17th Brazilian Congress of Thermal Sciences and Engineering
November 25th-28th, 2018, Águas de Lindóia, SP, Brazil

ENCIT-2018-0362
SPRAY CONE ANGLES BY A JET SWIRL INJECTOR FOR ATOMIZATION OF GELLED ETHANOL

Gustavo Alexandre Achilles Fischer
José Carlos de Andrade
Fernando de Souza Costa
Combustion and Propulsion Laboratory – LABCP
Brazilian Institute for Space Research – INPE
Rodovia Presidente Dutra, km 40, CEP 12.630-000
Cachoeira Paulista/SP – Brazil
fischer@lcp.inpe.br

Abstract. *Gelled propellants are promising for rocket propulsion applications since they combine advantages of solid and liquid propellants. However, gelled propellants are more difficult to atomize than conventional liquid propellants due to their non-Newtonian behavior and higher viscosity. The application of high pressures during injection allows to reduce viscosity and to liquefy the gelled propellant near the discharge orifice. High deformation rates within the injectors occur due to the sudden decrease of the cross-sectional area and the pseudoplasticity effect of the gels becomes essential in the process of atomization. Jet-swirl injectors have good atomization efficiency, forming a solid cone spray in a reduced volume. In these injectors, the interaction between the axial and centrifugal flows allows to adjust the spray characteristics in order to produce a relatively uniform distribution of drops. This paper compares theoretical and semi empirical results with experimental data for the injection of liquid ethanol and 72 º INPM gelled ethanol through a jet-swirl injector.*

Keywords: *jet swirl injector, atomization, spray cone angles, gelled ethanol*

1. INTRODUCTION

Demand for high-performance and improved safety propellants for various rocket engine applications has increased during the last decades and gelled propellants seem to be a promising answer to these requirements. Gel propellant is prepared from a liquid whose rheological properties have been altered by a gelling agent and, as a result, its behavior at rest resembles that of solid propellants. In fluid mechanics, gels behave as non-Newtonian shear thinning fluids. High shear rates can lead to extensive liquefaction of gelled fluids. This liquefaction offers the possibility to design engines, which can be throttled like engines with liquid propellants, but which have simple handling and storage characteristics like engines with solid propellants (Negri and Ciezki, 2010).

Injectors are used for atomization of liquid propellants into the combustion chamber of a rocket engine. An efficient atomization allows to significantly increase the surface area of liquid propellants, ensuring high rates of evaporation, mixing and burning. Small droplets are required to achieve rapid ignition and establish a flame front adjacent to the injection head. Large droplets take longer to burn and thus define the length of the combustion chamber (Khavkin, 2004).

The jet-swirl injectors combine characteristics of jet injectors and pressure swirl injectors. One part of the liquid flows like an axial jet and the other part as an annular jet in centrifugal motion. The jet mixture in a cross-section perpendicular to the jet axis can be arbitrarily adjusted as required. Therefore, it is also possible to obtain a uniform distribution and a greater efficiency in the transfer of heat and mass between the drops and the environment. This feature makes jet-swirl injectors advantageous in many applications (Bayvel and Orzechowski, 1993; Prywer, 2008).

The existence of yield stress and increased viscosity make gelled propellants very difficult to atomize and restrict their wide use for aerospace applications. In Newtonian fluids, large viscosity values produce coarse sprays, and in non-Newtonian fluids shear and extensional viscosities can be several orders of magnitude larger. This results in reduced performance, and a longer combustion chamber is required (increased weight). For high combustion efficiency, fine atomization is necessary (Fu *et al.*, 2014).

Atomization of gelled propellants is significantly different from the atomization of Newtonian liquids and very little is known about the influence of rheological properties, injector geometries and working conditions on the spray pattern of gelled propellants. Although many investigations have been performed to study the spray characteristics and atomization mechanism of non-Newtonian fluids such as viscoelastic fluids etc., the spray characteristics of the gelled propellants (or power-law fluid) have yet to be studied (Fu *et al.*, 2014).

In this work, the flow of an ideal fluid within a jet-swirl injector is described by a model presented by Bayvel and Orzechowki (1993) and the flow of a Newtonian fluid is described by the model developed by Fischer (2014). This model was extended for a non-Newtonian fluid using the friction factor derived by Kliachko (1962) with a generalized Reynolds number for power law fluids, as defined by Metzner and Reed (1955). Injector designs for the three models are presented and compared. Then, theoretical, semi-empirical and experimental atomization characteristics of a jet-swirl injector for the atomization of ethanol or gelled ethanol are compared.

2. THEORETICAL CONSIDERATIONS AND INJECTOR DESIGN

According to Bayvel and Orzechowki (1993) there are about 30 different configurations of jet-swirl injectors, with or without an insert. The non-insert models are like pressure swirl injectors, consisting of a vortex chamber, a conical section and a discharge orifice (Figure 1a). In them, a portion of liquid enters through an orifice at the base of the vortex chamber, forming an axial jet, and the entrance of a portion of liquid through tangential orifices, around the vortex chamber, forming a centrifugal jet. This jet with tangential component (centrifugal jet), when entering the vortex chamber, produces rotation in the axial jet. The insert injectors feature a pre-chamber, an insert section, a conical section and a discharge orifice (Figure 1b). The fluid only enters through a single hole in the base of the injector (pre-chamber). A portion of the fluid passes through a channel in the center of the insert and another portion passes through the slots slanted around the insert, acquiring tangential movement. The central jet acquires rotation in contact with the fluid in tangential movement (centrifugal jet) coming from the grooves.

Mass transfer and momentum transfer processes between centrifugal and axial components in jet-centrifugal injectors determine the liquid distribution at the discharge orifice and the quality of the atomization. This feature eliminates the typical non-uniform distribution of jet injectors and pressure swirl injectors.

This allows a greater flow of liquid to a same geometry, when compared to a pressure swirl injector, and guarantees the existence of drops throughout the region of the spray. However, jet-swirl injectors tend to offer coarser atomization at the center and finer at the periphery of the spray.

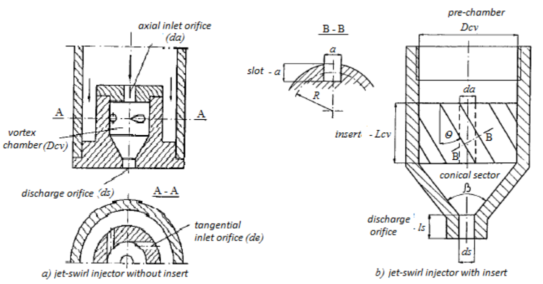


Figure 1. Schemes of jet-swirl injectors (adapted from Bayvel and Orzechowki, 1993).

Figure 2 shows a flow diagram through a jet-swirl injector without insert. At the exit of the conical section of the injector, at the boundary between the centrifugal and axial jets, a turbulent boundary layer develops and presents a significant shear stress. In this region the equalization of the axial and tangential components of the velocity of both jets occurs. The turbulent process inside the injector not only causes the exchange of amount of movement and energy, but also exchange of mass between the jets. A theoretical solution does not exist for this process and then empirical-theoretical solutions are used (Bayvel and Orzechowki, 1993).

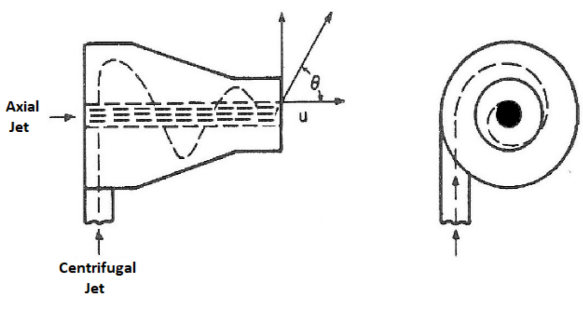


Figure 2. Flow of liquid through a jet-swirl injector without insert.

2.1 Ideal model

The following hypotheses are considered for analysis of the ideal liquid flow inside a jet-swirl injector (Bayvel and Orzechowki, 1993):

- Stable and axisymmetric flow;
- No effects of gravity;
- No radial velocity component;
- Turbulent flow within the injector and therefore approximately uniform velocity distributions;
- A common velocity distribution for both jets develops at a short distance, equivalent to three times the diameter of the exit orifice, from the point where the jets meet;
- The distribution of the tangential component at the outlet of the discharge hole satisfies the equation of a straight line (rigid vortex).

The characteristic geometric parameter (K) of a jet-swirl injector is defined by:

$$K = \frac{R}{r_s} \sin\theta \frac{A_s A_l}{\left(A_a + A_l\right)^2} \tag{1}$$

where $R = r_{cv} - r_e$ is the radius of the center to the tangential inlet channel (centrifugal radius), r_s the radius of the discharge orifice, θ is the angle of the insert grooves or side holes (θ = 90 °, if tangential), $A_a = \pi r_a^2$ the area of the orifice axial, $A_l = n\pi r_e^2$ the total area of the tangential inlet channels and n is the number of tangential inlet channels.

Other important parameters of the jet-swirl injectors are the liquid fraction area (ε), discharge coefficient (μ) and spray cone angle (α). All these parameters are directly related to K by equations (Bayvel e Orzechowki, 1997; Fischer, 2014):

$$K = \frac{(2-\varepsilon)\sqrt{2-\varepsilon}}{2\varepsilon\sqrt{\varepsilon}} \tag{2}$$

$$\mu = \frac{\varepsilon\sqrt{\varepsilon}}{\sqrt{2}} \tag{3}$$

$$\tan\frac{\alpha}{2} = \frac{2\varepsilon K}{2-\varepsilon} \tag{4}$$

A graphical solution of Eqs. (2), (3) and (4) is shown in Figure 3.

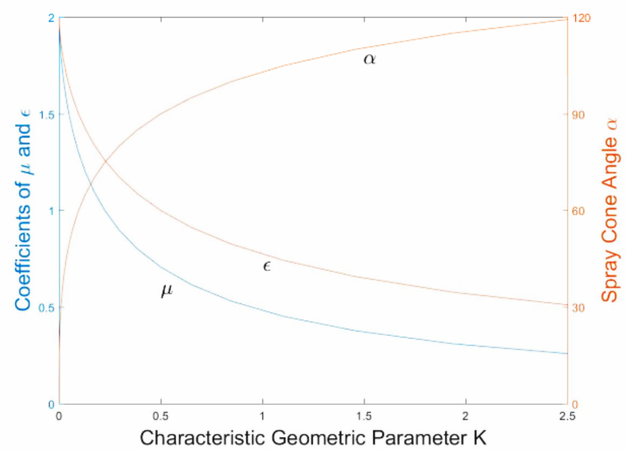


Figure 3. Discharge coefficient, liquid fraction area and spray cone angle vs geometric characteristic parameter of a pressure swirl injector.

The liquid fraction area (ε) is defined by:

$$\varepsilon = \frac{A_l}{A_s} = \frac{\pi\left(r_s^2 - r_{sna}^2\right)}{\pi r_s^2} = 1 - \frac{r_{sna}^2}{r_s^2} = 1 - S^2 \tag{5}$$

where A_l is the area occupied by liquid and r_{sna} the gas core radius in the discharge orifice.

2.2 Model considering viscous losses

Fischer (2014) extended the viscous solution by Klyachko (1962) for pressure swirl injectors and derived a geometric parameter (K_λ) for a jet-swirl injector:

$$K_\lambda = \frac{R r_s sin\theta}{\frac{(A_a + A_l)^2}{\pi A_l} + \left(\frac{\lambda}{2}\right) R \sin\theta \frac{(A_a + A_l)}{A_l}(R - r_s)} \tag{6}$$

where the coefficient of friction (λ) is a function of the Reynolds number (Re) of the inlet channels.

Friction coefficients of a jet swirl injector were estimated from Equation (7), valid for pressure swirl injectors in the range $Re = 10^3$-10^5. Values determined from this equation are significantly higher than from other equations commonly used in hydraulic systems (Bazarov *et. al*, 2004).

$$\log\lambda = \frac{25{,}8}{(\log \mathrm{Re})^{2{,}58}} - 2 \tag{7}$$

Thus, it is possible to recalculate the liquid fraction area (ε_λ) replacing K by K_λ in Eq. (2):

$$K_\lambda = \frac{(2-\varepsilon_\lambda)\sqrt{2-\varepsilon_\lambda}}{2\varepsilon_\lambda\sqrt{\varepsilon_\lambda}} \tag{8}$$

The friction of the liquid on the vortex chamber wall causes a decrease of the angular motion and energy losses. For a more precise calculation of the pressure drop it is necessary to consider the energy losses in the jet swirl injector. In the vortex chamber of an injector these losses can be considered as the work of the frictional force along the trajectory of the liquid. A discharge coefficient (μ_λ) for injection of a viscous fluid through a jet swirl injector was derived by Fischer (2014):

$$\mu_\lambda = \frac{1}{\sqrt{\frac{4K_\lambda^2}{(2-\varepsilon_\lambda)^2} + \frac{1}{\varepsilon_\lambda^2} + \xi_i \frac{K^2}{C^2} + \Delta}} \tag{9}$$

where $C = R/r_s$, $\xi = 1/K + \lambda C/2$ and:

$$\Delta = \frac{\lambda}{\xi^2}\left\{\frac{1}{\xi}\left(1 - \frac{1}{C}\right) + \lambda\left[\frac{K^2}{4} - \frac{1}{(2\xi-\lambda)^2} + \frac{K}{\xi} - \frac{2}{\xi(2\xi-\lambda)} + \frac{3}{2\xi^2}\ln\left(\frac{(2\xi-\lambda)KC}{2}\right)\right]\right\} \tag{10}$$

Note that in equations (9) and (10) appear K and K_λ. The friction coefficient through the tangential inlet channels depends on the Reynolds number (*Re*):

$$\mathrm{Re} = \frac{4\dot{m}}{\pi\mu_l\sqrt{n}d_e} \tag{11}$$

where $\dot{m}$ is the mass flow rate, d_e is the diameter and n the number of tangential inlet channels and μ_l is the dynamic viscosity of the fluid.

The total friction loss in the tangential channels (ξ_i) is computed by:

$$\xi_i = \xi_e + \lambda\frac{l_e}{d_e} \tag{12}$$

where the initial loss coefficient, ξ_e, is determined from Fig. 4, and the inclination of the tangential inlet channels, α_e, is obtained from:

$$\alpha_e = 90^o - \tan^{-1}\left(\frac{r_{cv}}{l_e}\right) \quad (13)$$

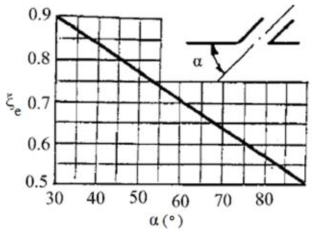


Figure 4. Initial viscous loss coefficient versus inclination of tangential inlet channels.

The corrected spray cone angle (α_λ) is calculated considering the effects of geometry and friction losses:

$$\tan\frac{\alpha_\lambda}{2} = \frac{2\mu_\lambda K_\lambda}{2-\varepsilon_\lambda} \quad (14)$$

2.3 Semiempirical models

Rizk and Lefebvre (Lefebvre, 1989) developed an equation for the cone angles of pressure swirl injectors considering the effects of liquid properties, geometrical parameter and injection pressure. The geometric parameter given by Eq. 1 was used to estimate the cone angle of a jet-swirl injector, based on the Rizk and Lefebvre equation:

$$\frac{\alpha}{2} = 6K^{0,15}\left(\frac{\Delta P d_s^2 \rho}{\mu_l^2}\right)^{0,11} \quad (15)$$

Benjamin (1998) validated an equation using a database and modified the coefficients indicated by Rizk and Lefebvre (Lefebvre, 1989) for large size injectors and obtained:

$$\frac{\alpha}{2} = 9.75K^{0,287}\left(\frac{\Delta P d_s^2 \rho}{\mu_l^2}\right)^{0,067} \quad (16)$$

2.4 Generalized Reynolds number for non-Newtonian fluids

To characterize or to compare the flow characteristics of fluids flowing through ducts, dimensionless numbers are often used. The Reynolds number for a Newtonian fluid can be written as

$$\text{Re} = \frac{\rho d\bar{u}}{\mu} \quad (17)$$

where ρ is the fluid density, d is the duct diameter, $\bar{u}$ is the average flow velocity, and μ is the constant Newtonian viscosity.

The rheological behavior of a gel is commonly described in the simplest form by the Ostwald-de-Waele or power-law (PL) equation:

$$\eta_{PL} = K\dot{\gamma}^{n-1} \quad (18)$$

where η and γ denote the shear viscosity and shear rate, respectively. K is called "consistency coefficient" and n is the flow index.

For the identification of different flow regimes, Metzner and Reed (1955) introduced a generalized Reynolds number valid for pure PL liquids. This number was derived from its relation to the Darcy friction factor and is given by:

$$\text{Re}_{GEN-PL} = \frac{\rho d^n \bar{u}^{2-n}}{K\left((3n+1)/4n\right)^n 8^{n-1}} \quad (19)$$

In the present work, the friction coefficient λ_{PL} for non-Newtonian fluids was assumed a function of the generalized Reynolds number Re_{GEN-PL} of the tangential inlet channels, and was based on the friction factor developed by Klyachko (1962) for pressure swirl injectors:

$$\log \lambda_{PL} = \frac{25{,}8}{(\log Re_{GEN-PL})^{2{,}58}} - 2 \tag{20}$$

3. EXPERIMENTAL METODOLOGY

A jet swirl injector for atomization of gelled ethanol was designed and fabricated for application in rocket engines, based on the methodology described by Fischer (2014).

The experimental system consists of a gel tank, injector, pressure and flow rate measurement system and a high-speed camera. A pressurized supply system was adopted. The gel simulant is fed into the injector by a piston in the tank.

3.1 Rheological characterization

The 72° INPM gelled ethanol obtained commercially was used as surrogate in the experiments, instead of gelled anhydrous ethanol. The physical properties of gel are presented in Table 1:

Table 1 – The physical properties of 72° INPM gelled ethanol.

Physical Properties	***Minimum***	***Maximum***	***Measured Value***
Alcohol content (w/w) °INPM	71.2	73.53	73.25
Alcohol content (w/w) °GL	78	80	79.8
pH	6	8	7.45
Density (kg/m³) at 20°C	845	850	824.2
Viscosity (cP), in rest, at 20°C	>4,000		4365
Burning Velocity (g/min)	2.86		3.54 ± 0.025

Rheological properties of the test fluid were characterized using a Brookfield cone-and-plate controlled stress rotational viscometer (CAP 200 model), with a 1.2 cm diameter and 1.8° truncated cone. Figure 5 shows the shear rheology for the 72° INPM gelled ethanol at 50°C.

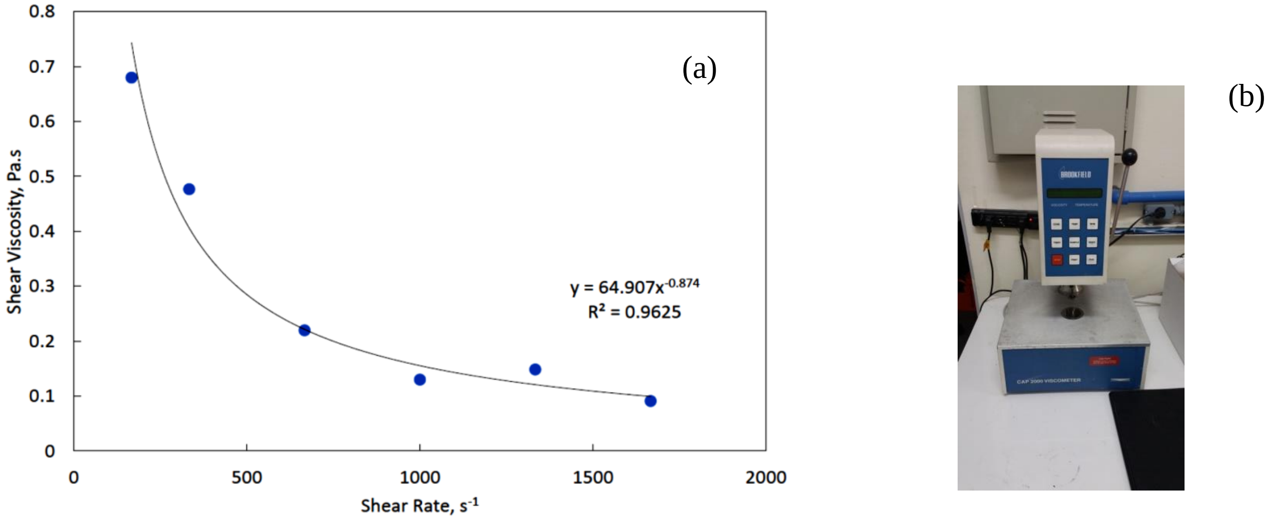


Figure 5. Rheological characterization of 80° INPM gelled ethanol.
(a) shear viscosity vs shear rate; (b) rotational viscometer.

The rheological behavior of the gel is commonly described by Eq. (19). From the rheological curve, we can obtain K = 64.907 Pa.s^n and n = 0.126.

3.2 The jet swirl injector

Table 2 shows a general overview of the jet swirl injector dimensions. Table 3 presents a general overview of the operational and geometric parameters for design of the pressure swirl injector, respectively.

Table 2. Jet swirl injector geometric data.

Injector dimensions	Values
Diameter of the discharge orifice – d_s (mm)	0.9
Length of the discharge orifice – l_s (mm)	4.5
Number of the tangential inlet channels – n	4
Diameter of the tangential inlet channels – d_e (mm)	0.8
Length of the tangential inlet channels – l_e (mm)	2.8
Effective radius of the vortex chamber – R (mm)	1.8
Diameter of the vortex chamber – D_{cv} (mm)	4.4
Length of the vortex chamber – L_{cv} (mm)	3
Transient cone angle – β (°)	90

Table 3. Characteristics of the jet swirl injector tested.

Input data				
Pressure drop – ΔP (MPa)			0.5066	
Mass flow rate – $\dot{m}$ (g/s)			9.5511	
Spray cone angle – α (°)			100	
Work fluid			Ethanol	Gelled Ethanol
Dynamic viscosity – μ_l (cP)			1.2	-
Density – ρ (kg/m³)			809.3	850
Injector parameters				
	No viscosity		With viscosity	
Work fluid	Ethanol	Gelled Ethanol	Ethanol	Gelled Ethanol
Friction coefficient (λ)	0	0	0.0838	0.4465
Reynolds number (Re)	0	0	4332.5	350
Spray cone angle – α (°)	100	100	97.7348	73.0089
Discharge coefficient (μ)	0.5312	0.5312	0.5585	0.5898
Liquid fraction area (ε)	0.8264	0.8264	0.8654	1.2922
Characteristic geometrical parameter (K)	0.8463	0.8463	0.7506	0.2027
Total injection velocity – V (m/s)	18.2855	18.2855	19.7603	20.303
Mass flow rate – $\dot{m}$ (g/s)	9.5511	9.5511	10.0418	10.6049

Figure 6 shows a picture of the manufactured injector.

Figure 6. Picture of the manufactured injector.

3.3 Spray angle measurement

The experimental setup used for measuring the spray cone angle by photographic techniques consists of a support to fix the injector on the test bench and a digital camera. The pictures were obtained by a Sony DSC-F828 digital camera, with 8 megapixels of effective resolution, or 3264×2448 pixels. The support has a mark that serves to indicate a known length to be used as a reference to relate the number of pixels and the true length of the image, allowing determine the experimental values of the spray cone angles from the respective images.

Figure 7 shows the GUI (Graphical User Interface) developed in MATLAB language by Vásquez (2011) to process spray images. The use of this GUI is relatively simple and the images can be treated in JPEG, TIFF or BMP formats.

After taking and selecting the appropriate images, the image processing is done with the GUI developed for this purpose. Finally, the experimental values of the spray cone angles of these images are registered. After data collection and treatment, the experimental curves are obtained and compared to the theoretical data.

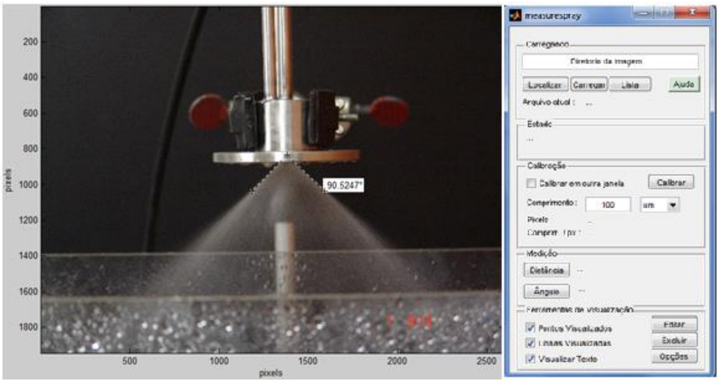


Figure 7. GUI for image processing.

4. RESULTS AND DISCUSSIONS

Figure 8 compares the theoretical and experimental values of the mass flow rates of ethanol and gelled ethanol versus injection pressure.

Figures 9 and 10 show, respectively, the discharge coefficients and spray cone angles versus the mass flow rates of the ethanol and gelled ethanol.

The test fluids used in all experiments were liquid ethanol (C_2H_6O, 95% m/m) and gelled ethanol (72^o INPM), respectively.

As seen in Figure 8a, experimental mass flow rates of liquid ethanol were lower than the analytical solution with viscous effects at the manometric injection pressures tested. The design point corresponds to 9.55 g/s and 2.7 bar with viscous losses. Smaller mass flow rates result in larger loss of angular momentum causing a discrepancy between the analytical solution and experimental data whereas larger mass flow rates produce lower angular momentum losses and, therefore, theoretical values depart from experimental ones.

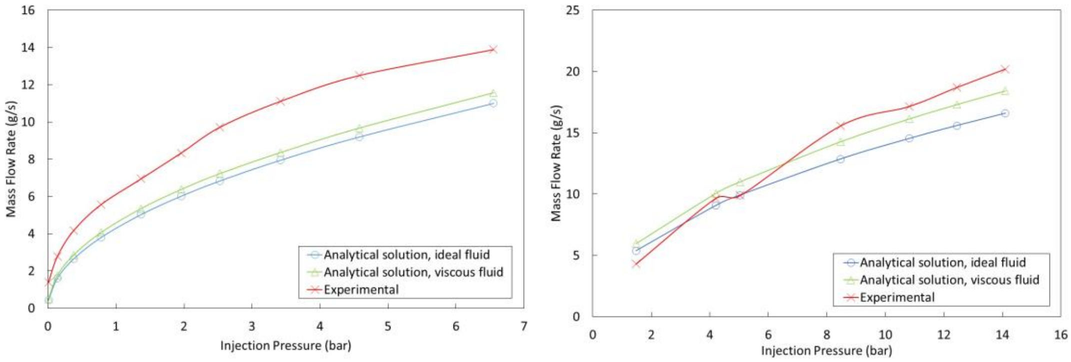
Flow of gelled ethanol started at injection pressures about 2 bar, with formation of a liquid jet, while initial spray formation occurred only above injection pressures above 6 bar, approximately. A good gel atomization efficiency occurred for injection pressures above 9 bar, approximately. Figure 8b shows gel injection pressures varying from 2 to 14 bar while mass flow rates increase from 5 to 20 g/s. Due to the viscosity of the gelled ethanol (about 0.12 Pa.s or 120 cP for a shear rate of 1500 s^{-1}) be about a hundred times larger than that of liquid ethanol (1.2 cP), the initial energy required to move the fluid is also greater.

As seen in Fig. 9a, the experimental discharge coefficients for injection of liquid ethanol were around 25% higher than the analytical solution with viscous losses over the entire operating range above one bar.

As seen in Fig. 9b, the discharge coefficient of gelled ethanol was about 6 % higher than the estimated value over the entire operating range above 6 bar. Although the coefficient of friction determined by the proposed model is significantly higher than that of other equations commonly used in hydraulic systems, for the case of non-Newtonian fluids, it is verified experimentally that the viscous effects are still underestimated and consequently the values obtained for the discharge coefficients were lower than in practice.

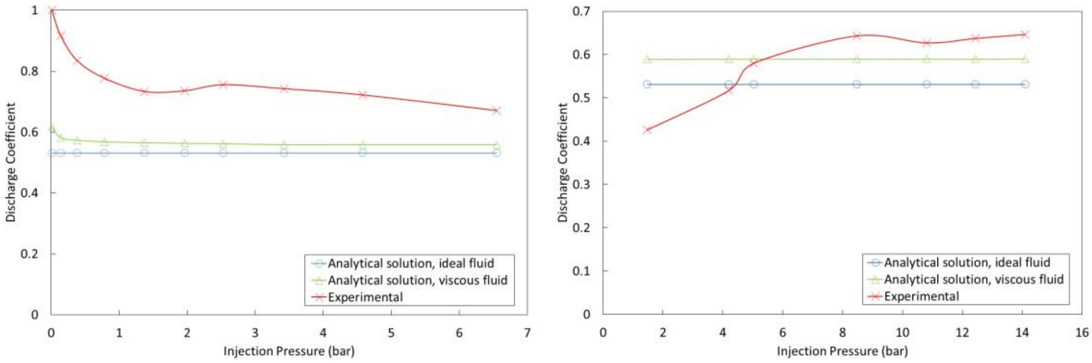
As seen in Fig. 10a, the Benjamin semi-empirical formulation provided a better estimate of the spray cone angle of liquid ethanol over the entire operating range below 2 bar. The experimental data of spray cone angles for injection of liquid ethanol were around 20 % higher than the analytical solution with viscous losses over the entire operating range above 2 bar. This is expected, since the theoretical solution is a function only of the injector parameters and does not consider the fluid properties and operating conditions. Another relevant fact is that analytical solution does not consider the length of the vortex chamber and discharge orifice.

As seen in Fig. 10b, the semi-empirical models could not be used for the gelled ethanol, because they do not consider the effect of the rheological properties of the non-Newtonian fluids on the flow in the jet swirl injector. The experimental data of spray cone angles for injection of gelled ethanol were more than two times higher than the analytical solution with viscous losses over the entire operating range above 6 bar. This is expected due to the same explanations mentioned above. Spray formation was observed only above 6 bar.



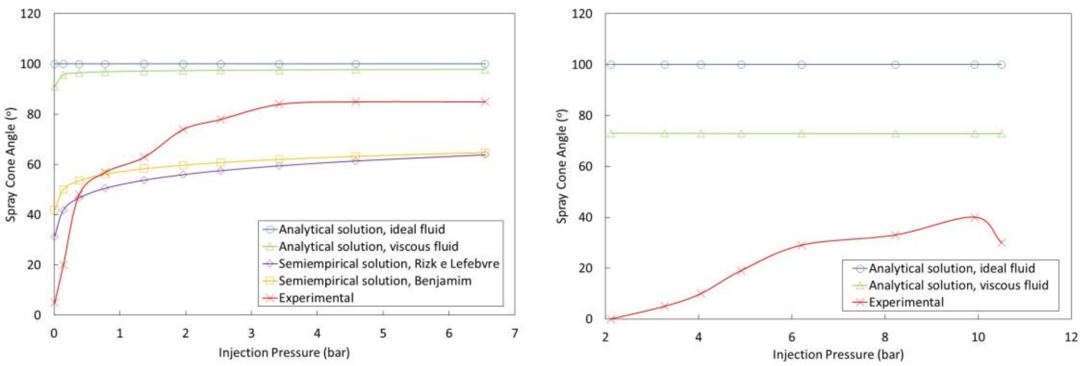
a) Liquid Ethanol b) Gelled Ethanol

Figure 8. Mass flow rate of ethanol and gelled ethanol versus pressure injection (gauge) in the jet swirl injector.



a) Liquid Ethanol b) Gelled Ethanol

Figure 9. Discharge coefficient versus mass flow rate of ethanol and gelled ethanol in the jet swirl injector.



a) Liquid Ethanol b) Gelled Ethanol

Figure 10. Spray cone angles of ethanol and gelled ethanol versus injection pressure in the jet swirl injector.

5. CONCLUSIONS

Models of the internal flows of ideal fluids, Newtonian fluids and Non-Newtonian fluids through a jet swirl injector were presented. A jet swirl injector was designed for atomization of liquid ethanol at 5 bar with mass flow rate of 9.55 g/s. The spray characteristics were compared for injection of liquid ethanol and gelled ethanol, and the experimental data were compared to theoretical and semi-empirical solutions. Semi-empirical models could not be used for gelled ethanol in the jet swirl injector, since they are based on Newtonian fluids.

Atomization of liquid ethanol produced a fully developed cone for pressures above 2 bar, whereas atomization of gelled ethanol provided a fully developed cone only for pressures above 6 bar. Experimental discharge coefficients of liquid ethanol were around 25 % higher than the theoretical solution considering viscous effects, for injection pressures above 2 bar. Experimental discharge coefficients of gelled ethanol were about 6 % higher than theoretical values, for operating pressures above 6 bar.

Experimental cone angles for injection of liquid ethanol, for injection pressures above 2 bar, were about 20 % lower than theoretical values for ethanol considered as a Newtonian fluid. Semi-empirical models based on pressure swirl injectors were applied to the jet swirl injector, but did not show a good agreement to the experimental data obtained with liquid ethanol. Experimental cone angles for gelled ethanol did not agree well with theoretical values, since the experimental friction factors adopted are significantly higher than predicted by Klyachko model.

Further studies are required for development of a friction factor adequate for jet swirl injectors. Also, new empirical or semi empirical models are required to describe more accurately the internal flow and determine the spray cone angles of non-Newtonian fluids in jet swirl injectors.

5. ACKNOWLEDGEMENTS

The authors acknowledge FAPESP for support to this project through process 2016/21957-0 and CNPq for the PhD scholarship granted to the first author.

6. REFERENCES

Bayvel, L. and Orzechowski, Z., 1993. “Liquid Atomization”, Taylor & Francis, Washington, DC.

Bazarov, V.; Vigor, Y. and Puri, P., 2004. “Design and dynamics of jet and swirl injectors, liquid rocket thrust chambers: aspects of modeling, analysis, and design”. United States of America: American Institute of Aeronautics and Astronautics.

Borodin, V.A.; Dityakin, Yu.F.; Klyachko, L.A. and Yagodkin, V.L., 1967. “Liquid Atomization”, Mashinostroenie, Moscow.

Fischer, G.A.A., 2014. “Injetores centrífugos duais e jato-centrífugos para aplicação em propulsão de foguetes”, Master thesis, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil.

Fu, Q., Duan, R., Cui, K. and Yang, L., 2014. “Spray of gelled propellants from an impingement-jet injector under different temperatures”, *Aerospace Science and Technology*, Vol. 39, No. 1, pp. 552-558.

Giffen, E. and Muraszew, A., 1953. “Atomization of Liquid Fuels”, Chapman and Hall, London.

Hamid, A. H. A.; Atan, H., 2009, Spray characteristics of jet-swirl nozzles for thrust chamber injector. Aerospace Science and Technology, Vol. 13, pp. 192-196.

Khavkin, Y.I., 2004. “Theory and practice swirl atomizers”, Taylor & Francis, New York.

Klyachko, L. A, 1962, The theory of a centrifugal injector. Teploenergetica, No. 3, pp. 34-38. Original em russo.

Kulagin, L.V. and Okhotnikov S.S., 1970. “Combustion of Heavy Liquid Fuels”, Mashinostroenie, Moscow.

Lefebvre, A.H., 1989. “*Atomization and Sprays*”, Hemisphere, New York.

Madlener, K., Frey, B., and Ciezki, H.K., 2007. “Generalized Reynolds Number for non-Newtonian Fluids”, *2nd European Conference for Aerospace Sciences* (EUCASS2007), Brussels, Belgium.

Metzner, A.B. and Reed, J.C., 1955. “Flow of non-Newtonian fluids – correlation of the laminar, transition and turbulent-flow regios”. AIChE J., Vol. 1, No. 4, pp. 434-440.

Natan, B. and Rahimi, S., 2001. “The status of gel propellants in year 2000”, in K. K. Kuo and L. DeLuca, Eds., *Combustion of Energetic Materials*, Begell House, New York, pp. 172-194.

Negri, M. and Ciezki, H.K., 2010. “Atomization of non-Newtonian Fluids with and Impinging Jet Injector: Influence of Viscoelasticity on Hindering Droplets Formation”, AIAA Paper 2010-6821.

Ortmann, J. and Lefebvre, A.H., 1985. “Fuel Distributions from Pressure-swirl Atomizers”, *Journal Propulsion and Power*, Vol. 1, No. 1, pp. 11-15.

Prywer, J, 2008, Flow Characteristics of Jet-Swirl Atomizers. Atomization and Sprays, Vol. 18, pp. 343-361.

Vásquez, R.A., 2011. “Desenvolvimento de um injetor centrífugo dual para biocombustíveis líquidos”, Master Thesis, Instituto Nacional de Pesquisas Espaciais, São José dos Campos, SP, Brazil.

Yang, L., Fu, Q., Zhang, W., Du, M. and Tong, M., 2011. “Atomization of Gelled Propellants from Swirl Injectors with Leaf Spring in Swirl Chamber”, *Atomization and Sprays*, Vol. 21, No. 11, pp. 949-969.

Yang, L., Fu, Q., Qu, Y., Zhang, W., Du, M. and Xu, B., 2012. “Spray Characteristics of Gelled Propellants in Swirl Injectors”, *Fuel*, Vol. 97, pp. 253-261.

7. RESPONSIBILITY NOTICE

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