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DEVELOPMENT OF A GAS-LIQUID INJECTOR FOR LIQUID ROCKET ENGINE

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Abstract. The injector is considered one of the main components of a liquid rocket engine. It is responsible for the atomization, and the quality of the propellant mixtures into the combustion chamber. The objective of this paper is to present the methodology developed to design a gas-liquid injector. The calculations showed in this paper are: orifice diameters of the propellant entrance into the injector, the number and the length of injection channels, and other important geometrical parameters. An injector designed using the proposed methodology was test laboratorial experiments to be validated, and results showed that the methodology can design injectors with satisfactory sprays for liquid rocket engine combustion.

***Keywords**: Aeroespatial Engineering, liquid rocket engine, combustion chamber, injector.*

1. INTRODUCTION.

For an accurate work of the combustion chamber of a liquid rocket engine, the propellants should be atomized and mixed in the most efficient manner as possible, in order to promote the complete burns of the fuel and oxidize. The injector should be efficient to provide such burn condition.

The injectors are used in many industries segments, processes and other applications, such as: medicine, agriculture besides the aerospace area. Numerous kinds of injectors have been developed and are generally utilized as atomizers. The atomization process occurs when one jet or blade of liquid is disintegrated in droplets by its instability, such instabilities are causing by forces such as: centrifugal, during its passage by the injector, and aerodynamics instabilities generated by gases or air around the jet or blade of liquid.

In the aerospace area, the injector has many applications in liquid rocket engine, being an important element in the combustion process. The injectors are responsible for correcting atomization and mixture of propellants in the combustion chamber. The burnt is a physics and chemistry process, and it depends on diffusion and, especially, of mixture facility rate that has to mix the propellants.

The injector is one of the most important part of the engine, it can be bipropellant (atomize two kinds of propellants simultaneously), or monopropellant (atomize only one type of propellant). It determines the distance covered by atomized propellant flow in the combustion chamber. Its main function is to assure the flow of the atomized liquid, facilitating the mixture between the propellants inside the combustion chamber of the liquid rocket engine. The type of injector and its position in the injector plate determine the grade of atomization, and the local mixture grade of fuel and oxidants in the combustion chamber.

The combustion of fuel in diesel engines, gas turbines, rocket engines and industrial furnace depends on atomizing efficiency to increase a free size surface of droplets and to reach great rate of mixture and evaporation of fuel and oxidants or propellants.

The final product of the atomization is a spray, which can be produced by many types of injectors such as; Jet, swirl besides others.

For many applications are used many kinds of swirl injectors, whose functioning occurs in the following way: The fuel is forced under high pressure to enter in the chamber of the injector, through tangential canals of feeding on the wall of the injector. The liquid forms a film with rotational movement around the wall of the internal chamber of the injector, commanding a region of low pressure in the center, being filled with the air or gas of the chamber where the injector will be connected. The fuel leaves the atomizer through an exit orifice with high angular speed forcing the liquid to disperse radially in the form of conical thin layers. This thin blade of liquid becomes unstable and it brakes into droplets form (Xue et al, 2004).

The sauter mean diameter depends on the initial thickness of liquid blade, of the gas speed rounding the liquid blade, liquid viscosity and its surface tension.

The injectors used in liquid rocket engines represent a connection between the propellant and the combustion chamber and are, swirl and jet types.

This work describes a procedure for designing a pressure atomizer. The spray cone angle, and the mass distribution are evaluated with the intention of showing the performance of designed injector.

2. DESIGN OF GAS LIQUID INJECTOR.

To begin the calculation of a gas liquid injector, firstly the swirl part of the jet should be separated into two different injectors. The separation of injector into two distinct models is necessary, because each case has different initial data, parameters and calculation methodology, which will be showed as follows.

The main purpose of this methodology, based in the Russian literature according to Kessaev (2006) and Bazarov et all (2004), is to verify through interactions, if the gaseous oxidant and fuel liquid will be atomized and if they mix adequately. For this purpose, it will be used a kinetic relation between gas speed and liquid speed (Z). This numeric parameter depends on the efficiency of the injector. The liquid propellant is fed in the injector through the lateral channels, and the gaseous entrance in the injector is at the superior part of the injector. The proposed injector showed in "Fig. 1" is based in Rd-170 rocket engine models.

The initial data for injector calculation, are: pressure of combustion chamber (P_k), total mass flow of oxidant ($\dot{m}_{rt}$) and fuel ($\dot{m}_{ft}$), fluid fuel density (ρ_f), temperature of gas oxidant in the injector (T_r), constant of gas (R), cinematic viscosity of fuel (υ_f) and fuel pressure variation in the injector (Δp_{inj}). To determinate the main parameters of the injector showed in figure 1, we must decide values for: diameter of fuel injector feed for jet part (d_{fj}) and oxidant (d_r), numbers of feeding fuel orifices for part jet (nh), number of tangential channels of fuel feed in the part swirl of the injector (n1), number of injector of injector plate (n), The ray of the chamber of the injector (r_{co}) and inlet fuel diameters channel for swirl part (r_{bx}). For calculation, initially the injector will be divided into two parts, jet part for all gas propellant and 85-90% of fuel propellants, and swirl part for 10-15% of fuel propellants.

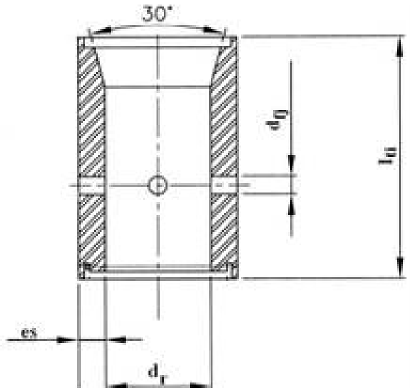

Figure 1. Main parameters of the jet part of the injector.

2.1 Calculation of the jet part of the injector.

To know the fuel speed of fuel in the exit of each injector orifice, it is necessary to know the mass flow of fuel in each orifice of the injector ($\dot{m}_{fl}$), utilizing the "Eq. (1)", being V the percentage of the mass flow used in this injector varying of 85-90%.

$$\dot{m}_{fl} = \frac{\dot{m}_{ft}.V}{n.nh} \tag{1}$$

The mass flow of oxidant for each injector ($\dot{m}_r$) is calculated by "Eq. (2)".

$$\dot{m}_r = \frac{\dot{m}_{rt}}{n} \tag{2}$$

With the decided value of the inlet diameter of the oxidant in the jet part (d_r), it is possible to determine the passage area of the oxidant for the injector (F_r) using "Eq. (3)".

$$F_r = \frac{\pi.d_r^{\,2}}{4} \tag{3}$$

Using the decided value of the diameter of the inlet of fuel in the jet part (d_{fj}), it is possible to determine the area of exit of fuel in the feeding canal (F_{fj}) using "Eq. (4)".

$$\mathbf{F_{fj} = \frac{\pi . d_{fj}^{2}}{4}} \tag{4}$$

With the purpose of obtaining the passage speed of the oxidant by the injector, it is necessary to calculate the gas density (ρ_r) , which varies as pressure and temperature vary, being obtained through "Eq. (5)". Being R the relation: 8314/ molecular weigh of gas.

$$\rho_r = \frac{P_K}{R.T_r} \tag{5}$$

The gas oxidant and liquid fuel speed in the injector channels (W_r) and (W_{fj}) respectively, can be calculated by the continuous equation as "Eq. (6)" and "Eq. (7)".

$$\mathbf{W_r = \frac{\dot{m}_r}{F_r . \rho_r}} \tag{6}$$

$$\mathbf{W_{fj} = \frac{\dot{m}_{fj}}{F_{fj} . \rho_f}} \tag{7}$$

To evaluate if the gas flow will be able to atomize the flow of a liquid fuel injected in jet part, it is made a kinetic relation between the speeds and densities of the gas by the liquid (Z). As shown by statistical data of experiments, the ideal value of this relations as Kessaev (2006) is 1, that is, vary the values of $d_{fj,}$ $d_{r,}$ n and nh to a possible value of Z more approximately to 1 in "Eq. (8)".

$$\mathbf{Z = \frac{\rho_r . W^2{}_r}{\rho_l . W_{fj}^{2}}} \tag{8}$$

The calculation of the minimum total length of the injector (l_{ti}) to occur a good mixture and atomization of propellants as Bazarov et al (2004) is in agreement to "Eq. (9)".

$$2.3 = \frac{l_{ti}}{d_r} \tag{9}$$

The calculation of the thickness of the injector (s) wall is obtained through "Eq. (10)" (Kessaev, 2006). Being U_{es} the relation between thickness of the wall and the diameter of liquid inlet. To avoid deformations, or in extreme cases explosion in the injector chamber the U_{es} value must be higher or equal to1.

$$\mathbf{U_{es} = \frac{es}{d_{fj}}} \tag{10}$$

2.2 Calculation of swirl part of the injector.

To determine the main parameters of the injector, the values of r_{co} and r_{bx}, and the number of tangential channels of fuel fed in the part swirl of the injector (n1) showed in the "Fig 2", must be decided. Remembering that, when deciding values, one must respect a recommendation of Bazarov et al (2004), which determines that the diameter of the orifice of feeding of the centrifugal injector (r_{bx}) must be between 0.5-2.5mm. Because, small diameters can obstruct the fluid passage and, the great ones, can lead to the loss of atomization efficiency.

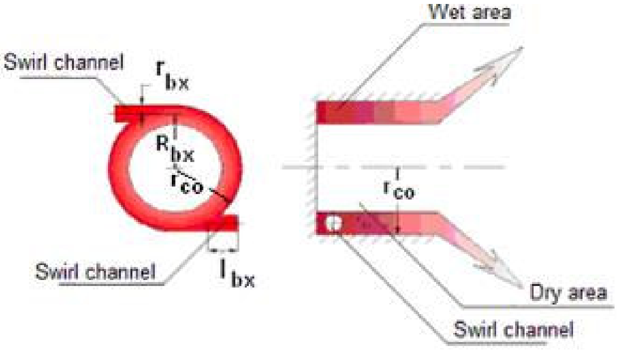

Figure 2. Opened centrifugal injector where the red color represents the fluid.

It must be taken into consideration the determined swirl injector parameters (r_{co} , r_{bx}), the distance considered between the injectors in the injector plate, the injector number, and diameter of combustion chamber.

Initially through "Eq. (11)" the geometric parameter (A_{inj}) is calculated, this parameter varies as the variation of the injector geometry. The value of R_{bx} represents the difference between r_{co} and r_{bx}.

$$\mathbf{A_{inj} = \frac{R_{bx}.r_{co}}{nl.r_{bx}^{\;2}}} \tag{11}$$

The coefficient of the free size of the injector (Φ) relates to the area of the centrifugal injector chamber where the propellants can cover freely. The value of this coefficient of free area is calculated equaling A_{inj} in "Eq. (11)" with the one in "Eq. (12)", being both equations removed from Kessaev (2006).

$$\mathbf{A_{inj} = \frac{(1 - \Phi).\sqrt{2}}{\Phi.\sqrt{\Phi}}} \tag{12}$$

As Kessaev (2006), the value of Φ calculated with help of "Eq. (11)" and "Eq. (12)", is used in "Eq. (13)" to determinate the discharge coefficient of the injector chamber (μ_{inj}).

$$\mathbf{\mu_{inj} = \Phi.\sqrt{\frac{\Phi}{2 - \Phi}}} \tag{13}$$

With the purpose of getting the ideal mass flow in the part swirl of the injector, it makes necessary the calculation of the exit area of the chamber of the swirl part of the injector (F_{fc}) that is given through "Eq. (14)".

$$F_{fc} = \pi.r_{co}^{\;2} \tag{14}$$

The ideal mass flow (m_{fi}) is calculated through "Eq. (15)".It is understood that for ideal mass flow, one should neglect hydraulical losses generated by attrition during the passage of the fluid for the injector channels, and in the inlet of the injector, and those generated by loss for angular moment. The loss for angular moment is due to the influence of the viscosity of the fuel liquid in the interior of the injector, where the fluid forms centrifugal vortices.

$$\dot{m}_{fi} = \mu_{inj}.F_{fc}.\sqrt{2.\rho_f.\Delta p_{inj}} \tag{15}$$

2.2.1. Calculation of fuel mass flow considering hydraulical losses.

With "Equation (16)" given by Kessaev (2006), the speed of passage of liquid fuel (W_{fc}) is obtained for each inlet tangential channel of the swirl part of the injector.

$$W_{fc} = \frac{\dot{m}_{fi}}{nl.\pi.r_{bx}^{2}.\rho_f} \qquad (16)$$

The length of the injection channel (l_{bx}), can vary from 2 to 3 times (Bazarov et al, 2004) as "Eq. (17)".

$$2...3 = \frac{l_{bx}}{2.r_{bx}} \qquad (17)$$

Using "Equation (18)" (Kessaev, 2006), it was obtained the real fuel mass flow (m_{fr}) of the swirl part of the injector, considering the total hydraulical losses (ξ_{ft}).

$$\dot{m}_{fr} = \frac{\pi.r_c^{2}.\sqrt{2.\rho_f.\Delta p_{inj}}}{\left(\frac{1}{\Phi^2} + \frac{A_{inj}^{2}}{1-\Phi} + (\xi_{ft}.nl).A_{inj}^{2}\right)^{0.5}} \qquad (18)$$

The values of r_{bx}, n_1 and $r_{co,}$ are varied and applied in the equations of development of the swirl part of the injector until it obtains a value of real mass flow approximated to the required one. Being this required value of 10-15% of total fuel mass flow for each injector used in the injector plate of the combustion chamber. The main parameters of injector developed are showed in the Tab. 1 and Tab. 2.

Table 1- The initial parameters data for to injector calculation.

Inlet diameter of oxidant (d_r).	0.01 m
Inlet diameter of fuel in part jet (d_{fj}).	0.0017 m
Number of inlet orifices of fuel in jet part (nh).	4
Number of injector in injector plate (n).	61
Ray of the injector chamber (r_{co}).	0.007 m
Ray of liquid inlet of injector (r_{bx}).	0.00025m
Number of inlet orifices of liquid fuel in swirl part (n1).	3
Mass flow of oxidant for each injector ($\dot{m}_r$).	0.308 kg/s
Mass flow of fuel in the jet part for each injector ($\dot{m}_{fl}$).	0.076 kg/s
Mass flow of fuel in the swirl part for each injector ($\dot{m}_{fr}$).	0.012 kg/s
Percentage of fuel in jet part (v).	86%

Table 2. Main values calculated for injector used in this paper.

Inlet oxidant diameter (d_r).	0.01 m
Inlet fuel diameter in jet part (d_{fj}).	0.0017 m
Kinetic relation oxidant/fuel (Z).	1.01
Minimum total length of the injector (l_{ti}).	0.023 m
Thickness of wall of the injector (es).	0.0017 m
The length of the injection channel (l_{bx}).	0.0015 m
Exit area of the chamber of the swirl part of the injector (F_{fc})	1.539×10^{-4} m²
Total hidraylicall losses (ξ_{ft}).	0.578

3. EXPERIMENTAL SETUP.

In order to get the performance results of the injector developed in this paper experimentally, it was used a test equipment showed in “Fig. 3”. The parameters tested were: spray angle and mass distribution. This technique is based in a work developed by Souza (2001) and Garcia (2005). During all the tests realized in this work, the oxygen was replaced by nitrogen, and alcohol was replaced by water. The importance of experimental tests is because, through the evaluation of the injector performance obtained in a trustworthy way, we know if the injectors gets atomized and mix the propellants, promoting a stable and efficient combustion inside the combustion chamber.

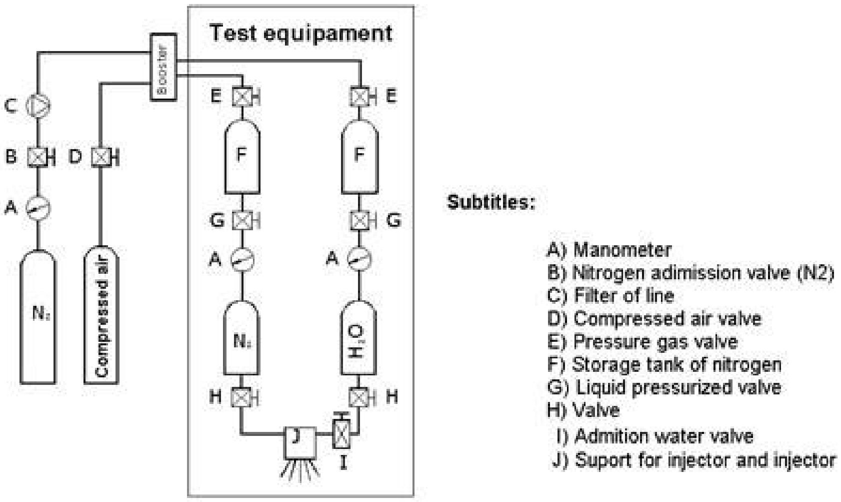

Figure 3- Experimental setup

3.1. Mass distribution test.

This test is important to determinate the distribution of the fuel in the rocket engine. In this test, it is avoided points in the rocket engine with excess of fuel, and points without fuel, thus preventing instability problems in the rocket engine. Therefore a correct propellant concentration in the combustion chamber prevents explosion in regions with fuel excess occurring thrust losses and leading rocket to instability. For this test, it is used an apparatus for water storage divided into 90 parts and each part collects water, representing places inside of the combustion chamber showed in “Fig. 4”.

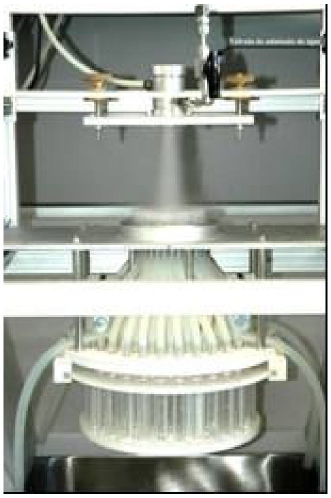

Figure 4- Apparatus utilized in the water storage.

The water spray produced by the injector for four seconds approximately, is stored in a chemistry tube inside in the apparatus showed in “Fig. 4”. Each chemistry tube is separately weighed empty and after the test, the difference is written representing the weigh of water that dropped in the corresponding chemistry tube.

3.2. Cone angle.

This procedure is utilized to determine the numerical value of the cone angle formed by the atomized fluid in the injector exits. This test is important, because through it, one knows if inside of the combustion chamber will occur the ideal mixture of propellants atomized by the injectors supported in the injector plate.

The essay of the cone angle of existent atomized fluid begins when water is sprayed by the tested injector. With the aid of a digital camera with a flash, the spray formed in the exit of the injector is photographed. After that, this photo is taken to the computer and, with the aid of AutoCAD software, it is proceeded the measurement of the cone angle of the spray formed in the exit of the injector. This procedure is showed in “Fig. 5”.

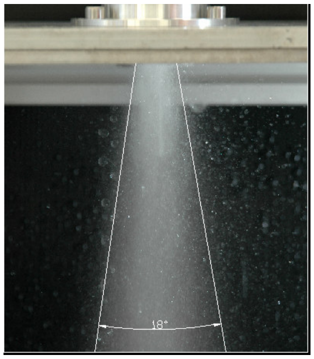

Figure 5. Digital photo of measurement of the cone angle of spraying.

4. RESULTS AND DISCUSSION

For the test, three conditions were required varying the propellant and oxidant entrance pressure in the injector. this condition is showed in Tab. 3.

Table 3.Referring to the inlet pressures of the elements in the injector

Condition	Inlet pressure of nitrogen (Pa).	Inlet pressure of water (Pa).
A	3.0×10^5	7.5×10^5
B	2.0×10^5	6.5×10^5
C	4.0×10^5	8.5×10^5

The A case is the project condition. The B and C conditions were tested, to verify the pressure effect in the injector performance. This pressure condition used was chosen through visual observation of the changes in the injector behavior.

4.1. Distribution of mass in the combustion chamber.

The results are showed in "Fig. 6", being the scale 1 for greater value and 0 for the minor value.

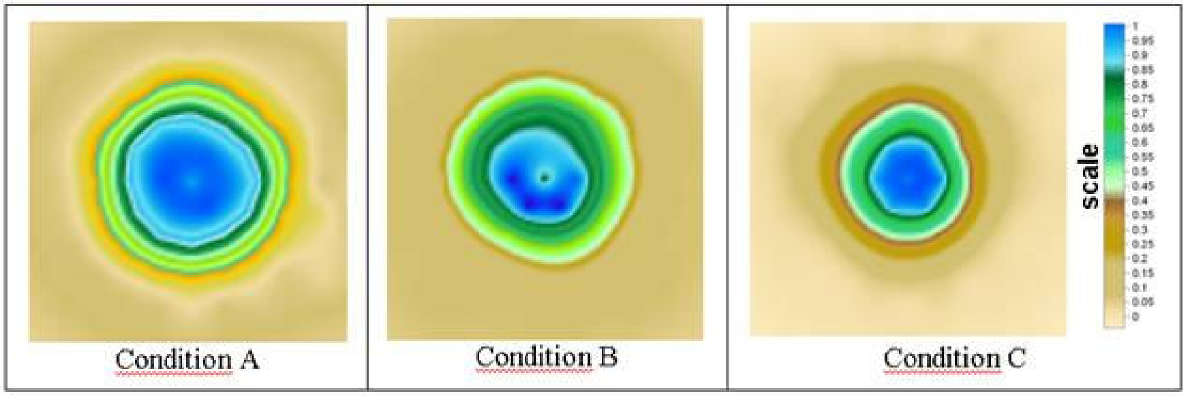

Figure 6. Diagram of mass distribution.

As seen in the diagram showed in "Fig. 6" that in condition A, the distribution of mass was concentrated in the central part of the apparatus that has the chemistry tubes assay in the test. This fact is common for jet injectors, whose opening of the angle of exit of the fluid is narrow (Lefebvre, 1989). As the injector is fed by about 86% of this mass flow by jet part, such behavior is expected.

The graph showed in "Fig. 6" that in condition A, the one color perfect circle expected did not happen, without variation of the mass concentration of the liquid throughout its distribution. Some referring distortions of variations of concentrations of liquid mass are observed through the change of color, shape and amount of the circle formed in the graph.

The distributions of the drops atomized for the injector are governed by the symmetry and uniformity of the spray created in the exit of the injector (Lefebvre, 1989). This symmetry and uniformity mentioned by Lefebvre (1989) are affected by the its manufactures, therefore, during the manufacture of the injector, the appearance of great roughness on its internal wall might occur, as well as, the presence of barbs that affect the flow of propellants through the injector, harming the formation of spray in the exit of the same.

Observing the graphs of "Fig. 6", condition B and C, it is verified that the effect of the variation of the inlet pressure of the elements in the injector has direct effect in the mass distribution of the liquid atomized by the injector. The reduction of the pressure of feeding of the injector, in relation to the nominal one, tends to increase the differences of mass liquid concentration throughout its distribution, distorting even more the circles formed in the central part of the graph in comparison to case A and B.

The increase of the inlet pressure of the elements of the injector (case C) in relation to the nominal pressure tends to lightly increase the dispersion of the fluid throughout the apparatus, and the variation of concentration throughout its mass distribution. This difference is observed by the comparison between the graphs in case A and C showed in "Fig. 6".

This described behavior in the two previous paragraphs makes sense, because the pressure variation of the elements feeding modifies the flows of the gas and the liquid inside the injector chambers, modifying the mass distribution of spray formed in the exit of the injector.

Another important factor is the density variation of the gas, it varies as the change of the pressure affects its passage for the inside injector chamber.

4.2. Angle of the cone of exit of atomized fluid.

The results obtained through the assay of the cone of exit of atomized fluid are in Tab. 4.

Table 4. Angle of cone of spray formed in the exit of the injector.

case	Angle of the cone.
A	18°
B	17°
C	17°

The results showed in Tab.4. are in agreement to the expected one, therefore jet injector has as a characteristic, the formation of narrow spray (Lefebvre 1989), that is, of low value on the cone angle formed in the exit of the atomizer. The injector developed in this paper is predominantly jet, justifying the values obtained and showed in Tab. 4.

As showed in Tab 4., it practically does not have variation between the values of the cone angle. This fact, show us that pressure variation does not change the angle of the cone of the exit atomized fluid. This fact occurs, because for liquids of low viscosity such as: water and ethanol, the formation of cone angle of atomized fluid in the injector exit is led mainly by the injector dimensions, such as: the area of the entrance orifice and propellant exit in the injector and the size of the diameter of the chamber of the injector (Lefebvre 1989).

5. CONCLUSIONS.

The mass distribution of spray formed in the exit of the injector was satisfactory; however it can be improved with the manufacture of an injector with better finishing. Especially on its internal walls, diminishing its roughness and eliminating the barbs formed mainly in the orifices of injector feeding.

The Angle of the cone of atomized fluid exit was in agreement expected for predominantly jet injector, that is, of small angle if compared to the swirl injectors. This is due to the geometry of the injector, which propitiates this type of narrow jet.

The increase and reduction of the inlet pressure of the elements in the injector have had great influence in the distribution and mass flow of the injector, showing that inlet pressure of propellants in the injector must be always required by the engine designer, being this kept constant, therefore small variations of pressure affect the quality of the propellants mixture and the combustion of the rocket engine will be affected.

As the answers of the assay of performance for this model of injector developed in this paper were favorable, the same can be tested in a liquid rocket engine.

6. ACKNOWLEDGEMENTS.

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