encit 2020

Associação Brasileira de Engenharia e Ciências Mecânicas

18th Brazilian Congress of Thermal Sciences and Engineering
November 16-20, 2020 (Online)

ENC-2020-0580
DESIGN AND ESTIMATED DROPLET SIZE OF A TWIN-FLUID Y-JET INJECTOR FOR ATOMIZATION OF FOSSIL FUELS AND BIOFUELS BLENDS

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Abstract. *Due to the continuous increase in oil prices and the fact that environmental legislation has become increasingly rigorous, recommending strict limits for pollutant emissions in engines, turbines, furnaces, boilers and industrial combustion processes, it is verified that is in the best interest of the country and companies to investigate the use of biofuels such as mixtures of these fuels with fossil fuels in industrial applications, aiming to reduce costs, increase the efficiency of operations, and reduce the emission of pollutants. Combustion of liquid fuels depends on efficient atomization to increase the surface area of the fuel and thus achieve high rates of mixing and evaporation. In order to promote combustion with maximum efficiency and minimum emission of pollutants, an injector must provide a fuel spray that evaporates and disperses rapidly to produce a homogeneous mixture of vaporized fuel and air. Since a significant portion of the industrial combustors operate with liquid fuels and the injector is a fundamental part in combustion systems using such fuels, the present work aims designing a Y-jet injector for the atomization of fuel blends that will be used in future applications for combustion systems. However, the purpose of this work is to determine the theoretical median mass diameter (MMD) and the theoretical Sauter mean diamenter for different blends of biofuels (soybean biodiesel and bovine tallow and hydrated ethanol) and conventional fuels (common gasoline) for different ratios of blends.*

Keywords: *Spray, Y-jet injector, ethanol, biodiesel, gasoline*

1. INTRODUCTION

Concerns about the rising fuel price and global climate change have led to the search for alternative fuels and blends of biofuels with gasoline in combustion systems and industrial applications aiming to reduce costs, increase the efficiency of operations, and reduce the emission of pollutants. The liquid droplets atomization is the key process of the behavior of a liquid-fuel-fired combustion system and has important applications in several industrial processes and in many aspects of the engine's combustion performance, such as gas turbines and rocket motors. In liquid fuel combustion systems the atomization process to produce sprays represents one of the main methods for obtaining high evaporating and mixing rates of the fuel, with subsequent ignition and flame formation.

The process of atomization is a process where a liquid jet or sheet is broken up by the kinetic energy of the liquid itself or by exposure to high velocity air or gas (Lefebvre, 1989). The droplets formed during the atomization process are directly related to the mixing and vaporization rates of the fuel, so in general aspects, the small droplets generated through the atomizers devices increases the specific surface area of the fuel leading to high rates of mixing and evaporation as near as possible to the desired design. There are many ways to generate a spray, however, for large-scale facilities such as boilers and industrial furnaces where large flow rates of very viscous fuels have to be handled, one of the nozzles most commonly used is the steam-assisted type with a "Y" configuration (Barreras *et al.*, 2006).

One of the twin-fluid atomizers widely used in industrial combustors is the so-called Y-type injector (Fig. 1). The multiphase flow in the Y-jet is created by injecting of the liquid into the air stream radially, under a particular angle to the axis (Y-shaped junction). The two-phase flow is created inside the mixing chamber and it disintegrates when it reaches the discharge orifice.

For the Y-jet injector, the atomizing gas is considered to enter at a high velocity as the liquid fuel is injected at a given pressure. Flowing into the mixing chamber at a high velocity, the air abruptly expands, creating a recirculation zone. The recirculation drags a small number of fuel droplets that flows towards the mixing chamber through the duct side. The airflow expansion recovers some of the droplets and returns them to the flow core. The encounter of air and liquid flow occurs at the so-called mixing point, generating a transition zone, where part of the liquid accumulates on the wall of the mixing duct, creating a liquid film, and the other part remains dispersed in the liquid flow core. This last liquid fraction disintegrates into small droplets due to the shear forces which appear at the gas/liquid interface. Many studies were found in literature referring to designs and characterization of Y injectors, such as Mullinger and Chigier (1974), Graziadio *et al.* (1987), Couto *et al.* (1992) Andreussi *et al.* (1992), Song and Lee (1994), Lacava *et al*. (1998), Lacava (2000) and Pacífico, (2000).

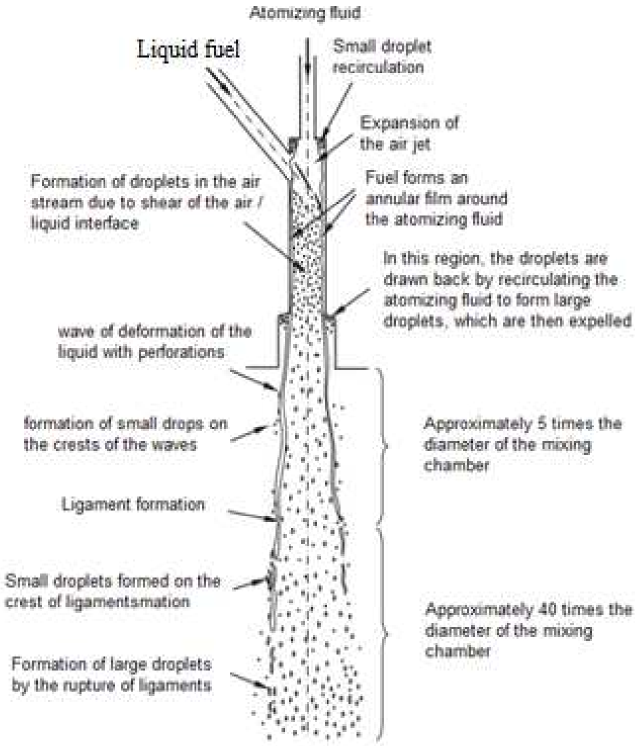

Figure 1. Droplet formation mechanism in type Y injector (Mullinger and Chingier, 1974).

Since many industrial combustors operate with liquid fuels and the injector is an important device in the combustion systems using such fuels, the present work aims to design a Y-jet injector for the atomization of fuel blends that will be used in future applications for combustion systems. However, the purpose of this work is to determine the theoretical median mass diameter (MMD) of the droplets generated by the proposed Y injector from the equation proposed by Wigg (Mullinger and Chigier, 1974) and the theoretical Sauter mean diameter for different blends of biofuels (soybean biodiesel and bovine tallow and hydrated ethanol) and conventional fuels (common gasoline) for different ratios of mixtures.

2. Y-JET INJECTOR DESING

For the Y-jet injector it is considered that the atomization gas enters with a high velocity as the liquid fuel is injected at a given pressure. The following considerations are adopted for calculating the injector geometric parameters (Lacava, 2000; Mullinger and Chigier, 1974):

- Fuel flow is considered one-dimensional and incompressible under permanent regime;
- Atomization gas flow is considered unidimensional and isentropic, with a constant ratio of specific heats;
- The physicochemical properties of the fuel and the atomizing gas are known;
- At the exit orifice the air reaches sonic conditions (M=1), which assures a maximum mass flow of atomizing gas.

Figure 2 shows the geometric scheme of the Y-type injector. The recommendations for the injector geometric parameters were obtained by Mullinger and Chigier (1974), who conducted an experimental research on this injector type.

In order to develop the design of the Y-jet injector were admitted a flow rate ($\dot{m}_l$) of 2 g/s, were adopted a stagnation pressure (P_0) of 400 kPa and stagnation temperature (T_0) of 298 K. The calculation presented follow the procedure developed by Lacava (2000), based on the recommendations of Mullinger and Chigier (1974).

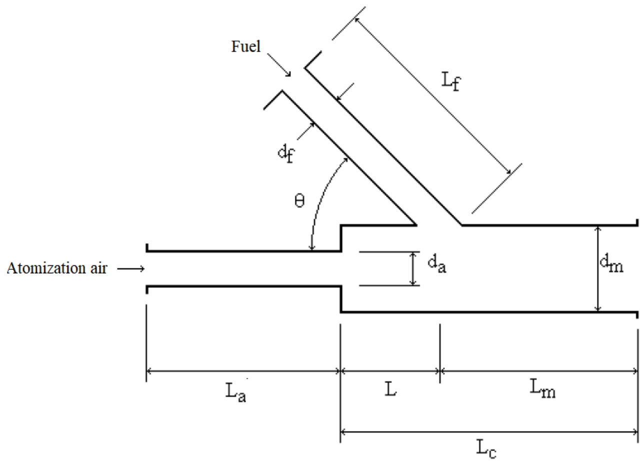

Figure 2. Geometric design scheme of Y-type injector (Mullinger and Chigier, 1974).

Mullinger and Chigier (1974) determined the ratio between atomization air and liquid (GLR), recommending a value in the range of 0.5 - 0.15. In this case was adopted GLR equal to 0.1, such as:

$$GLR = \frac{\dot{m}_g}{\dot{m}_l} = 0.1 \Rightarrow \dot{m}_g = 0.2\, {}^{g}\!/\!{}_{s} \tag{1}$$

being:
GLR Gas / liquid mass flow ratio (dimensionless);
$\dot{m}_g$: Gas mass flow rate (g/s);
$\dot{m}_l$: Liquid mass flow rate (g/s).

It is assumed that at the the injector nozzle exit (mixing chamber inlet) the atomization gas has critical conditions (M = 1) ensuring maximum gas velocity. Then, in the nozzle exit the critical properties of the gas are given by:

$$\frac{T^*}{T_0} = \frac{2}{k+1} \Rightarrow T^* = 238.4K \tag{2}$$

$$\frac{P^*}{P_0} = \left(\frac{2}{k+1}\right)^{k/k-1} \Rightarrow P^* = 2.11 \cdot 10^5\, Pa \tag{3}$$

$$\rho^* = \frac{P^*}{RT^*} \Rightarrow \rho^* = 2.96\, {}^{kg}\!/\!{}_{m^3} \tag{4}$$

being:
T^* : Critical output temperature (K);
T_0 : Stagnation temperature (K);
k : Ratio of specific heats (dimensionless).
P^* Critical output pressure (MPa, kPa);
P_0 : Stagnation pressure (MPa, kPa);
R : Gas constant (J/kg-K);
ρ^* : Especific mass (kg/m^3, g/cm^3).

The atomizing gas velocity at the mixing chamber inlet will be calculated according to the Eq. (5):

$$V^* = \sqrt{kRT^*} = 315.85\, {}^{m}\!/\!{}_{s} \tag{5}$$

being:
V^* : Velocity at camera input (m/s);

Considering that the gas flow conditions are critical, the mass flow rate will be maximum ($\dot{m}_{MAX}$) and can be found with the equation (6):

$$\dot{m}_{\max} = m^* = \frac{A_g^* P_{0g}}{\sqrt{RT_0}} \cdot \sqrt{k\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \quad (6)$$

From this equation we can be found the area and diameter of the nozzle, using the Eq. (7) and Eq. (8):

$$A_g^* = \frac{m^* \sqrt{RT_0}}{P_{0g}\sqrt{k}} \cdot \left(\frac{2}{k+1}\right)^{-\frac{k+1}{2(k-1)}} = 1.95 \cdot 10^{-5} m^2 \quad (7)$$

$$d_a = \sqrt{\frac{4 \cdot A}{\pi}} = 4.98 \cdot 10^{-4} m \quad (8)$$

being:
A_g^* : Atomizing air area (m²);
d_a : Atomizing air diameter (m).

From the atomizing air diameter, it is possible to calculate the others geometrical parameters of the injector following the recommendations of Mullinger and Chigier presented in Table 1.

Table 1. Recommendations for designing the dimensions of the Y-jet injector (Mullinger and Chigier, 1974).

Parameter	Recommended
Diameter of the atomizing gas line	d_a
Diameter of the fuel line	$d_f = d_a$
Diameter of mixing chamber	$d_m = (1.4-1.8)d_a$
Pre-mixing length	$L = (1-2)d_a$
Mixing length	$L_m = (4-5)d_a$
Total length of the mixing chamber	$L_c = L + L_m$
Length of atomizing gas line	$L_a \succ 2d_a$
Length of fuel line	$L_f \succ 2d_a$
Fuel Line Shaft Angle	θ=52º

3. DROPLETS SIZE

Due to the random nature of the atomization process, the spray produced by an injector is composed of droplets with a great variability of diameters. Therefore, in order to characterize a spray with a single droplet diameter value, it is necessary to have some statistical function of the sizes of the measured droplets. In this study will be theoretically determined the mass median diameters (MMD) and the Sauter mean diameter for different blends composed by hydrated ethanol (E), soybean biodiesel and bovine tallow (B) and common gasoline (G). The blends to be analyzed are shown in Table 2.

The mass median diameter (MMD) is the representative diameter such that 50% of the total mass of the atomized liquid consists of droplets with diameters greater than the indicated value and 50% is composed of drops with diameters smaller than the indicated value.

The median mass diameter (µm) for the proposed Y injector will be determined using the Wigg equation (Mullinger and Chigier, 1974):

Table 2. Fuel blends.

Sample	Proportion (%)
G-E	90-10
G-E	75-25
G-E	60-40
G-E	40-60
G-E	20-80
G-B	90-10
G-B	75-25
G-B	60-40
G-B	40-60
G-B	20-80

$$MMD = D_{50} = \frac{20 \cdot \nu^{0.5} \cdot \dot{m}_c^{0.1} \left(1 + 1/r_{atm}\right)^{0.5} R_m^{0.1} \sigma^{0.2}}{\rho_{ar}^{0.3} \cdot \Delta u} \quad (9)$$

being,
ν : kinematic viscosity of the fuel (cP);
$\dot{m}_c$: fuel mass flow (g/s);
R_m : radius of the mixing chamber (cm);
σ : surface tension of the fuel (dynas/cm);
ρ_{ar} : specific mass of the atomizing fluid (g/cm³);
Δu : relative velocity between the liquid and the air (m/s);
$r_{atm} = \dot{m}_{ar,atm} / \dot{m}_c \geq 0.1$ the air-liquid ratio.

According to (Liu, 2000), the Wigg equation gives good results for very viscous liquids, but great divergence for liquids like water.

The discrete representation most used in spray studies, with special interest in mass transfer and combustion, is the D_{32} or Sauter mean diameter (SMD), defined as the characteristic droplet diameter whose volume - surface area ratio is proportional to the volume - surface ratio of the entire spray:

$$SMD = D_{32} = \frac{\sum N_i D_i^3}{\sum N_i D_i^2} \quad (10)$$

For Y injector, according to Simmons (1997), for practical spray formation:

$$MMD / SMD = 1.20 \quad (11)$$

with a 5% error. So, this equation can be used to determine the mean droplet diameter of the working fluid (Lacava, 2000).

4. RESULTS AND DISCUSSION

4.1 Injector design

Once the parameters design has been established and the obtained value for the gas exit diameter is known it is possible to calculate the others injector geometric parameters following the recommendations formulated in Table 1. The results are presented in Table 3.

From the obtained values a 2D model of the injector was projected using the mechanical modeling software Autodesk Inventor 2015, as demonstrated by the Figure 3, that presents a schematic and the characteristic measurements of the injector.

For the Y- jet injector design was considered the atomization gas as the compressed air to atomize the fuel blends.

Table 3. Internal geometry of the Y-jet injector.

Parameter	Adopted	Value (mm)
Diameter of the atomizing gas line	-	0.498
Diameter of the fuel line	$d_f = d_a$	0.498
Diameter of mixing chamber	$d_m = 1.6d_a$	0.796
Pre-mixing length	$L = 1.5d_a$	0.747
Mixing length	$L_m = 4.5d_a$	2.241
Total length of the mixing chamber	$L_c = L + L_m$	2.988
Length of atomizing gas line	$L_a = 2.5d_a$	1.245
Length of fuel line	$L_f = 2.5d_a$	1.992
Fuel Line Shaft Angle	$\theta = 52°$	$\theta = 52°$

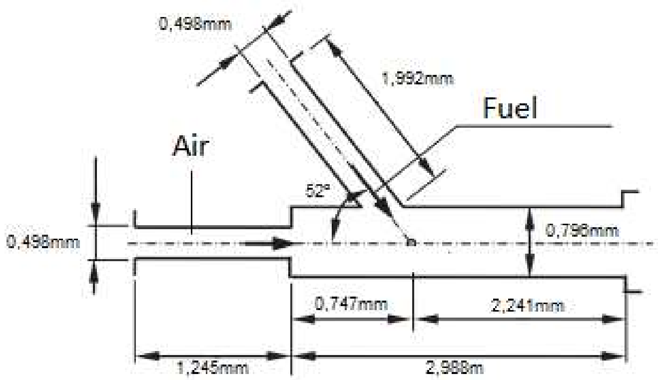

Figure 3. 2D model of Y-jet Injector.

4.2 Droplets diameter

In the present work were determined the theoretical mass median diameters (MMD) and the theoretical Sauter mean diameter for each blend analyzed.

Figures 4 and 5 show the effect of the air-liquid ratio (ALR) on the MMD and SMD for a constant fuel mass flow equivalent to 2 g/s for each fuel blend and Table 4 shows the ALR and theoretical average diameters obtained.

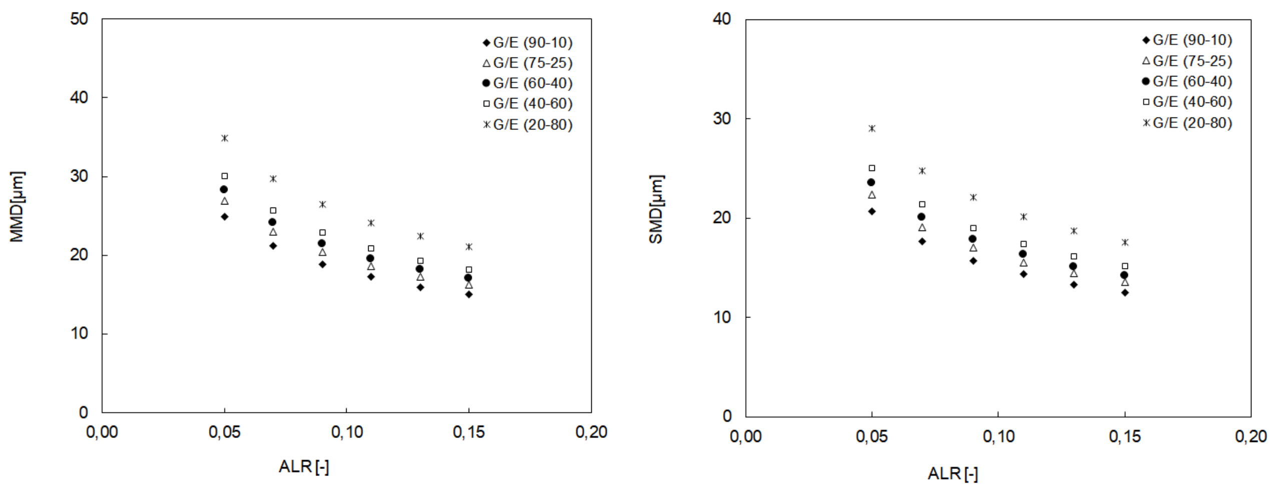

Figure 4 – Theoretical MMD and SMD for the G-E blends.

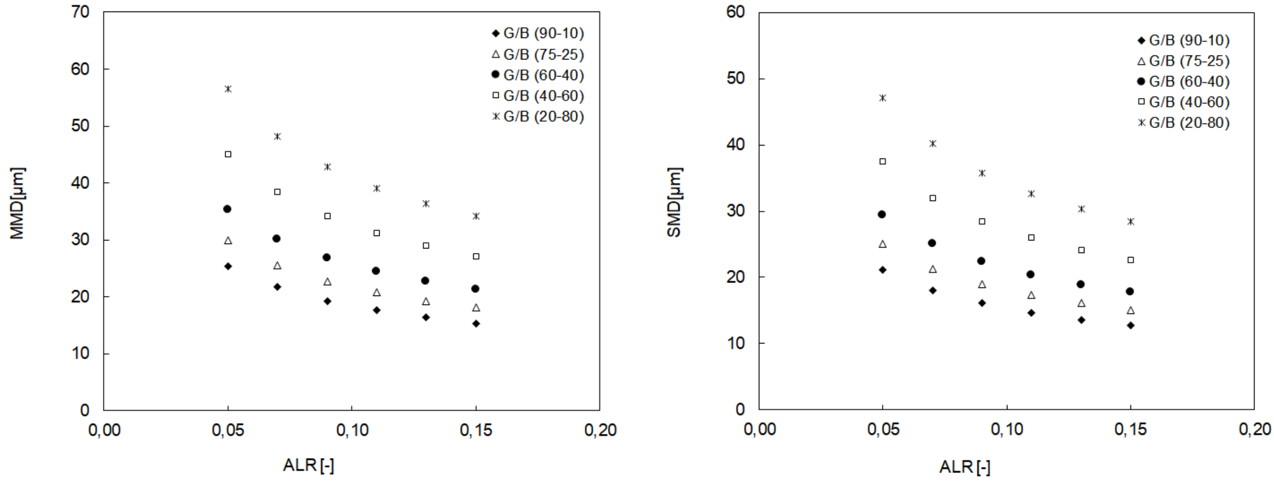

Figure 5. Theoretical MMD and SMD for the G-B blends.

For all the analyzed cases, it is verified that the average diameter of the droplets is a non-linear function of the ALR and an increase in the air-liquid ratio, ALR, leads to a decrease in droplet size, such as the spray has a good quality, generating small droplets.

Table 4. Range of ALR and average diameters.

Sample	ALR (-)	SMD (µm)	MMD (µm)
G-E / 90-10	0.05 - 0.15	12.51 – 20.71	15.01 – 24.85
G-E / 75-25	0.05 - 0.15	13.54 – 22.41	16.25 – 26.90
G-E / 60-40	0.05 - 0.15	14.21 – 2351	17.05 – 28.21
G-E / 40-60	0.05 - 0.15	15.14 – 25.06	18.17 – 30.07
G-E / 20-80	0.05 - 0.15	17.55 – 29.05	21.06 – 34.86
G-B / 90-10	0.05 - 0.15	12.81 – 21.20	15.37 – 25.43
G-B / 75-25	0.05 - 0.15	15.11 – 25.00	18.13 – 30.00
G-B / 60-40	0.05 - 0.15	17.75 – 29.37	21.30 – 35.25
G-B / 40-60	0.05 - 0.15	22.66 – 37.51	27.19 – 45.00
G-B / 20-80	0.05 - 0.15	28.44 – 47.07	34.12 – 56.48

It is observed that for all the blends a good atomization can be obtained using a relatively low ARL, ie, only a small amount of air is needed to obtain a spray composed of small droplets. It is observed that the largest droplet sizes are obtained for the G-E / 20-80 and G-B / 20-80 blends since such blends presented the highest densities, viscosities, and surface tensions.

It is known that the increase in density leads to an increase in droplet size since less interaction occurs with the atomizing air stream, a greater amount of air is necessary to obtain a good atomization.

Likewise, increasing the viscosity causes an increase in droplet size, since increasing the viscosity causes an increase in undisturbed liquid sheet length and jet penetration, prevents wave formation, reduces the turbulence, and consequently, the production of spray with larger droplets.

It is also known that an increase in the surface tension also leads to an increase in droplet size, once an increase in fluid resistance to a shear force occurs and an increase in surface tension also leads to an increase in droplet size, once a high surface tension represents a consolidation force and during the atomization process counteracts any distortion of the surface of the liquid so that by increasing the surface tension a delay in the formation of ligaments and droplets occurs resulting in larger sizes of drops.

5. CONCLUSION

In the present work was presented the design of a twin-fluid y-jet injector for atomization of different blends of conventional fossil fuels (gasoline) and biofuels (hydrous ethanol and soybean biodiesel and bovine tallow). Besides were determined the theoretical mass median diameter (MMD) and the theoretical average Sauter diameter (SMD) produced by the injector for different fuel blends.

For all gasoline blends, it has been verified that increasing the biodiesel and ethanol percentage causes an increase in the theoretical diameter since an increase in the biodiesel and ethanol percentage leads to an increase in the densities, viscosities and surface tensions of the blends.

For all the blends analyzed, it has been found that an increase in the air-liquid ratio, ALR, leads to a decrease in droplet size, such as sprays with good quality is obtained in all the cases, generating small droplets. It was also verified that the larger droplet sizes are obtained for the G-E / 20-80 and G-B / 20-80 blends, since such blends presented the highest densities, viscosities, and surface tensions, making the atomization process difficult.

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