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PRELIMINARY DESIGN OF A PINTLE INJECTOR FOR ATOMIZING GELLED ETHANOL AND HYDROGEN PEROXIDE

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Abstract. *Bipropellant propulsion systems are used for placing payloads into orbit or change of orbit of satellites and space vehicles. In the last decade, there has been a great interest in the use of high-performance, low toxicity and low cost space propellants. Gelled propellants also have been tested allowing better performance and safer operation. Injectors are used for atomizing and distributing the propellants throughout the thruster combustion chamber. The atomization process aims to increase the surface area of the propellants, to increase the rates of vaporization, mixing and burning. Pintle-type injectors allow the control of the injection area and the mass flow rates of propellants, and show few instability problems. This work describes the preliminary design of a pintle injector for atomization of gelled hydrous ethanol (C_2H_5OH 95/05) and hydrogen peroxide (H_2O_2 90/10). Initially the theoretical performance curves of the propellant combination were obtained, to determine the optimum operating conditions and the fuel/oxidizer mass flow rates for application in a 200 N bipropellant thruster. The main geometric parameters of a pintle injector with a movable pintle tip and different tip angles were calculated assuming stoichiometric conditions and a spray cone semi-angle of 45º.*

Keywords: *Pintle injector, gelled propellants, liquid rocket engine, CEA NASA, ethanol, hydrogen peroxide*

1. INTRODUCTION

Liquid propellant propulsion systems can produce large thrust levels with relatively high specific impulses. Therefore they allow placement of payloads into orbit and perform space maneuvers with high velocity increments in a reduced time. In the last decades, green propellants have been considered for application in rocket propulsion systems since they present low environment impact and have lower toxicity than conventional liquid propellants (Aggarwal et al., 2015). Gelled propellants also have been considered in last years for application in rockets due to their propulsive performance and safety characteristics. Gelled propellants present non-Newtonian behavior, decreasing their viscosity as the shear rate increases. As a result they behave as liquid propellants during the injection process when the shear stress increases and behave as solid propellants during storage (Fischer, 2019; Song et al. 2021).

An injection plate is used for atomization of propellants to form a spray and, consequently, to increase the surface area of liquids or gels in order to increase the vaporization, mixing and burning rates. Injectors located in the injection plate must atomize and spread the spray droplets in the correct proportion throughout the combustion chamber. The droplet sizes and velocities influence the chamber length and, usually, a uniform spray of small droplets is required for application in propulsion systems (Sutton & Biblarz, 2001).

Different types of injectors can be used to atomize fluids, such as single orifice jets, coaxial or dual orifice jets, impinging jets, pintle, blurry and pressure swirl injectors (Dias, 2020). Pintle injectors do not present instabilities and allow throttling (Erkal et al., 2019). A pintle injector was used initially as the main injector in the lunar module of the Apollo mission (Casiano et al., 2010; Gilroy and Sackheim, 1989; Betts and Frederick, 2010).

Son et al. (2017) developed a design procedure of a movable pintle injector and designed a 500 N combustor. Their procedure was based on spray characteristics to achieve proper performance under all throttling conditions. The Sauter mean diameter of the droplets and the spray angle were critical performance parameters.

Erkal et al. (2019) described the design and a cold flow experiment procedure of a pintle injector similar to the one designed by Son et al. (2017). They mentioned that a pintle injector may cover the entire chamber instead of having a heavier injector plate using other injector types. Then, a pintle injector is cheaper to fabricate and launch. Secondly, a pintle injector has the ability to throttle with control of area at the injection gaps. In their study, a design methodology was developed and used to design a 750N pintle injector. Three different inner geometries were tested to have uniform flow for spray cone formation. The injector was manufactured and tested with cold flow using air and water to validate the spray cone angle found by analysis. Moreover, the manufactured injector was investigated at different throttle levels and the spray cone angles were measured with a high-speed shadowgraphy system and the Sauter mean diameters were measured by a PDPA system.

Song *et al* (2021) analysed the atomization of gelled kerosene by a multi-hole pintle injector using water as an oxidizer simulant. They have devised new methods to increase the mixing performance of the gelled fuel. The liquid kerosene was gelled with 5 wt% of Thixatrol ST. The spray characteristics of flat and deflector type injectors were determined via a backlight image method. Spray angles were calculated based on the total flow momentum ratio and were compared with experimental data. The measured spray angle of the deflector type injector satisfied the expected spray angle. The main difference of spray characteristics between flat and deflector type injectors was found in terms of the presence of a liquid jet stream, related to breakup and atomization processes. In the case of the flat type injector, the liquid jet stream was observed even for a high total momentum ratio. Nevertheless, for the deflector type injector, the liquid jet stream was not observed with an increase in the total momentum ratio.

Several injection systems and atomization studies have been developed in the last two decades at the Combustion and Propulsion Laboratory (LCP) of the Brazilian Space Research Institute (INPE) related to green and gelled propellants (Vazquez, 2011; Azevedo, 2013; Fischer, 2019; Dias, 2020). Therefore, the present work describes a preliminary design of a pintle injector with a movable tip for atomization of gelled ethanol (C_2H_5OH/H_2O - 95/05) and hydrogen peroxide (H_2O_2/H_2O - 90/10) for application in a 200 N thruster.

2. METHODOLOGY

In order to identify the optimum propulsive parameters and evaluate the theoretical performance of mixtures of C_2H_5OH/H_2O (95/05) and H_2O_2 (90/10) for different equivalence ratios, thermodynamic properties and propulsion parameters were obtained with help of CEA-NASA (2004) code. Figures 1, 2 and 3 present, respectively, plots of the calculated specific impulses, chamber temperatures and characteristic velocities, considering chamber pressures 10, 20, 40 and 80 bar and fuel/oxidizer equivalence ratios 0.4 to 2.5. Average equilibrium and frozen flow properties were considered, for expansion in vacuum through a nozzle with expansion ratio equal to 50. Figure 4 depicts the oxidizer/fuel (O/F) mass ratio versus equivalence ratio.

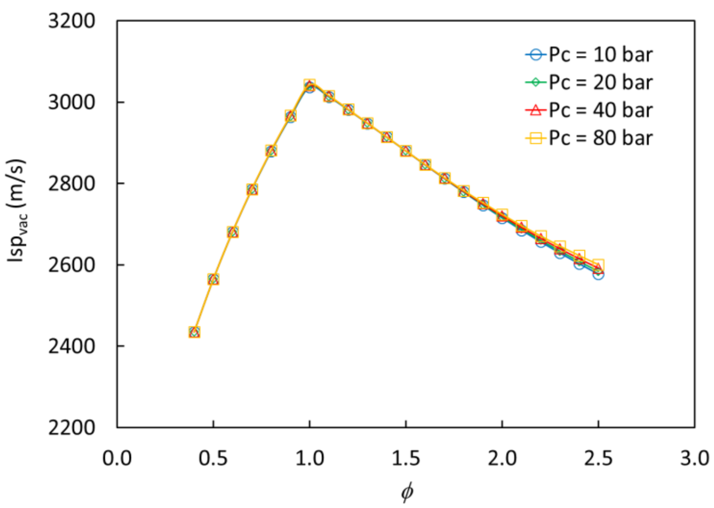

Figure1.Vacuum specific impulses (Isp_{vac}) versus equivalence ratio (ϕ) for combustion of C_2H_5OH/H_2O (95/05) + H_2O_2 (90/10)

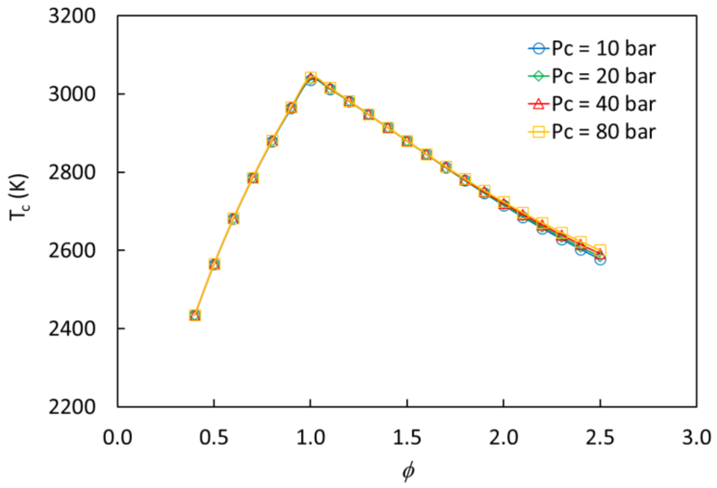

Figure 2. Chamber temperature (T_c) versus equivalence ratio for combustion of C_2H_5OH/H_2O (95/05) + H_2O_2 (90/10).

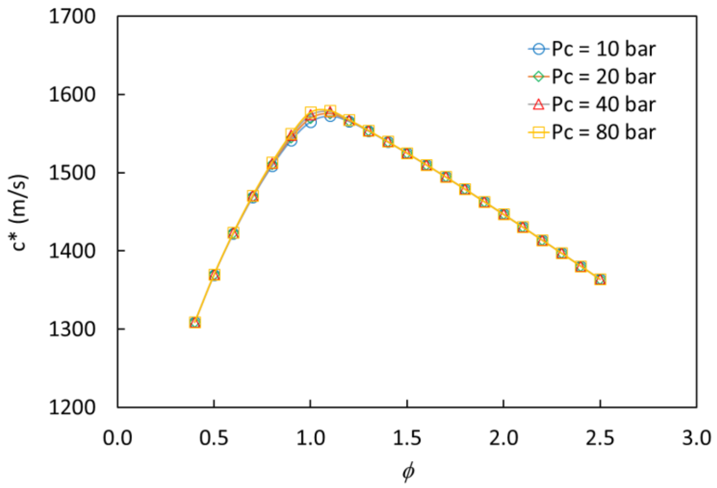

Figure 3. Characteristic velocity (c*) versus equivalence ratio for combustion of C_2H_5OH/H_2O (95/05) + H_2O_2/H_2O (90/10).

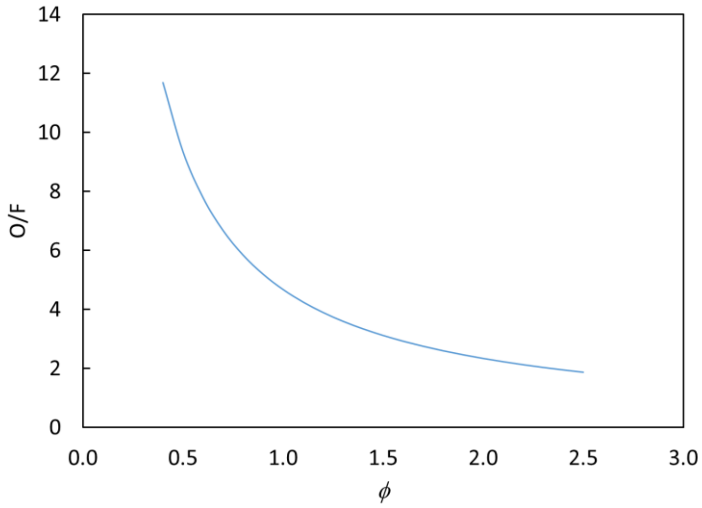

Figure 4. O/F mass ratio versus equivalence ratio for combustion of C_2H_5OH/H_2O (95/05) + H_2O_2/H_2O (90/10).

Figures 1, 2 and 3 indicate that chamber pressures have no significant effect on propulsive properties. Maximum values of specific impulse, chamber temperature and characteristic velocity are close to stoichiometric conditions. Table 1 depicts the stoichiometric values of theses parameters for the different pressures.

Table 1 – Stoichiometric values

P_c (bar)	T_c (K)	Isp_{vac} (m/s)	c* (m/s)
10	2574	3037	1565
20	2604	3039	1570
30	2632	3041	1574
40	2657	3043	1577

A pintle injector with a movable tip, similar to the one developed by Son *et al* (2017), was adopted, since it allows an easy control of the pintle geometry and change the spray angle. Figure 5 shows a scheme of the pintle injector where the fuel (gelled ethanol) is fed through the center gap and the oxidizer (hydrogen peroxide) is fed through the annular gap. In Son et al.'s injector the fuel was fed through the annular gap and the oxidizer was fed through the central gap.

Figure 6a shows the minimum opening distance L_{min} which is measured along the perpendicular line from the post tip to the pintle tip slope. The area A_{min}, with side L_{min}, which corresponds to the lateral area of a truncated cone, is also depicted in Figure 6a. Amin is plotted in Fig. 6b against L_{min}. When A_{min} is equal to the center gap area A_{cg} a transition point in the flow is reached, with generation of instabilities.

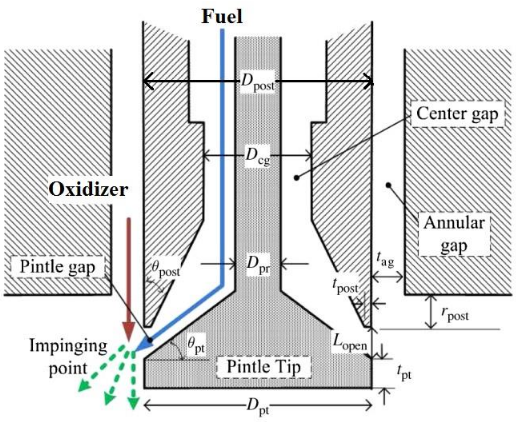

Figure 5. Scheme of the pintle injector tip region (adapted from Son *et al*, 2017).

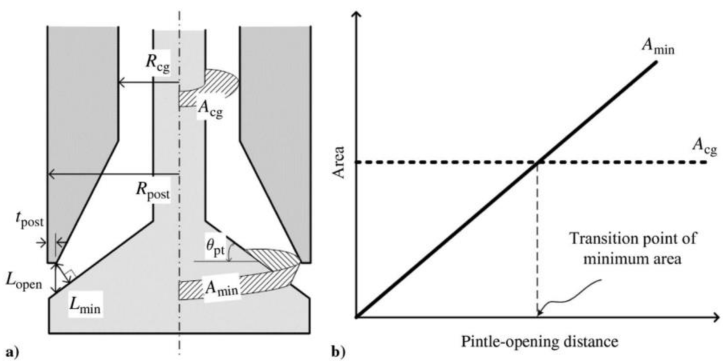

Figure 6. Remarkable dimensions for minimum-area transition: pintle injector schematic and b) transition point (adapted from Son el al, 2017).

The pintle injector for green propellants was designed considering stoichiometric conditions, with O/F mass ratio 4.676. Consequently, the total mass flow rate is $\dot{m} = \frac{F}{Isp_{vac}} = 200/3037 \cong 65.854\ \frac{g}{s}$, the fuel mass flow rate is $\dot{m}_F = \dot{m}/(1+O/F) = 11.602$ g/s and the oxidizer mass flow rate is $\dot{m}_O = O/F\ \dot{m}_F = 54.252$ g/s.

According to Cheng et al. (2017), the total momentum ratio (*TMR*) and spray cone semi angle (θ) of a pintle injector can be estimated, respectively, by:

$$TMR = \frac{\dot{m}_f V_{f,i} \cos\theta_{pt}}{\dot{m}_0 V_{0,i} + \dot{m}_f V_{f,i} \sin\theta_{pt}} \tag{1}$$

and

$$\cos\theta = \frac{1}{1+TMR} \tag{2}$$

Assuming $\theta = 45^0$, the total momentum ratio is:

$$TMR = \frac{1}{\cos 45°} - 1 = \sqrt{2} - 1 \cong 0.4142 \tag{3}$$

The oxidizer inlet velocity can be calculated in terms of the pintle tip angle, θ_{pt}:

$$V_{0,i} = \frac{\dot{m}_f}{\dot{m}_0}\left(\frac{\cos\theta_{pt}}{TMR} - \sin\theta_{pt}\right) V_{f,i} \tag{4}$$

Fuel and oxidizer inlet areas are given, respectively, by:

$$A_{f,i} = \frac{\dot{m}_f}{\rho_f V_{f,i}} \tag{5}$$

$$A_{0,i} = \frac{\dot{m}_0}{\rho_0 V_{0,i}} \tag{6}$$

where $\rho_f = 797$ kg/m^3 and $\rho_O = 1380$ kg/m^3 are the ethanol and hydrogen peroxide densities, respectively.

The inlet areas are annular areas and can be also calculated, respectively, by:

$$A_{f,i} = (\pi/4)\left(D_{cg}^2 - D_{pr}^2\right) \tag{7}$$

$$A_{0,i} = (\pi/4)\left(\left(D_{post} + 2t_{ag}\right)^2 - D_{post}^2\right) \tag{8}$$

where D_{cg} is the center gap diameter, D_{pr} is the pintle rod diameter, D_{post} is the post external diameter and t_{ag} is the annular gap thickness.

Once D_{pr} and D_{cg} are specified, the fuel inlet area is obtained from Eq. (7) and, consequently, the fuel inlet velocity can be calculated using Eq. (5). Then the oxidizer inlet velocity and the oxidizer inlet area can be obtained from Eqs. (4) and (6), respectively.

If the oxidizer tube diameter, $D_{oxid} = D_{post} + 2t_{ag}$, is also specified, the post external diameter and the annular gap thickness can be calculated:

$$D_{post} = \sqrt{D_{oxid}^2 - \frac{4}{\pi} A_{0,i}} \tag{9}$$

$$t_{ag} = \left(D_{ext} - D_{post}\right)/2 \tag{10}$$

The fuel exit area $A_{f,out}$ corresponds to the minimum exit area A_{min}, as showed in Figure 6. A_{min} is the lateral area of a truncated cone, i.e.,

$$A_{f,out} = A_{min} = \pi L_{min}(R + r) \tag{11}$$

where

$$R = R_{post} - t_{post} \tag{12}$$

$$r = R_{post} - t_{post} - L_{min} \sin\theta_{pt} \tag{13}$$

3. RESULTS

The main dimensions of a pintle injector for atomization of gelled hydrous ethanol and hydrogen peroxide were calculated based on Eqs. 1 to 13 and on manufacturing limitations. The values obtained are presented on Table 2.

Fuel and oxidizer inlet velocities are shown on Figure 7 in terms of pintle rod diameter, considering D_{cg} = 2.50 mm.

Figure 8 shows the variation of A_{min} versus L_{min} calculated by Eqs. 11-13 for different tip angles.

Table 2 – Main dimensions of the pintle injector.

Parameter	Value
Post diameter D_{post}, mm	6.15
Center gap diameter D_{cg}, mm	2.50
Pintle rod diameter D_{pr}, mm	1.50
Pintle tip diameter D_{pt}, mm	6.15
Oxidizer tube diameter D_{oxid}, mm	8.00
Annular gap thickness t_{ag}, mm	0.925
Post angle θ_{post}, deg	30º
Pintle tip angle θ_{pt}, deg	10º, 20º, 30º, 40º
Pintle tip thickness t_{pt}, mm	1.00
Post recess length r_{post}, mm	2.50
Post thickness t_{post}, mm	0.50
Pintle-opening distance, L_{open}, mm	0.192 (θ_{pt} = 20º)

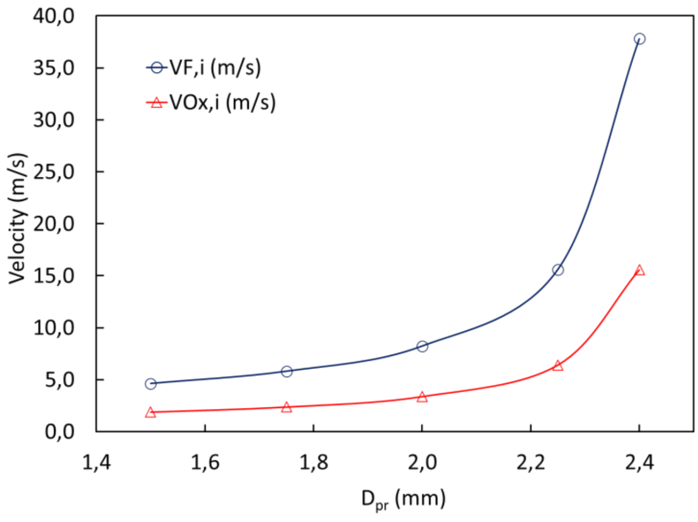

Figure 7. Fuel and oxidizer inlet velocities versus pintle rod diameter (D_{pr}), considering D_{cg} = 2.50 mm.

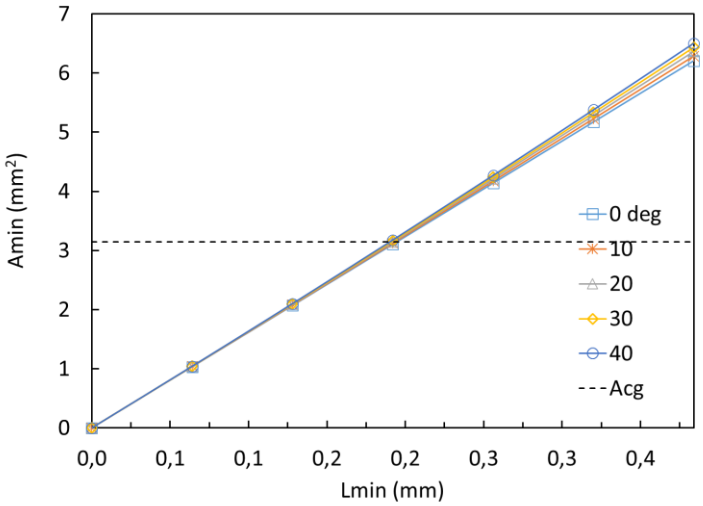

Figure 8. Variation of Amin.

Figure 9 shows a cut view and 3D views of the pintle injector prototype. A perforated disk is used to provide a uniform distribution of the gelled fuel around the pintle rod while a perforated ring is used to distribute the liquid peroxide around the post. The liquid and gel mass flow rates should be kept uniform and symmetrical around the post.

Since peroxide tends to decompose, rapid velocity variations should be also avoided. Consequently, rounded corners are used in the peroxide chamber. In the gel entrance chamber round corners are also used to reduce pressure losses.

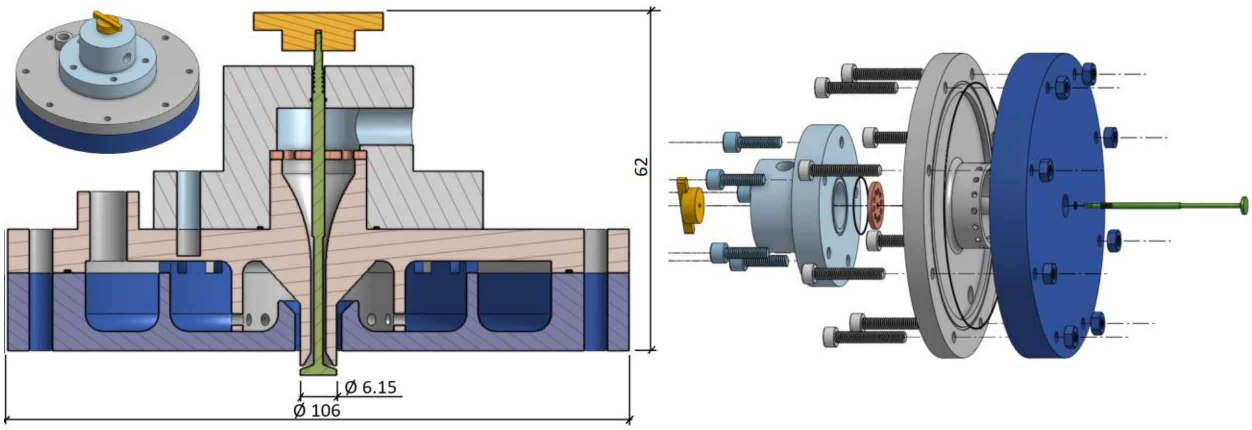

Figure 9 – Cut view and 3D views of the pintle injector prototype.

4. CONCLUSIONS

This work presented the preliminary design of a pintle injector for atomization of gelled hydrous ethanol (C_2H_5OH 95/05) and hydrogen peroxide (H_2O_2 90/10) for use in a 200 N thruster. The main dimensions of the propellant exit region were determined for a movable pintle configuration with different pintle tip angles. A cone spray semi-angle of 45º was adopted and the total momentum ratio was calculated assuming stoichiometric conditions. Manufacturing limitations and instability conditions were also considered to obtain an appropriate design.

5. ACKNOWLEDGEMENTS

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