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CHARACTERISTIC DIAMETERS OF BIODIESEL SPRAYS BY A BLURRY INJECTOR

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Abstract. *The combustion processes in engines and turbines are heavily dependent on the quality of atomization. A blurry injector is an air-blast injector that presents a backflow of gas into the liquid feed tube and can generate a relatively uniform spray with small droplets. This paper presents and compares the characteristic diameters of B100 soy biodiesel through a blurry injector as function of the air-liquid mass ratio with different liquid mass flow rates. Two exit geometries of the blurry injector were considered: cylindrical and divergent. Most mean characteristic diameters have decreased continuously with air liquid mass ratio, for both nozzle geometries and for all liquid mass rates considered. De Brouckere diameter, D_{43}, presented differentiated behaviour probably caused by the more significant influence of the larger droplets. In most cases D_{jk} varied, approximately, linearly with D_{30}, for $D_{30} < 150$ μm, and with the square of D_{30}, for $D_{30} > 200$ μm.*

Keywords*: characteristic diameters, blurry injector, soy biodiesel*

1. INTRODUCTION

In the last decades there has been a significant interest in new combustion technologies using biofuels in order to reduce energy production costs, increase operating efficiency, reduce pollutant emissions and improve the performance of power generation.

Among various alternative fuels, biodiesel is one of the most widely studied biofuels, due to their similarity to conventional diesel fuels (Raghavan *et al.*, 2009; Desantes *et al.*, 2009; Park *et al.*; 2011). Biodiesel is an environmentally clean and renewable energy source, produced from vegetable and animal oils through a transesterification process, in which the triglycerides from vegetable oils react with an alcohol in the presence of a catalyst such as sodium or potassium hydroxide to form biodiesel and glycerol.

Several studies have been performed to evaluate performance of the biodiesel as an alternative energy source for diesel engines (Anand *et al.*, 2011; Kannan and Anand 2012; Özener *et al.*, 2014), internal combustion engines (Xue *et al.*, 2011; Kuti *et al.*, 2013; Lee and Baik, 2014) and gas turbine (Hashimoto *et al.*, 2008; Panchasara *et al.*, 2009a; Chong and Hochgreb, 2012).

The atomization of a liquid into small droplets in the form of a spray is an important process in combustion and propulsion systems, including applications in power generation. Liquid fuels are atomized through injectors, aiming to increase the contact area between the fuel and oxidizer and, therefore, to increase the rates of fuel evaporation and mixing, thus reducing the time available and the volume required for complete combustion inside liquid fueled combustion systems (Lefebvre, 1989).

Since the combustion of liquid fuels involves many complex processes such as atomization, dispersion and vaporization of the fuel and mixing of the fuel and gaseous oxidizer, new atomization technologies are needed in order to produce sprays with fine droplets, which are necessary to minimize emissions of nitric oxides (NO_x), carbon monoxide (CO), unburned hydrocarbons (UHC) and particulate matter (PM).

Gañan-Calvo (2005) presented a new twin fluid injector, the so-called flow-blurring injector, that yields high atomization efficiency, producing a spray with highest surface-to-volume ratio as compared to conventional air-blast injectors for a given values of liquid flow rate and total energy input. Figure 1 shows a scheme of the geometry and flow structure inside a blurry injector.

The flow blurring injector consists of a fuel tube and a discharge orifice both of inside diameter *d* and separated by gap *H*. When $H/d \leq 0.25$, the surrounding air flows back into the liquid tube tip, creating a two phase flow with air bubbles within the liquid exit. This two-phase mixture undergoes sudden decrease in pressure while exiting through the discharge orifice. Consequently, the air bubbles explode due to the pressure drop at the injector exit orifice and then break-up the surrounding fuel into droplets.

Previous studies compared experimentally a flow blurring injector with a commercial airblast injector and showed that the flow blurring injector produces a finer spray than the airblast injector for equivalent conditions, whereas requires lower energy input or lower pressure drop in the atomizing air line (Simmons *et al.*, 2009; Simmons and

Agrawal, 2010). Combustion experiments show that for a given equivalence ratio, heat release rate, and atomizing air-to-liquid mass ratio, the flow blurring injector produced three to five times lower NO_x and CO emissions in diesel and kerosene flames, compared to the air blast injector (Panchasara *et al*., 2009b). Besides, liquid fuel, such as kerosene, diesel, biodiesel, straight vegetable oil and glycerol, atomized by a flow blurring injector can mainly burn under lean premixed mode producing extremely low emissions of CO and NO_x (Simmons and Agrawal, 2012; Jiang *et al*., 2012).

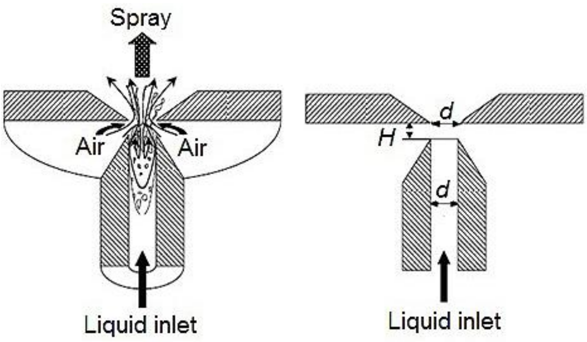


Figure 1. Schematic of a flow-blurring injector: flow structure and geometric details.
Source: Panchasara, H.V. *et al.* (2009).

Rapid fuel vaporization and mixing with oxidizer are key requirements for liquid-fueled small-scale combustion systems. The flow-blurring injector presents high atomization efficiency adjacent to the nozzle tip and excellent fuel vaporization and mixture with air, favoring its application in different combustion systems.

The mean diameter of spray droplets is used to describe the quality of atomization, trajectory and penetration of the spray, facilitate correlation with physical parameters and fitting of experimental data by suitable distribution functions. A droplet size distribution is evaluated by the characteristic diameter D_{jk} defined by

$$D_{jk} = \left[\frac{\sum_{i=1}^{N} N_i D_i^j}{\sum_{i=1}^{N} N_i D_i^k} \right]^{\frac{1}{j-k}} \quad (1)$$

where N_i is the number of droplets with diameter D_i and N is the total number of droplets within the spray.

Table 1 depicts common mean diameters and their fields of application (Mugele and Evans, 1951; Elkotb, 1982).

Table 1. Common mean diameters.

k	*j*	*k+j*	*Name*	*Field of application*
0	1	1	Linear mean diameter	Comparisons, evaporation
0	2	2	surface mean diameter	Absortion
0	3	3	Volume mean diameter	Hydrology
1	2	3	Surface/length mean diameter	Adsortion
1	3	4	Volume/length mean diameter	Evaporation/molecular diffusion
2	3	5	Sauter mean diameter	Combustion, mass transfer and efficiency studies
3	4	7	De Brouckere diameter	Combustion equilibrium

Therefore, this work presents and compares mean diameters of SME (soy B100 biodiesel) sprays formed by a blurry injector, considering cylindrical and divergent nozzle exit geometries, for different operational conditions.

2. EXPERIMENTAL SETUP

The experimental setup for investigating the biodiesel sprays is shown in Fig. 2. SME biodiesel was used as test fuel. 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) and repeatability of ± 0.5 %. The flow rate of B100 soy biodiesel was measured by rotameter, with the uncertainty in the measurements being ± 2% and repeatability of ± 0.5 %.

Supply pressures in the fuel and atomizing air lines were measured using pressure transducers at locations depicted in Fig. 2. For correction in air density, the supply pressure and temperature of the atomizing air were closely monitored using a pressure gauge and a K-thermocouple.

The number of droplets within a given volume range (or diameter range) at atmospheric conditions were measured by a laser diffraction system (Spraytec/Malvern Instruments Inc.). The operating principle of this system is the laser scattering produced by the droplets. The data acquisition rate was set at 10 kHz and a 300 mm lens was used for droplet size range of 0.1–900 µm with accuracy of ±1% of full scale and repeatability of ± 1%. Measurements were taken along the centerline of the spray cone for all tests at a distance of 50 mm below the exit of the atomizer, since the characteristic diameters were approximately constant from 40-70 mm.

The properties of the SME biodiesel used in this study are listed in Table 1.

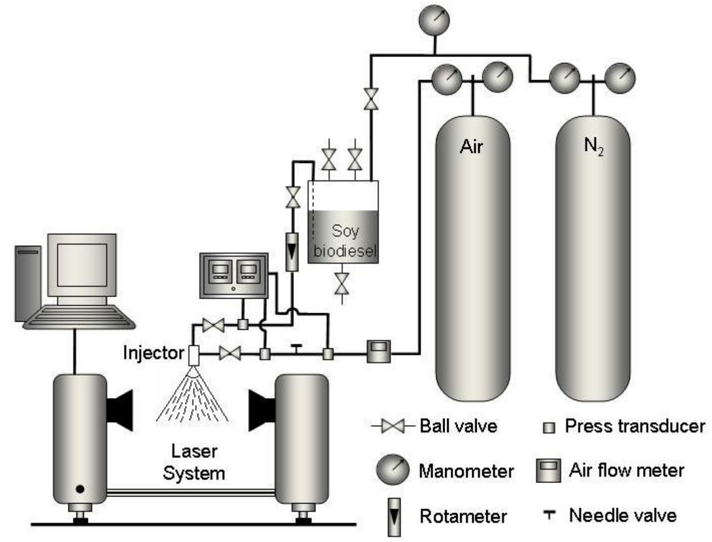


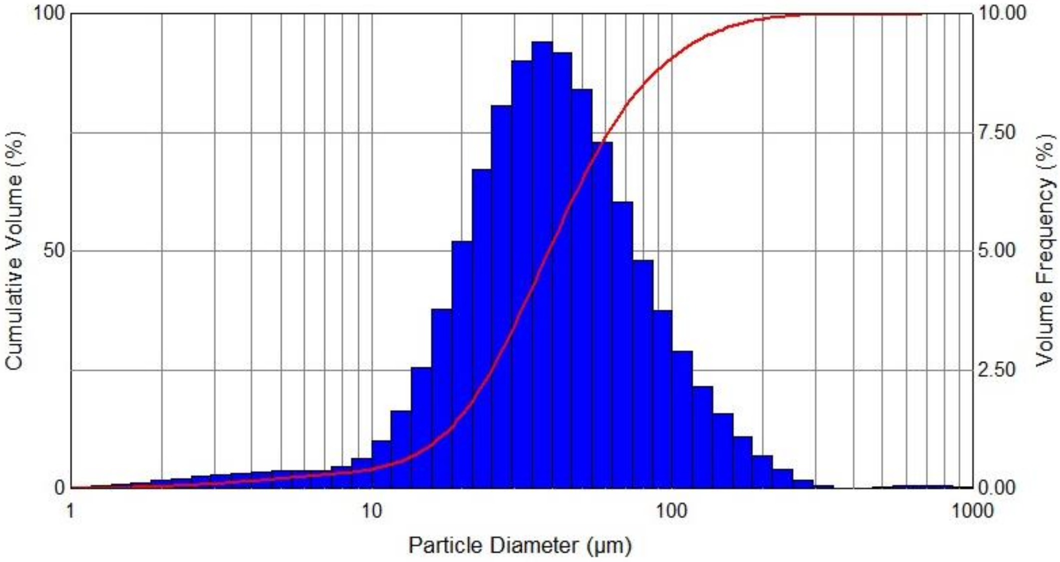
Figure 2. Schematic representation of the experimental setup.

Table 1. SME biodiesel properties.

Property	**Units**	**Methods**	**Values**
Density (20 °C)	kg/m^3	ASTM D - 1298	880.6
Flash pt.	°C	ASTM D - 93	143
Viscosity (40 °C)	mm^2/s	ASTM D - 445	4.21
Cetane number	-	EN ISO 5165	52
Ester contents	% m/m	EN 14103	98.7
Carbon residue	% m/m	ASTM D - 4530	0.030
Free glycerin	% m/m	ASTM D - 6584	0.010
Total glycerin	% m/m		0.140
Monoglyceride	% m/m		0.010
Diglyceride	% m/m		0.300
Triglyceride	% m/m		0.780
Methanol	% m/m	EN 14110	0.020
Oxidation Stability (110 °C)	h	EN 14112	18

Source: BioVerde Industria e Comercio de Biocombustiveis S.A. (Brazil).

In the present study, for a given liquid flow rate, the air flow rates were varied to obtain the variation in the air-to-liquid mass ratio (ALR) in the injector. The air flow rate was varied from a minimum of 1.10 - 2.50 l/min and the liquid flow rate ranged from 0.01 to 0.05 l/min. For each experimental condition, the spray volume distribution was provided by the Spraytec laser system, as depicted in Figure 3.



Size (µm)	% V <	% V	Size (µm)	% V <	% V	Size (µm)	% V <	% V
0.117	0.00	0.00	2.51	0.65	0.20	54.12	68.91	8.39
0.136	0.00	0.00	2.93	0.89	0.24	63.10	76.18	7.27
0.158	0.00	0.00	3.41	1.17	0.28	73.56	82.20	6.02
0.185	0.00	0.00	3.98	1.49	0.32	85.77	87.01	4.81
0.215	0.00	0.00	4.64	1.84	0.35	100.00	90.76	3.75
0.251	0.00	0.00	5.41	2.20	0.36	116.59	93.63	2.87
0.293	0.00	0.00	6.31	2.57	0.37	135.94	95.78	2.15
0.341	0.00	0.00	7.36	2.95	0.38	158.49	97.35	1.57
0.398	0.00	0.00	8.58	3.41	0.46	184.79	98.43	1.08
0.464	0.00	0.00	10.00	4.04	0.64	215.44	99.12	0.69
0.541	0.00	0.00	11.66	5.05	1.00	251.19	99.51	0.39
0.631	0.00	0.00	13.59	6.67	1.62	292.87	99.69	0.18
0.736	0.00	0.00	15.85	9.22	2.55	341.46	99.75	0.06
0.858	0.00	0.00	18.48	12.99	3.77	398.11	99.75	0.01
1.00	0.00	0.00	21.54	18.20	5.21	464.16	99.76	0.00
1.17	0.02	0.02	25.12	24.91	6.71	541.17	99.78	0.02
1.36	0.07	0.05	29.29	32.97	8.05	630.96	99.83	0.05
1.58	0.16	0.09	34.15	41.97	9.00	735.64	99.90	0.07
1.85	0.28	0.12	39.81	51.36	9.39	857.70	99.96	0.06
2.15	0.45	0.16	46.42	60.52	9.16	1000.00	100.00	0.04

Figure 3. Volume distribution of a biodiesel spray from the Spraytec analyser.

Equation (1) was rewritten in terms of the measured droplet volume fractions in order to calculate the mean diameters D_{10}, D_{20}, D_{30}, D_{21}, D_{31}, D_{32} and D_{43}.

The volume of N_i droplets within the spray having diameter D_i is

$$V_i = N_i V_{d,i} = N_i \frac{\pi D_i^3}{6} \tag{2}$$

and the volume fraction of droplets with diameter D_i is:

$$f_{V,i} = \frac{V_i}{V} = \frac{N_i}{V}\frac{\pi D_i^3}{6} \tag{3}$$

Therefore, the number of droplets with diameter D_i is $N_i = f_{V,i} 6V / \pi D_i^3$, which can be replaced in Eq.(1), yielding:

$$D_{jk} = \left[\frac{\sum_{i=1}^{N} f_{V,i} D_i^{j-3}}{\sum_{i=1}^{N} f_{V,i} D_i^{k-3}} \right]^{\frac{1}{j-k}} \tag{4}$$

3. RESULTS AND DISCUSSION

Tables 2 and 3 show the operational ranges of the injector with divergent nozzle exit and a cylindrical nozzle exit, respectively.

Table 2 – Operational range of injector with divergent nozzle exit.

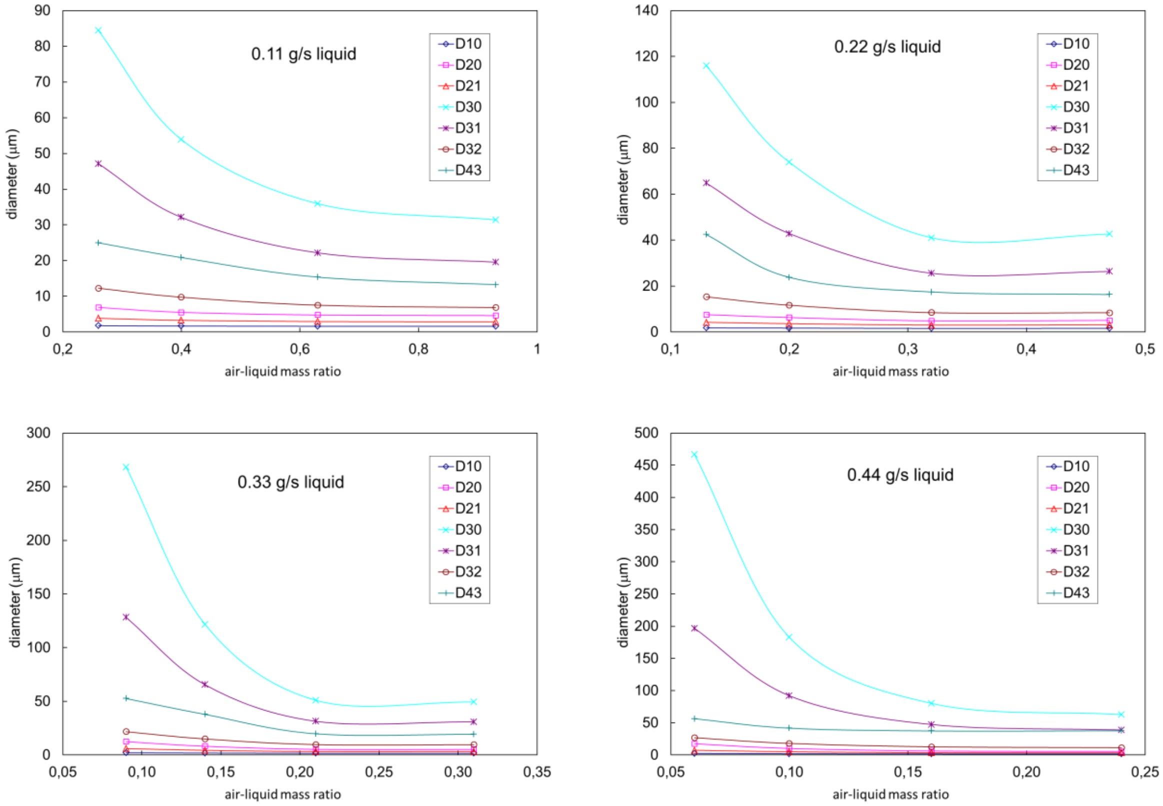
$\dot{m}_l$ (g/s)	$\dot{m}_{air}$ (g/s)	ALR (-)
0.11	0.029 - 0.102	0.26 - 0.93
0.22	0.029 - 0.103	0.13 - 0.47
0.33	0.029 - 0.104	0.09 - 0.31
0.44	0.029 - 0.105	0.07 – 0.24
0.56	0.029 - 0.107	0.05 – 0.19

Table 3 – Operational range of injector with cylindrical nozzle exit.

$\dot{m}_l$ (g/s)	$\dot{m}_{air}$ (g/s)	ALR (-)
0.11	0.026 - 0.089	0.24 - 0.81
0.22	0.026 - 0.092	0.12 - 0.42
0.33	0.027 - 0.094	0.08 - 0.28
0.44	0.027 - 0.094	0.06 – 0.21
0.56	0.027 - 0.096	0.05 – 0.17

Figures 4 and 5 present several characteristic mean diameters, versus air liquid mass ratios, with different liquid mass flow rates, for sprays produced by blurry injectors with a divergent nozzle exit and a cylindrical nozzle exit, respectively.

Most characteristic mean diameters decreased continuously with air liquid mass ratio, in most operational conditions considered, for both nozzle geometries. D_{43} presented differentiated behavior in some cases, probably due to the more significant influence of the larger droplets.



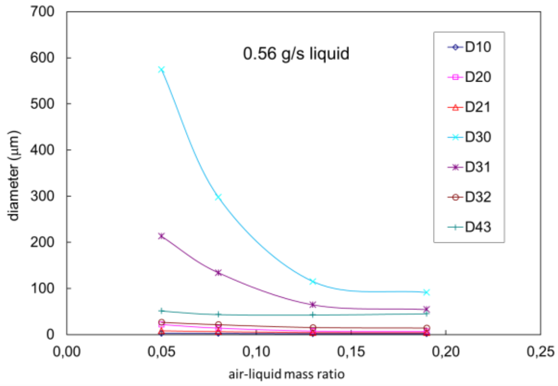
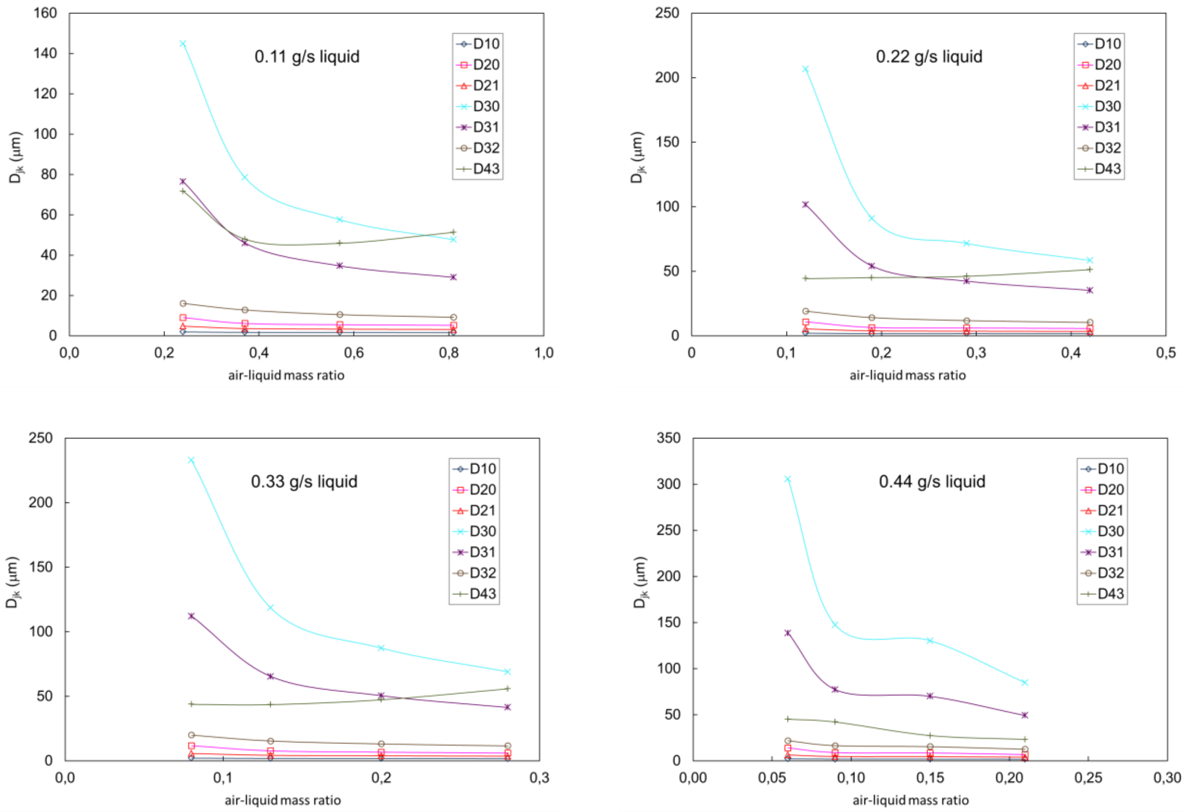


Figure 4. Characteristic diameters vs air-liquid ratio of biodiesel sprays, using a divergent nozzle exit, for different liquid mass flow rates.

Figures 6 and 7 show mean diameters vs Sauter mean diameter D_{32} and volume mean diameter D_{30} of the biodiesel sprays, for all cases, using divergent and cylindrical nozzle exits, respectively. Power curves were adjusted to experimental data and are shown in the figures with the corresponding correlation coefficients.

Plots in Figures 6 and 7 converge approximately linearly to zero, for small diameters, except the De Brouckere diameter D_{43} for the cylindrical nozzle, probably due to the greater influence of larger droplets, as mentioned before.

In general, the correlation coefficients of mean diameters with volume mean diameter were higher than for Sauter mean diameters.



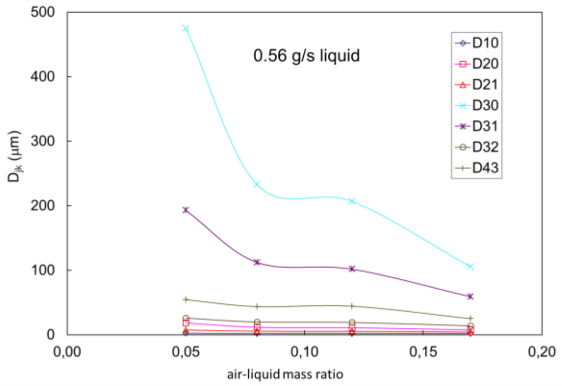


Figure 5. Characteristic diameters vs air-liquid ratio of biodiesel sprays, using a cylindrical nozzle exit, for different liquid mass flow rates.

The mean diameters could be compared to theoretical ones for different drop size probability functions (Mugele and Evans, 1951), for example:

a) Logarithmic probability distribution function:

$$\frac{dV}{dy} = \frac{\delta}{\sqrt{\pi}} e^{-\delta^2 y^2} \tag{5}$$

where $y = \ln \frac{D_{jk}}{D_{30}}$ and δ is the distribution factor, with theoretical mean diameters:

$$D_{jk} = D_{30} e^{\frac{k+j-6}{4\delta^2}} \tag{6}$$

b) Rosin-Rammler probability distribution function:

$$\frac{dV}{dD} = \frac{\delta D^{\delta-1}}{D_{ref}^{\delta}} e^{-\frac{D}{D_{ref}}\delta} \tag{7}$$

where D_{ref} is a characteristic size (=D_{30}) and δ is the distribution factor. The theoretical mean diameters are:

$$D_{jk}^{j-k} = D_{ref}^{j-k} \frac{\Gamma\left(\frac{j-3}{\delta}+1\right)}{\Gamma\left(\frac{k-3}{\delta}+1\right)} \tag{8}$$

where Γ is the gamma function.

c) Nukiyama-Tanasawa probability distribution function:

$$\frac{dV}{dD} = \frac{b^6/\delta}{\Gamma(3/\delta)} D^5 e^{-bD^{\delta}} \tag{9}$$

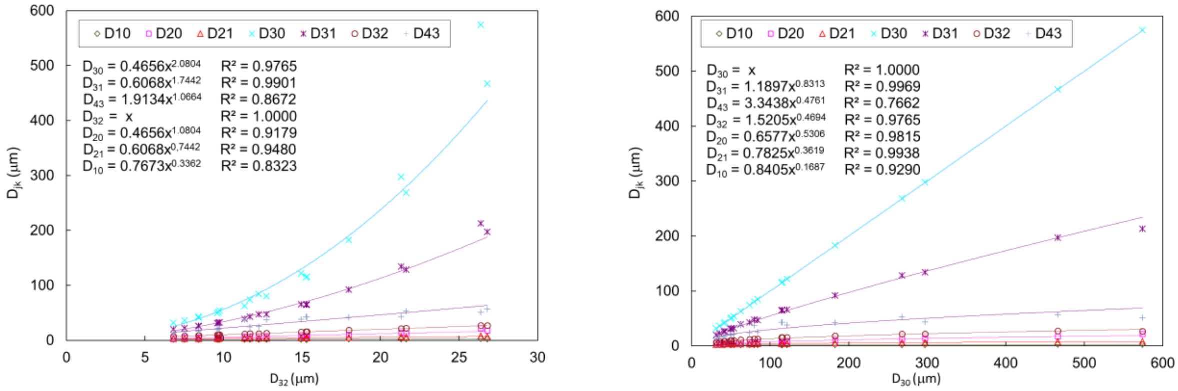
where δ is the distribution factor and b is a size parameter, with theoretical mean diameters calculated by:

$$D_{jk}^{j-k} = b^{-\frac{j-k}{\delta}} \frac{\Gamma\left(\frac{j+3}{\delta}\right)}{\Gamma\left(\frac{k+3}{\delta}\right)} \tag{10}$$

The theoretical mean diameters D_{jk} based on the previous distribution functions vary linearly with the reference diameter, and this behavior is confirmed for small diameters (D_{30} < 150 μm) in most of the experimental data depicted in Figures 6 and 7.

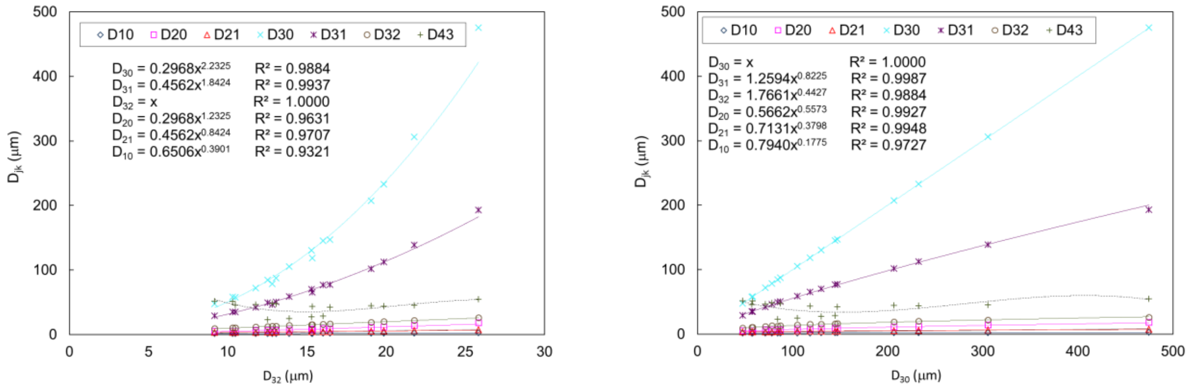
Figure 8 presents normalized mean diameters (D_{jk}/D_{30}) versus the mean volume diameter D_{30}.

Initially, for smaller $D_{30,}$ there is a significant decrease of the normalized mean diameters, but for larger drop sizes, D_{30} > 200 μm, the normalized mean diameters decrease approximately linearly with D_{30}. As a consequence, for larger droplets, the mean diameters vary approximately with the square of the reference diameter D_{30}.



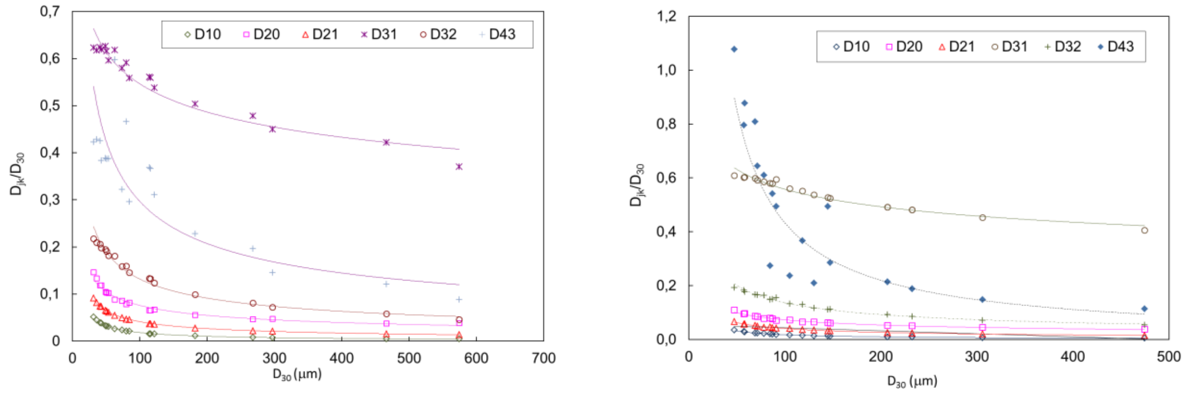
a) b)

Figura 6. Mean diameters of biodiesel sprays using a divergent nozzle exit, vs a) Sauter mean diameter and b) volume mean diameter, for all cases.



a) b)

Figura 7. Mean diameters of biodiesel sprays using a cylindrical nozzle exit, vs a) Sauter mean diameter and b) volume mean diameter, for all cases.



a) Divergent nozzle b) cylindrical nozzle

Figure 8. Normalized mean diameters versus D_{30}.

4. CONCLUSIONS

The mean diameters of B100 soy biodiesel sprays by a blurry injector were determined, as function of air-liquid mass ratio and liquid mass flow rate. Two exit geometries of the blurry injector were considered: cylindrical and divergent. Most mean diameters have decreased monotonically with air-liquid mass ratio for all liquid mass flow rates for both geometries tested. Except De Brouckere diameter D_{43}, the other characteristic diameters were adjusted by power curves to Sauter mean diameters D_{32} and to volume mean diameters D_{30}, yielding reasonably good correlation coefficients. In most cases D_{jk} varied approximately linearly with the reference diameter D_{30} for small diameters ($D_{30} <$ 150 µm) and varied approximately with the square of the reference diameter D_{30} for larger drop diameters ($D_{30} >$ 200 µm).

5. ACKNOWLEDGEMENTS

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