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PRELIMINARY DESIGN OF A PRESSURE-SWIRL ATOMIZER FOR BIODIESEL OPERATION IN A MICROTURBINE

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Abstract. *Several studies have shown the technical viability of ethyl-esters (biodiesel) operating as fuel in stationary microturbines. Pressure-swirl atomizers are largely used for atomization of the liquid fuels in gas turbines. This kind of atomizer imparts a swirling motion to the fuel what leads it to be spread in a hollow cone, as a result of the rotational and axial motion interaction, as soon as the fuel leaves the exit orifice. The main characteristic of the spray is the cone angle, which defines the combustor length and the Sauter Mean Diameter (SMD) of the fuel droplets, defining the degree of the mixing rate between the air and the fuel. The physical-chemical properties of the fuel that impact these characteristics are: surface tension, viscosity and gravity. This work presents a study of these properties in several kinds of ethyl-esters and their influence in the spray. In addition a theoretical design of a simplex pressure-swirl atomizer for operation in an automotive turbocharger based microturbine.*

Keywords: *biodiesel, atomization, gas turbines.*

1. INTRODUCTION

The atomization of liquid fuels on the injection process plays a paramount role on combustion efficiency. Atomization is the process of breaking the liquid film into small droplets in order to increase the contact surface and mixing rates between the liquid fuel and the surrounding oxidizing gases.

The process of atomization is the one in which a liquid jet or sheet is disintegrated either by the kinetic energy of the liquid itself or by its exposure to high-velocity air or gas, or as a result of the mechanical energy applied externally through a rotating or vibrating device (Lefebvre, 1989)

Pressure-swirl atomizers work by feeding the liquid which must be disintegrated into a swirl chamber via a defined number of tangential holes or slots. The swirling chamber induces a high angular velocity creating an air cored vortex. The swirling motion induces the fluid to exit the nozzle of the atomizer spreading radially outward as a thin sheet and forming a hollow cone spray.

The large slip velocity between the liquid sheet and the surrounding air provokes the Kevin-Helmholtz instability that causes the liquid sheet to break into ligaments and then into droplets in the form of a well-defined hollow cone spray (Marchione et al, 2007). Figure 1 shows a pressure-swirl atomizer schematic. The development of the hollow cone is shown in Fig. 2.

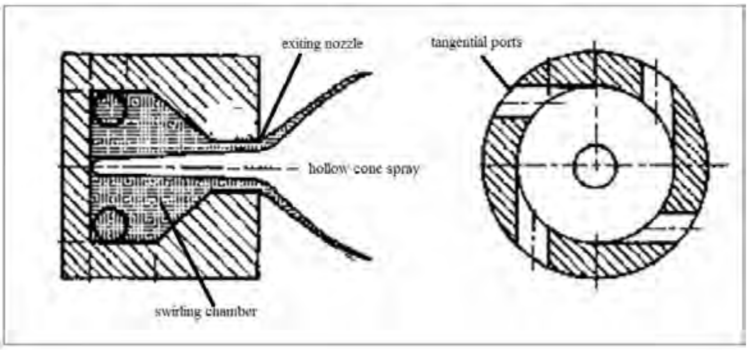

Figure 1. Pressure-swirl atomizer

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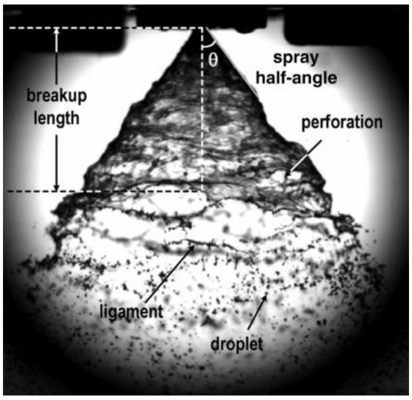

Figure 2. Hollow cone development

In order to design an atomizer, the following data is required: a surface tension, gravity and viscosity (the fuel properties), discharging ambient pressure and density, mass flow rate and injector pressure differential.

Biodiesel is a blend of several esters obtained from the transesterfication between a fatty acid and a primary alcohol (usually methanol or ethanol) in a catalyst presence. The reaction generates glycerol as by-product. This mixture of esters has physical-chemical properties similar to the diesel fuel derived from petroleum. Biodiesel is called methyl-ester (ME) or ethyl-ester (EE) according to the alcohol used. Figure 3 shows the reaction for the production of ethyl-ester.

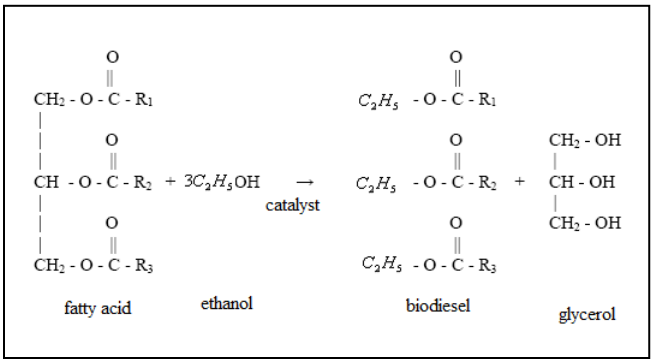

Figure 3. Transesterfication reaction

The physical-chemical characteristics of the biodiesel are strongly related to the raw fatty acid used in the reaction. Once the fatty-acid used is known, these properties can be defined.

Microturbines are very small generators that burn liquid and gaseous fuels, performing a Brayton cycle and ranged at less than 250 kW. The ambient characteristics of the combustion chamber may be defined by analyzing the Brayton cycle in the turbine.

The liquid injection conditions are also defined by analyzing the thermodynamic cycle.

2. DEFINING THE DESIGN PARAMETERS

The preliminary design of the pressure-swirl atomizer follows was made by using the extension of the Dombrowski and Johns (1963) model developed formerly by Couto *et al*. (1987) and then by Lacava *et al*. (2004) and Couto *et al*. (2009).

Since the most of biodiesel produced in Brazil uses ethanol as primary alcohol, ethyl-esters shall be considered in this work.

2.1 Biodiesel characterization

The three physical-chemical characteristics which influence the behavior of the spray are: surface tension, gravity and viscosity.

Surface tension (σ) of the ethyl-ester may be defined according to the method shown in Allen *et al*. (1999) as an average weight between mass fraction (y_i) and the surface tension (σ_i), of the fatty acid. A weight factor (w_i) is also

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introduced in order to compute the ethyl-ester surface tension. Equation 1 computes the mean surface tension of the biodiesel (N/m).

$$\sigma_{EE} = \sum_{i=1}^{n} w_i . y_i . \sigma_i \tag{1}$$

Similarly the viscosity may be defined by the weighted average between the component viscosity (μ_i) and the mass fraction (Allen *et al*., 1999.a). Equation 2 defines the viscosity of the biodiesel (mPa.s)

$$\ln \mu_{EE} = \sum_{i=1}^{n} y_i . \ln \mu_i \tag{2}$$

Then the gravity (ρ) may be defined by Eq. 3 (kg/m³) (Tat and Van Gerpen, 2000)

$$\rho_{EE} = \sum_{i=1}^{n} y_i . \rho_i \tag{3}$$

There are five main carbon/hydrogen chains which may assume the positions of R1, R2 and R3 of the animal and vegetal triglycerides. These chains are designated by two numbers separated by colons. The first number designates the number of carbon atoms in the chain and the second designates the number of double bounds. They are: palmitic (16:0), estearic (18:0), oleic (18:1), linoleic (18:2) and linolenic (18:3). Table 1 shows the percentage of these chains of each fatty acid present in common fats and oils. Note that the carbon atoms designated by the second number does not include the carboxylic carbon atom which is double bounded to the oxygen at the end of fatty acid (Shanks *et al.* 2004).

Table 1. Composition of various oils and fats

Oil or Fat	**14:0**	**16:0**	**18:0**	**18:1**	**18:2**	**18:3**	**20:0**	**22:1**
Soybean		6-10	2-5	20-30	50-60	5-11		
Corn	1-2	8-12	2-5	19-49	34-62	-		
Peanut		8-9	2-3	50-65	20-30			
Olive		9-10	2-3	73-84	10-12	-		
Cottonseed		0-2	20-25	1-2	23-35	40-50		
Hi Linoleic Safflower		5.9	1.5	8.8	83.8			
Hi Oleic Safflower		4.8	1.4	74.1	19.7			
Hi Oleic Rapeseed		4.3	1.3	59.9	21.1	13.2		
Tallow	3-6	24-32	20-25	37-43	2-3			

Once the percentage of the chains is defined, the mass fraction of each fatty acid on the esters may be computed by using the molar mass of each chain.

The physical-chemical properties of biodiesel, computed using the Eq. 1, Eq. 2 and Eq. 3 are summarized in Tab.2

Table 2. Properties of biodiesel

Ethyl-Ester	**σ [mN/m]**	**μ [mPa.s]**	**ρ [g/ml]**
Soybean	23.41	3.47	0.876
Corn	22.65	3.58	0.874
Peanut	22.22	3.71	0.872
Olive	22.05	3.83	0.870
Cottonseed	26.93	3.42	0.879
Hi Linoleic Safflower	22.64	3.34	0.878
Hi Oleic Safflower	21.80	3.75	0.871
Hi Oleic Rapeseed	22.86	3.60	0.874
Tallow	25.07	4.10	0.865
Kerosene(1)	26.00	1.60	0.800
Water(1)	73.40	1.00	1.000

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(1) from Couto *et al*. (1987)

2.2 Microturbine

The microturbine is an assembling of 110/55 AQM compressor of the Swchitzer S500 turbocharger and an 87PJ1 turbine of a Swichtzer S400 turbocharger. Compressor and turbine are both single stage and centrifugal. The combustion chamber is a single-can type operating in reversal flow. Natural gas is fed via a single gas injector connected to a pressure reducer valve. The design point was chosen on the compressor performance map analysis for 77 krpm.

At this point the compressor isentropic efficiency is 75.40%. The turbine chart defines the maximum Turbine Inlet Temperature (TIT) of 923.15 K. At this condition the mass fuel flow is 6.42 x 10^{-3} kg/s for methane. Performing the thermodynamic analysis, it was been found that the compressor outlet temperature is 447,07 K and the compressor outlet pressure is 310 kPa.

The combustion analysis according Gosselin et al. (1999), computes the combustor recirculation zone mean temperature as 1257 K. Table 3 summarizes the main microturbine characteristics. Figure 4 shows the performance map of the compressor and Fig. 5 , the microturbine assembly.

Table 3. Microturbine Characterization

Parameter	**Value**
RPM	77 krpm
Compressor Isoentropic Efficiency	75.40 %
Compressor Outlet Temperature	447 K
Compressor Outlet Pressure	310 kPa
Turbine Inlet Temperature	923.15 K
Recirculation Zone Mean Temperature	1257 K

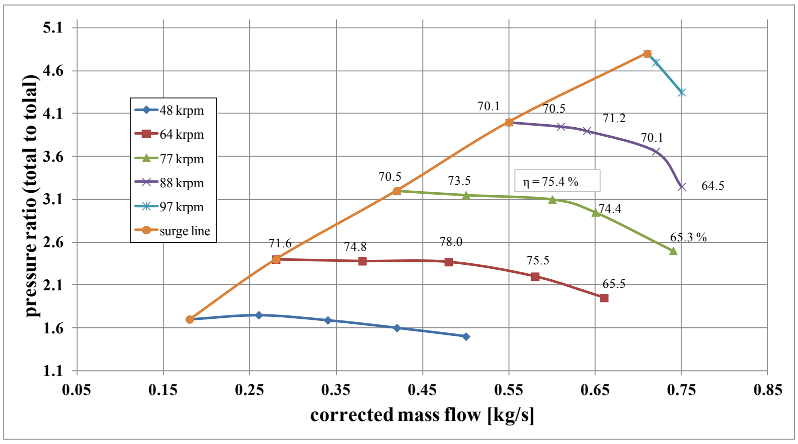

Figure 4. Compressor Performance Map

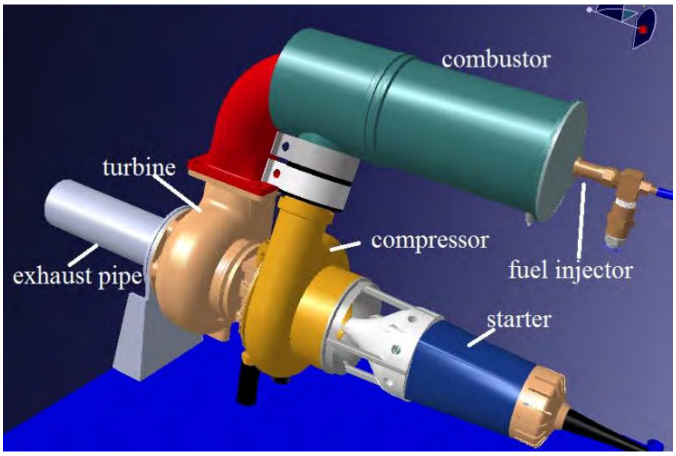

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Figure 5. Microturbine Assembly

3. THEORETICAL BACKGROUND

The theoretical model for the design development is the one described by Couto *et al*. (2009) as an extension of the Dombrowski and Johns (1963) model.

The effective flow area of a pressure atomizer is usually described in terms of the flow number, which is expressed as the ratio of the nozzle throughput to the square root of the fuel-injection pressure differential

Once the liquid fuel mass flow ($\dot{m}_L$) is defined, the fuel density (ρ) and the injector pressure differential (ΔP_L), the injector flow number (FN) shall be defined by Eq. (4)

$$FN = \frac{\dot{m}_L}{\sqrt{\rho_L \Delta P_L}} \tag{4}$$

Then the discharge diameter (D_0) shall be chosen in order to define the other remaining atomizer geometrical parameters, considering the following dimensionless groups: $A_p/(D_s.D_0)$, D_s/D_0, L_s/D_s, L_0/D_0, and L_p/D_p; where the A_p is the tangential entry passage cross section area, and the other important geometrical parameters are shown in Fig. 4.

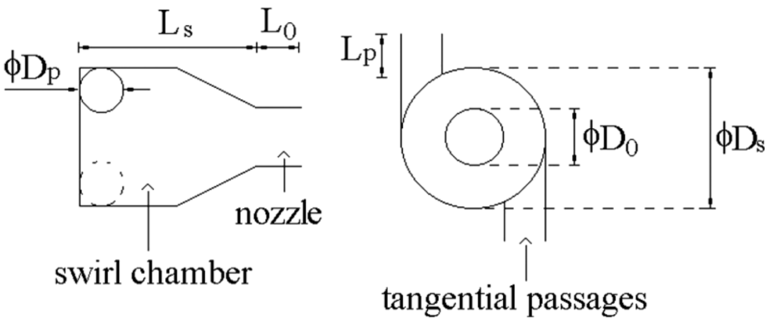

Figure 5. Pressure-swirl atomizer schematic

However ratio Ls/Ds should be reduced in order to minimize the wall friction losses, a limiting value shall be defined to ensure the liquid flow stabilization and formation of a uniform vortex sheet. Elkobt et al (1978) defined 1.0 as a typical value for proper design. Couto et al. (2009) defines 0.5 as a lower limit.

The parameter L0/D0 should also be reduced to minimize friction losses in the atomizer exit. Further, the ratio Lp/D p cannot be smaller than 1.3 because a short tangential inlet passage channel may generate a diffuse discharge leading to an unstable spray (Tipler and Wilson,1959). Finally, one has to watch out for the obvious limitations of the manufacturing process itself.

The other two dimensionless groups, i.e., $A_p/(D_s.D_0)$ and D_s/D_0, both have a considerable influence in the discharge coefficient, Cd, which can be calculated by the Eq. (5).

$$Cd = \frac{\dot{m}_L}{A_0.\sqrt{2.\rho_L.\Delta P_L}} \tag{5}$$

The ratios $A_p/(D_s.D_0)$ and D_s/D_0 can be obtained from empirical relations for Cd developed by Carlisle (1955), Risk and Lefebvre (1985), and Jones (1982), Equations (6), (7), and (8), respectively. In fact, the Cd calculated using the flow parameters in Eq. (5), can be used to choose appropriate values for $A_p/(D_s.D_0)$ and D_s/D_0 with Carlisle result (Eq. (6)), and the Cd is recovered with Risk and Lefebvre and Jones equations (i.e., Eq. (7) and (8), respectively) to check for discrepancies. Nevertheless, intervals ranging from 0.19 to 1.21 and from 1.41 to 8.13 are recommended for $A_p/(D_s.D_0)$ and D_s/D_0, respectively (Lefebvre,1989).

$$Cd = \left(0.0616\frac{D_s}{D_0}.\frac{A_p}{D_s.D_0}\right) \tag{6}$$

$$Cd = 0.35\left(\frac{D_s}{D_0}\right)^{0.5}.\left(\frac{A_p}{D_s.D_0}\right)^{0,25} \tag{7}$$

$$Cd = 0.45\left(\frac{D_0.\rho_L.U_0}{\mu_L}\right)^{-0.02}.\left(\frac{L_0}{D_0}\right)^{-0.03}.\left(\frac{L_s}{D_s}\right)^{0.05}.\left(\frac{A_p}{D_s.D_0}\right)^{0.52}.\left(\frac{D_s}{D_0}\right)^{0.23} \quad (8)$$

Equation (8) reported by Jones (1982), is the most elaborated one, showing that the ratios $A_p/(D_s.D_0)$ and D_s/D_0 are the dominant dimensionless parameters in the calculation of Cd.

The semi-angle (θ) shall be estimated by the expression developed by Giffen and Muraszew (1953) for a pressure-swirl atomizer:

$$\sin\theta = \frac{(\pi/2).Cd}{K.(1+\sqrt{X})} \quad (9)$$

where $K = A_p/(D_s.D_0)$ and X is the ratio between the air core area (A_a) and the nozzle orifice exit area (A_0) , estimated by Eq. (10) below:

$$D_0 = 2.\sqrt{\frac{FN}{\pi.(1-X).\sqrt{2}}} \quad (10)$$

With the flow number (FN) and the spray cone semi-angle (θ), obtained from Eq. (4) and (9), it is possible to estimate the liquid sheet thickness at the nozzle tip, h_0, as suggested by Couto et al. (1987).

$$h_0 = \frac{0.00805.FN\sqrt{\rho_L}}{D_0.\cos\theta} \quad \text{(MKS units)} \quad (11)$$

Dombrowski and Johns (1963) derived an expression to estimate the ligament diameter, D_L, formed on the liquid film break up of a thin plane sheet atomizer as the one generated by a fan-spray atomizer.

Couto et al. (1987) extended this result for a pressure-swirl atomizer. They assumed that the conical sheet possesses, a rupture radius much larger than its thickness, that once the conical sheet is established, the amplitude of any disturbance (ripple) away from the injector tip is much smaller than the cone diameter (so that the ripple “sees” the conical sheet as a plane sheet) and that the wavelength of any ripples formed in the liquid film grows until its amplitude is equal to the ligament radius, so that one droplet is produced per wavelength. Then, the ligament diameter is given by

$$D_L = 0.9615\cos\theta\left(\frac{h_0^4\sigma^2}{U_0^4\rho_a\rho_L}\right)^{1/6}.\left[1+2.6\mu_L\cos\theta\left(\frac{h_0^2\rho_a^4U_0^7}{72\rho_L^2\sigma^5}\right)^{1/3}\right]^{0,2} \quad (12)$$

Where σ (dyne/cm) is the liquid surface tension, ρa (g/cm3) is the density of the surrounding medium, here taken to be the air in the combustion chamber, μ_L (cp) is the liquid dynamic viscosity, and U_0 (cm/s) is the velocity of the liquid at the atomizer tip, given by Eq. (13).

$$U_0 = \sqrt{\frac{2.\Delta P_L}{\rho_L}} \quad (13)$$

The most important mean diameter for combustion applications is the Sauter mean diameter, which is usually abbreviated to SMD or D_{32}. This is the diameter of a drop within the spray whose ratio of volume to surface area is the same as the one of the whole spray.

According to Rayleigh mechanism (in Lefebvre, 1989), assuming that the collapse of a ligament with diameter D_L will generate a droplet, consequently one may write (Couto et al, 1987):

$$SMD = 1.89D_L \quad (14)$$

If the semi-angle θ and the SMD estimated above are not adequate for the atomizer purposes, then a new set of dimensions must be chosen.

4. DESIGN ANALYSIS

A preliminary analysis of the influence of the biodiesel properties on the spray characteristics have been made by simulating the use of these ethyl esters on the pressure-swirl atomizer used on Couto *et al.* (2009). Considering the same dimensions of the designed atomizer two studies were performed.

Firstly the mass flow rate of the ethyl-esters were computed using the liquid density and varying the pressure differential from $2x10^5$ Pa to $6x10^5$ Pa. Discharge coefficient was assumed as 0.27. Then the spray characteristics were computed.

After that the mass liquid flow was varied from 4 g/s to 8 g/s at the design point of *Couto et al*. (2009) paper and the spray characteristics were defined.

As *Couto et al*. (2009) used water on their study, the atomizer performance was compared to this fluid. In addition a comparison with Jet-A kerosene was performed. Fig. 5 shows the behavior of the droplets SMD and Fig. 6 shows the cone angle.

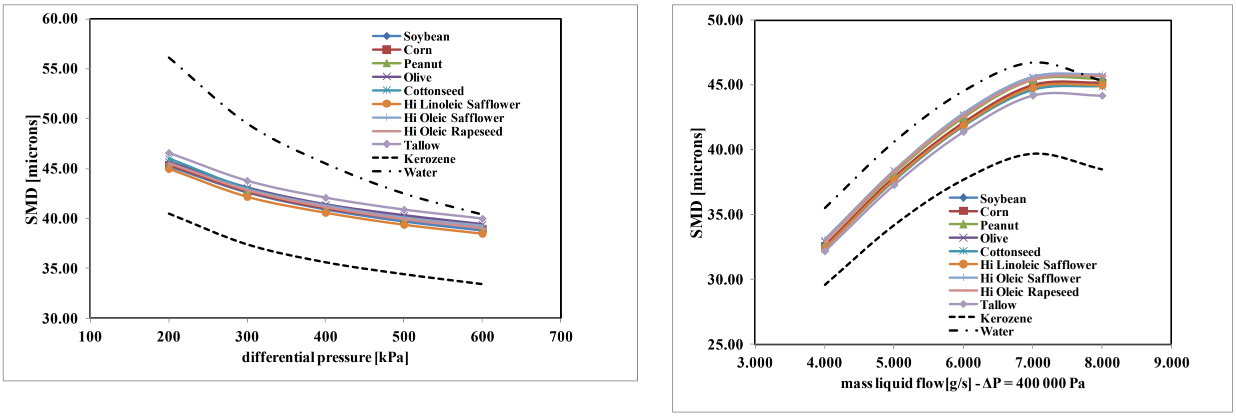

Figure 6. Sauter Mean Diameter

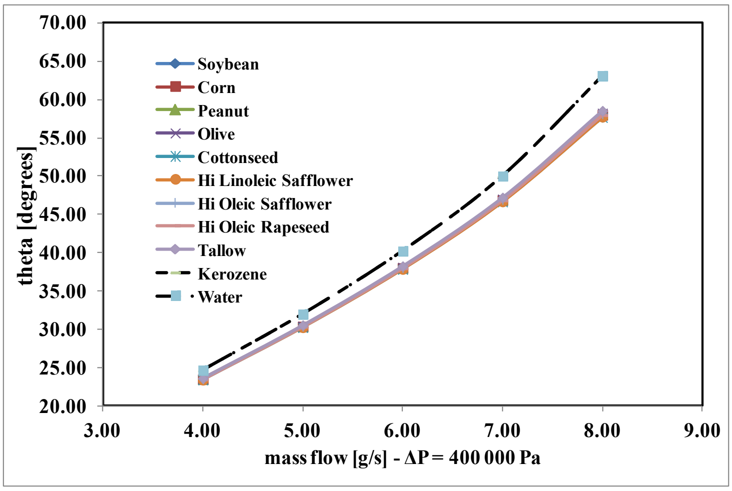

Figure 7. Spray angle

Analyzing Fig. 5, we conclude that even though the droplets diameter is greater than ethyl esters due to the difference between physical-chemical properties, the variation of SMD of these EE may be negligible.

Analyzing and Fig. 6, it is possible to conclude that the same occurs regarding the spray angle.

For these reasons the Tallow ethyl-ester may represent the other biodiesels and as its properties are well defined on the study used of Silva et al. (2010), it has been chosen for the design. Density of the ox tallow ethyl ester (OTEE) used in Silva et al. (2010) is 846.67 kg/m³ (quite lower than the one calculated by Eq.(3)) and the Lower Heating Value (LHV) is 40.5 MJ/kg. Considering the LHV of methane as 50 MJ/kg, the mass fuel flow recomputed for OTEE is 7.93 x 10^{-3} kg/s.

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The ambient density is defined by considering air as perfect gas at the combustion chamber and its value is 0.841 kg/m³ at the recirculation zone conditions.

5. RESULTS

The dimensionless parameters are shown on Tab 4 and the dimensions selected are shown on Tab 5.

Table 4. Atomizer dimensionless parameters

Parameter	Value
D_s / D_0	1.10
L_s / D_s	1.26
L_0 / D_0	1.00
$A_p / D_0 . D_s$	0.40
L_p / D_p	1.60

Table 5. Atomizer dimensions

Parameter	Value
D_0	1.00 mm
D_s	1.10 mm
Ls	1.39 mm
L_0	1.00 mm
A_p	0.44 mm²
D_p	0.40 mm
L_p	0.60 mm

The simulation for SMD and spray semi-angle is shown in Fig. (6).

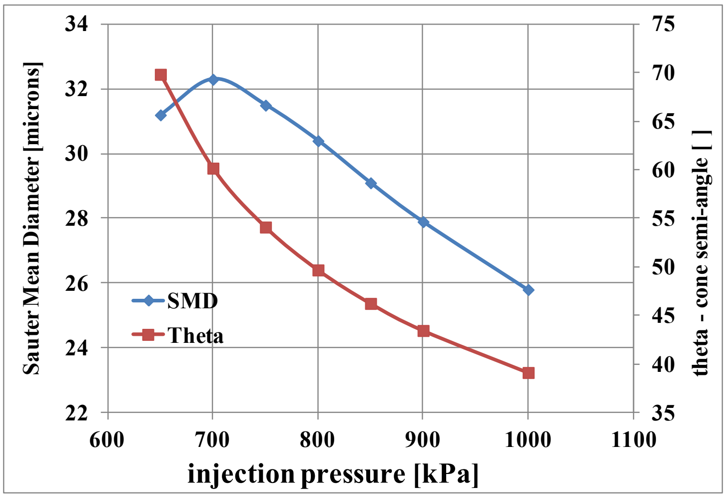

Figure 7. Spray characteristics for OTEE

For the OTEE operation, injection pressure bellow 650 kPa simulation has not converged. According to *Couto et al*. (2009), the best range of droplets diameter is from 20 to 100 microns because at this range the penetration on oxidant a and also the vaporization time are all adequate. If droplets are smaller than 19 microns low penetration, high fuel concentration closely to the atomizer occurs and also an increase in soot formation and exhaust smoke. If droplets are greater than 100 microns an increase of the length and burning regions is needed due to the high vaporization time.

Analyzing Fig. 6 it may be concluded that for the operating conditions and the chosen dimensions of the atomizer the SMD is suitable for every pressure injection.

As the combustion chamber is small (diameter of 110 mm and length of 230 mm), the length of the recirculation zone is 60 mm and the droplets diameter is feasible, the angle of the spray shall be used to determine the pressure injection.

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A set of 32 microns of droplet size and 120° on spray angle seems to be the more adequate.

6. CONCLUSION

It concludes that even though the physical-chemical properties on biodiesel fuels are different than those of kerosene and the diameter of the droplets are coarse in ethyl-esters, SMD are still within the acceptable range defined by Couto et.al (2009).

This conclusion corroborates with the fact of the studies by Silva et al. (2010), Nascimento et al (2008) and Rehman (2011) were performed without any modification on injection system. Even the lasts were used diesel fuel atomizers, which have the properties quite near of kerosene.

However, for best performance of the turbine a proper design shall be developed for the specific liquid fuel that will be used for operation.

The pressure-swirl atomizer have been designed according the suggested methodology and the values of the main spray characteristics are very suitable for operation at the microturbine which the fuel system is developed for.

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