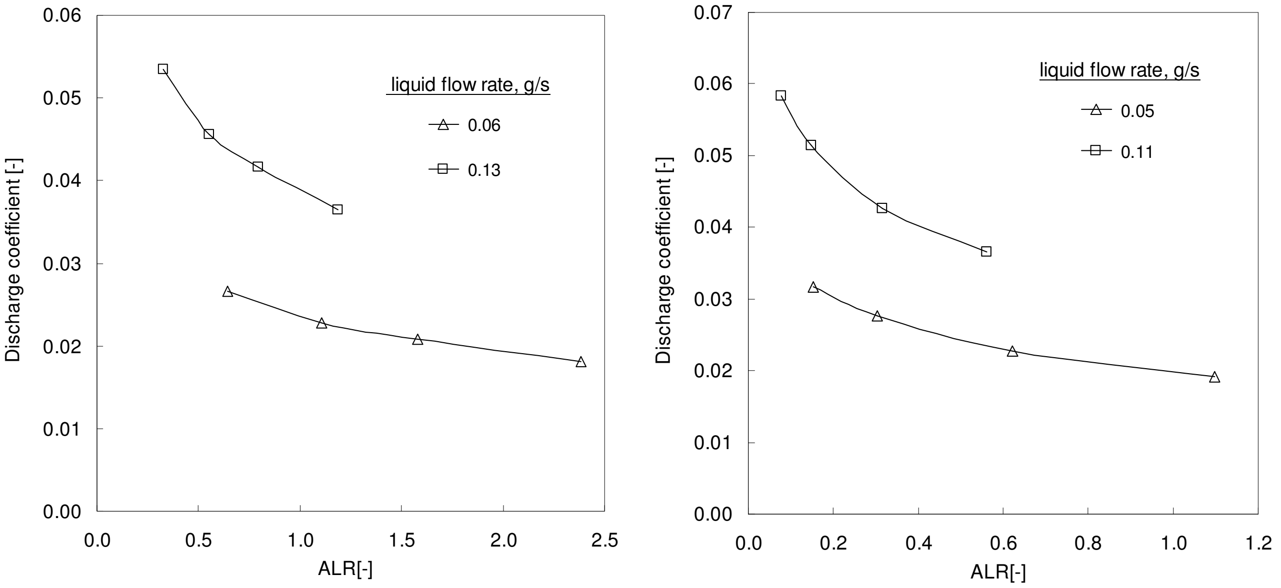
The discharge coefficient of an atomizer is an important parameter governing the throughput of the liquid at a given value of injection pressure. Owing to the presence of the gas bubbles in the flow, the discharge coefficient of the blurry injector would be smaller compared to a plain orifice pressure injector

The discharge coefficient is the ratio between the experimental mass flow rate and the maximum theoretical mass flow rate of the liquid in the injector. It is given by (Delmeé, 1983):

$$c_d = \frac{\dot{m}_l}{A\sqrt{2\rho_l \Delta P_l}} \tag{1}$$

where $c_d$ is the discharge coefficient of the liquid; $\dot{m}_l$ the experimental liquid mass flow rate, kg/s; $A$ the total cross sectional area of the discharge orifices, m$^2$; $\Delta P_l$ the pressure difference of the liquid flow across the nozzle, Pa; and $\rho_l$ density of the liquid, kg/m$^3$.

In order to establish a functional relationship between the liquid flow rate, the ALR and the liquid supply pressure, the discharge coefficient variation with respect to ALR was estimated using Eq. (1) and the results are plotted in Fig. 6.



a) Hydrous ethanol b) B100 soy biodiesel

Figure 6. Variation of discharge coefficient with ALR.

Figure 6 shows that the discharge coefficient decreases as the ALR is increased. Lefebvre, 1983 has defined the discharge coefficient to be a measure of the extent to which the liquid flowing through the final discharge orifice makes full use of the available flow area. Therefore, as the ALR is increased, the flow area occupied by the liquid must decrease. The values of discharge coefficient shown in Fig. 6 vary from 0.02 to 0.053 for hydrous ethanol and vary between 0.02 and 0.058 for soy biodiesel, over the entire operating range.

The functional relationship between the discharge coefficient and ALR is given by:

$$c_d = -0.05\ln(ALR) + 0.04\,;\ r^2 = 0.93 \text{ for hydrous ethanol} \tag{2}$$

$$c_d = -0.02\ln(ALR) + 0.02\,;\ r^2 = 0.93 \text{ for soy biodiesel} \tag{3}$$

According to Eqs. (2) and (3), the rate of change of $c_d$ with ALR is inversely proportional to ALR. Therefore, the rate of change decreases with an increase in ALR, which is responsible for slower rate of decrease in the liquid flow rate at higher values of ALR.

### 3.4. Drop size

Spray mean drop size and drop size distribution are the parameters of greatest interest in most applications. Different characteristic diameters can be obtained to represent a spray. In this work the Sauter mean diameter (SMD) and the mass median diameter (MMD) were obtained with aid of the laser system.

The air-to-liquid mass flow ratio (ALR) is an important operating parameter in most applications since it is desirable to minimize the amount of atomizing gas supplied while maintaining a small mean drop size.

Figure 7 illustrate the effect of air-to-liquid mass flow ratio on the SMD and MMD at different liquid mass flow rate for hydrous ethanol and soy biodiesel.

The data presented in Fig. 7 shows that the droplet size decreases with an increase in ALR for a given liquid flow rate. It is verified that a decrease in liquid mass flow rate causes a decreasing in the mean drop size. The higher the ALR is, the higher the air flux will be, then the higher smashing energy can be provided for liquid atomization. Therefore, the droplet size will decrease as the ALR is increased. An increase in ALR leads to an increase in exit velocities and turbulence inside the injector, resulting in a more efficient atomization. As the ALR is increased the effective area occupied by liquid decreases and the effective area occupied by air increase, increase in air flow area is beneficial to atomization because it reduces the area available for the liquid flow, i.e., it squeezes the liquid into thinner films and ligaments as it flows through the injector orifice. It is verified that SMD for hydrous ethanol varies from 10.71 μm to 6.29 μm and MMD varies from 15.27 μm to 7.77 μm over the entire operating range. For B100 soy biodiesel the data presented in Fig. 7 show that SMD varies between 26.40 μm to 9.59 μm and MMD decreases from 38.94 μm to 1.19 μm over the entire operating range.

The functional relationship between the SMD and ALR is given by:

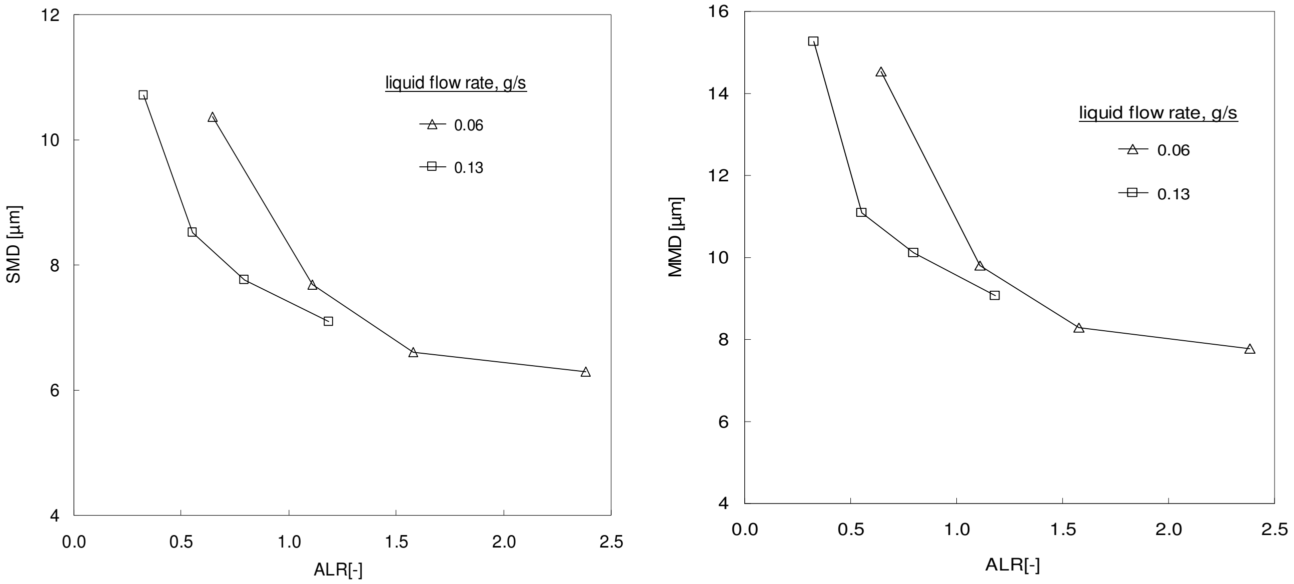
$$SMD = 7.88(ALR)^{-0.34}\ ;\quad r^2 = 0.91 \text{ for hydrous ethanol} \tag{4}$$

$$SMD = 10.02(ALR)^{-0.37}\ ;\quad r^2 = 0.95 \text{ for soy biodiesel} \tag{5}$$

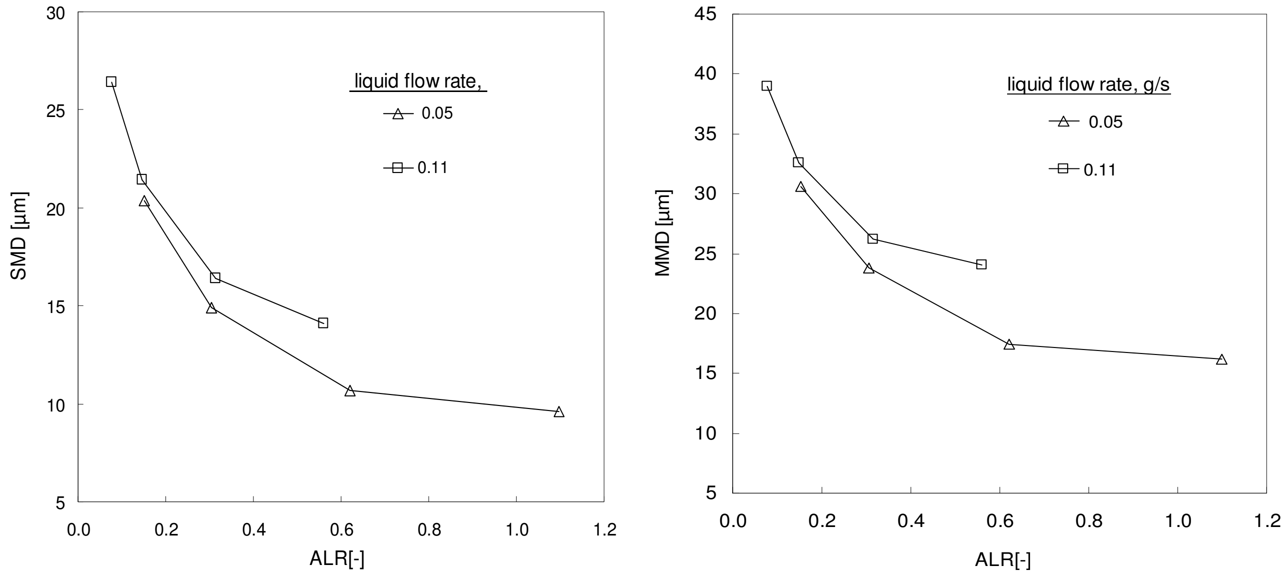
The functional relationship between the MMD and ALR is given by:

$$MMD = 10.26(ALR)^{-0.41}\ ;\quad r^2 = 0.90 \text{ for hydrous ethanol} \tag{6}$$

$$MMD = 17.32(ALR)^{-0.33}\ ;\quad r^2 = 0.95 \text{ for soy biodiesel} \tag{7}$$



a) Hydrous ethanol

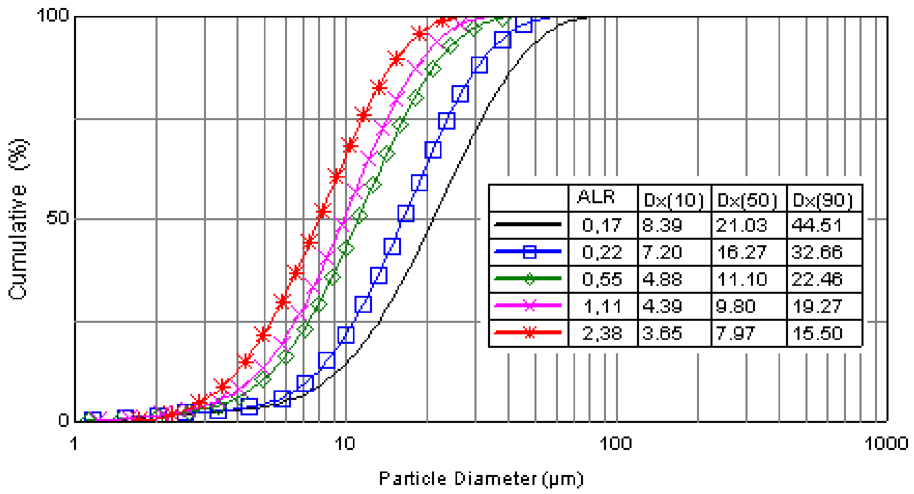


b) B100 soy biodiesel

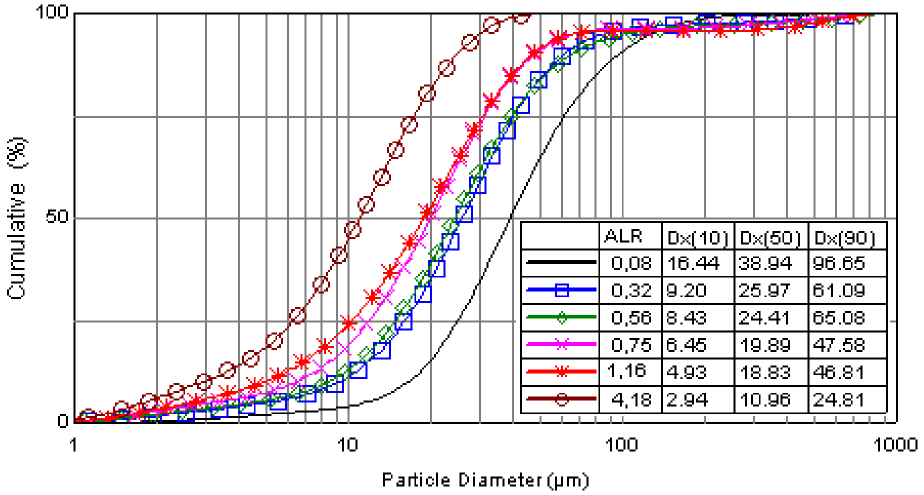
Figure 7. Experimental SMD and MMD.

The effect of air-liquid ratio on the drop size distributions are shown in Fig. 8.

The particle size distribution at a low ALR depicts the presence of larger droplets compared to the case of higher ALR where the percentage of smaller size droplets have increased significantly, reflecting an improved atomization at higher ALR.



a) Hydrous ethanol



b) B100 soy biodiesel

Figure 8. Cumulative drop size distributions.

## 4. CONCLUSIONS

A blurry injector has been developed for applications in a compact flameless combustion chamber and the spray characteristics were obtained for injection of ethanol and B100 soy biodiesel. The discharge coefficient is seen to decrease with an increase in air-to-liquid mass flow ratio, which is attributed to a decrease in available area for liquid flow with increasing air flow. The injector produced a spray with both smaller droplets and a narrower range of droplet diameters. The droplet diameter decreased with increasing ALR, but with a trend of diminishing returns. The droplet diameter is seen to decrease with an increase in air liquid mass ratio due to an increase in exit velocities and turbulence inside the injector. For the studied operating conditions, for hydrous ethanol SMD varies from 10.71 µm to 6.29 µm and MMD varies from 15.27 µm to 7.77 µm, and for B100 soy biodiesel SMD varies between 26.40 µm to 9.59 µm and MMD decreases from 38.94 µm to 1.19 µm.

## 5. ACKNOWLEDGEMENTS

The authors acknowledge Vale Soluções em Energia for providing a scholarship to the first author, FAPESP for financial support and Bioverde for providing the B100 soy biodiesel for tests.

## 6. REFERENCES

Azevedo, C.G., Costa, F.S., Couto, H.S., Characterization of a blurry injector for biofuels, Proceedings of 21st Brazilian Congress of Mechanical Engineering, Natal, RN, Brazil, 2011.

Delmeé G. J., 1983, “Manual de Medição de Vazão”, São Paulo: Editora Edgard Blucher. 474p.
Gañán-Calvo, A. M., 2005, “Enhanced Liquid Atomization: From Flow-Focusing to Flow-Blurring”, Applied Physics Letters 86.
Lefebvre, A.H., 1983, “Gas Turbine Combustion”, Hemisphere, Washington, D.C.
Lefebvre, A.H., 1989, “Atomization and Sprays”, Hemisphere, New York.
Panchasara, H. V., Sequera, D. E., Schreiber, W. C., Agrawal, A. K., Emissions Reductions in Diesel and Kerosene Flames Using a Novel Fuel Injector, Journal of Propulsion and Power. Vol. 25, No. 4, 2009.
Simmons, B., Agrawal, A. K., Spray Characterization of a Flow-Blurring Atomizer, Atomization and Sprays, Vol 20, pp. 821–835, 2010.
Wünning, J. A., Wünning, J. G., 1997, “Flameless Oxidation to Reduce Thermal No-formation”, Progress in Energy and Combustion Science, 23, Issue 1, 1997, p.81-94.

## 7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.