DEVELOPMENT OF A DUAL PRESSURE SWIRL INJECTOR FOR ETHANOL AND HYDROGEN PEROXIDE

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Abstract: *Hydrogen peroxide and ethanol are alternative green propellants for spacecraft thrusters. Different types of injectors can be used for proper atomization of liquid propellants into combustion chambers. A dual pressure swirl injector has two independent concentric chambers which can provide independent rotational levels to a single liquid or two different liquids. This paper presents a theoretical study of a dual pressure swirl injector for atomization of ethanol and hydrogen peroxide for design of a 100 N liquid bipropellant thruster. Data are obtained for injection of ethanol in the primary chamber and hydrogen peroxide through the secondary chamber of the injector.*

Keywords: *dual pressure swirl injector, ethanol, hydrogen peroxide*

1 Introduction

Injectors are devices used to atomize the propellant in a combustion chamber of an engine. The atomization process is to increase the surface area of one or more fluids in order to reduce the time of vaporization, mixing and burning. After being vaporized propellants are mixed by molecular diffusion or turbulent convection within the chamber, and producing hot gases after burning are ejected from the nozzle by the thruster.

The choice of element type injector and your specific project are dependent on the physical state of the propellants, the mixture ratio, chamber pressure, the pressure drop in the injector, the chamber geometry, the performance of the atomizer, the requirements of the mission in addition to the designer's experience. These factors should be determined before the design and testing of the injector, through mathematical modeling, computational analysis and experimental results with the help of previous successful. An optimal design of injector is one that meets the expected performance and mission requirements of the propulsion system.

In the past, the designs of injectors were developed primarily through trial and error. Many designers started to copy the successful projects, but the results were not always the desired ones. Eventually, the engineers who were successful were not copying the device in question, but the correct scale and control of the combustion process. A good design for a given application may fail in others, because of subtle differences in the requirements or operating system restrictions. Many analytical tools have already been developed or are under development to assess the critical processes of combustion so that the candidate designs can be evaluated and optimized conceptually, thus avoiding or minimizing stages of design, fabrication and testing.

Ethanol and hydrogen peroxide are two propellants that are being investigated in several research centers and universities, due to, among others, the low environmental impact of their use and manufacture, ease of handling and storage, low cost and availability in market. Ethanol and peroxide are not hypergolic therefore require an ignition system or process suitable, for example, burning aids, additives, catalysts, dischargers or heaters.

In this work, it is projected a dual pressure swirl injector using ethanol and hydrogen peroxide as the liquid atomization process. Tab. (1) presents the physical and chemical characteristics of the propellants studied.

Table 1. Physical and chemical properties of propellants studied.

Propellants	Ethanol 95% + 5 % water	Hydrogen Peroxide 90% + 10 % water
Molecular Formula	CH_3CH_2OH	H_2O_2
Molecular Weight (g/mol)	42.36	32.41
Density (kg/m³)	799.55	1405
Dynamic Viscosity (mPa.s)	1.2	1.245
Boiling Point (K)	350.15	414.15
Melting Temperature (K)	155.15	262.15

2 Theoretical considerations and project analysis

2.1 Operation of pressure swirl injectors

A pressure swirl injector (Fig. 1) is formed by a vortex chamber, tangential channels inlet and an outlet orifice. The tangential inlet channels are located in the vortex chamber and are tangential to the chamber wall thereof. The outlet orifice usually has smaller diameter than the vortex chamber. In the vortex chamber, pressure decreases from the wall to the center. In the radial distance at which the pressure is null forms a hollow core, since the liquid does not support negative. The flow through the outlet orifice is formed by a film with a thickness of only a few tenths of a millimeter. Upon exiting the orifice, the liquid film has the shape of a truncated cone. With an increase in the radius of the cone decreases the film thickness and the film of liquid is broken into droplets of very small dimensions. These droplets have dimensions much smaller than the droplets generated in a jet from a single orifice. Besides the advantage of better atomization, such injectors also have the advantage that, for a given mass flow and pressure drop of the geometric dimension of the same is greater than the dimension of a simple orifice for the same flow rate and pressure drop, which makes it less susceptible to clogging.

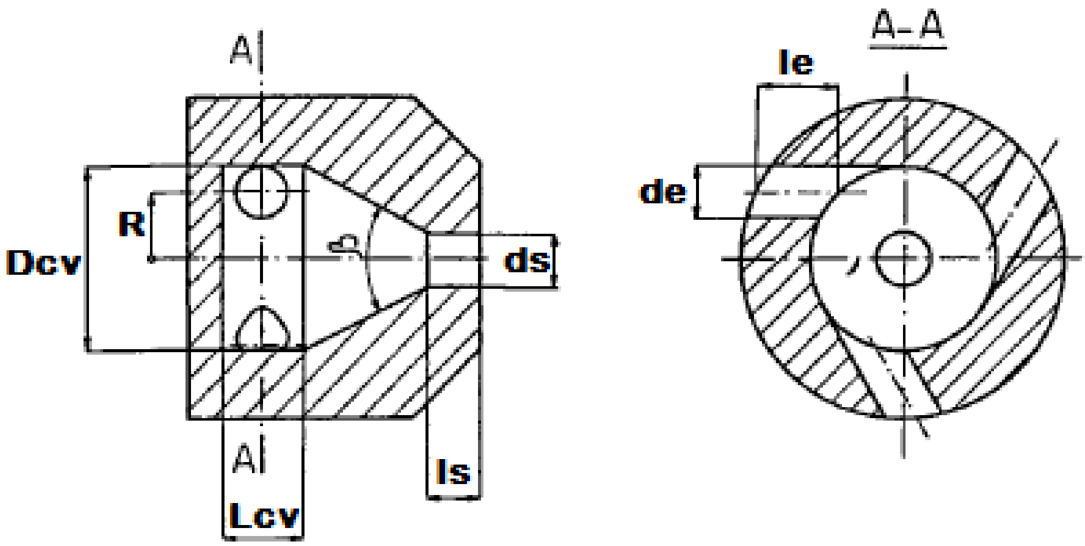

Figure 1. Basic dimensions of a pressure swirl injector.
Source: Adapted from Bayvel (1993).

A dual pressure swirl injector has two independent concentric chambers which can provide independent rotational levels to a single liquid or two different liquids (Fig. 2). The two chambers are aligned concentrically so that their throats pour the liquid forming a single spray.

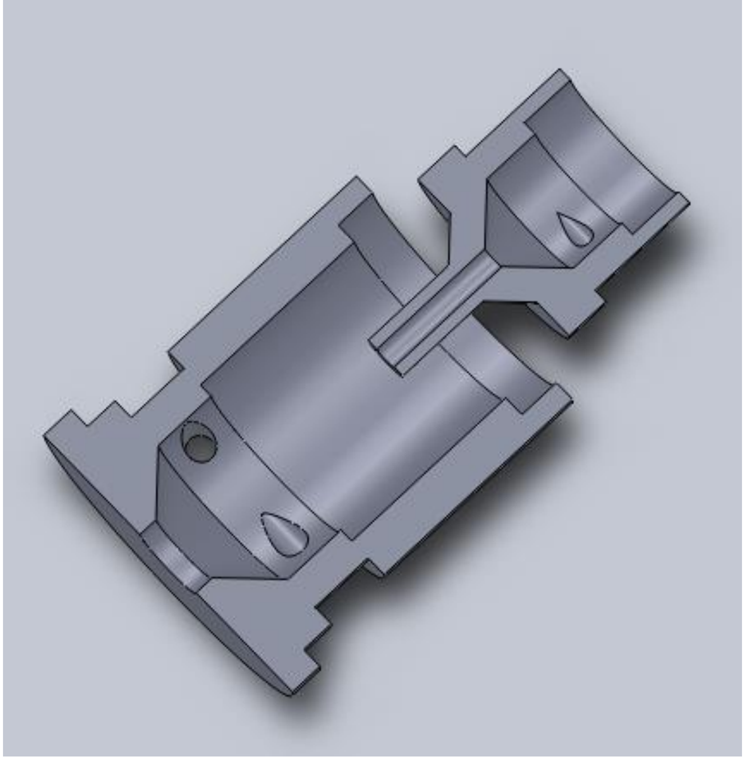

Figure 2. Schematic of a dual pressure swirl injector.

2.2 Procedure of Calculation

A theoretical procedure to design a dual pressure swirl injector for ethanol and hydrogen peroxide is presented below, based on studies by Bayvel (1993) and Bazarov (2004).

When designing an injector, the mass flow rate $\dot{m}$, the pressure drop ΔP, the spray cone angle α and the properties of the propellant, such as density ρ and dynamic viscosity μ, are generally known. The first part of the calculation relates to a liquid ideal. It is required to evaluate the discharge coefficient μ and the dimensionless parameters K and ε, to obtain the dimensions of the injector. Then, one should take into account losses due to viscosity by determining the friction coefficient λ, and fix all the dimensionless parameters and dimensions of the injector previously calculated. The calculation is performed as follows:

1. Prescribe the spray cone angle α based on the conditions of injector operation (typically between 90 and 120 degrees, lower values can be used for special cases). The characteristic geometric parameter K and the discharge coefficient μ is then determined from the graphs in Fig. (3).

2. Prescribe the pressure drop ΔP based on the conditions of injector operation. The pressure drop across the injector is usually set at values between 15 and 25% of the chamber pressure, in part to obtain high injection velocities, which aid in atomization and droplet breakup.

3. Determine the diameter of the discharge orifice:

$$d_s = \sqrt{\frac{4\dot{m}}{\pi\mu\sqrt{2\rho\Delta P}}} \quad (1)$$

4. Specify the number of tangential inlet orifices n (usually between two and four) and the distance from center to center of the tangential inlet orifices R (usually between two and four times the radius of the discharge orifice $r_s = d_s / 2$). Then, the diameter of the tangential inlet orifice is obtained:

$$d_e = \sqrt{\frac{2Rd_s}{nK}} \qquad (2)$$

5. Find the Reynolds number *Re* in the tangential inlet orifices using:

$$\mathrm{Re} = \frac{4\dot{m}}{\pi\mu\sqrt{n}d_e} \qquad (3)$$

6. The friction coefficient λ from the following equation:

$$\log\lambda = \frac{25.8}{(\log\mathrm{Re})^{2.58}} - 2 \qquad (4)$$

Equation (4) has been established as a result of extensive investigations of atomizers with $Re = 10^3$ to 10^5. Values λ determined from the equation above are significantly greater than those from other equations known and used in hydraulic systems. This is due to the high transverse pressure gradients in the boundary wall.

7. Determining the equivalent characteristic parameter K_{eq} given by:

$$K_{eq} = \frac{Rr_s}{nr_e^2 + \left(\frac{\lambda}{2}\right)R(R - r_s)} \qquad (5)$$

where r_e is the radius of the tangential inlet orifices.

8. Find ε_{eq} from the following equation:

$$K_{eq} = \frac{(1-\varepsilon_{eq})\sqrt{2}}{\varepsilon_{eq}\sqrt{\varepsilon_{eq}}} \qquad (6)$$

9. Recalculate μ_{eq} discharge coefficient from the following equation:

$$\mu_{eq} = \varepsilon_{eq}\sqrt{\frac{\varepsilon_{eq}}{2-\varepsilon_{eq}}} \qquad (7)$$

10. Find the angle of the spray cone equivalent α_{eq}, from the following equation:

$$\alpha_{eq} = 2\arctan\left[\frac{2\mu_{eq}K_{eq}}{\sqrt{\left(1+\sqrt{1-\varepsilon_{eq}}\right)^2 - 4\mu_{eq}^2K_{eq}^2}}\right] \qquad (8)$$

11. Recalculate items 3 and 4.

Tangential inlet orifices occurs contraction of the liquid and therefore the current area of the cross section $A_e^2 = \pi r_e^2$ each inlet orifice should be increased so that the jet has a cross-sectional area A_e'. The contraction coefficient φ is defined as the ratio of areas between the contracted jet and orifice:

$$\varphi = \frac{A_e}{A_e'} = \frac{d_e}{d_e'} \qquad (9)$$

12. Assume a contraction coefficient φ between 0.85 and 0.90 based on the operating conditions of the injector and correct the diameter of the tangential inlet orifice, d_e' given by:

$$d_e' = \frac{d_e}{\varphi} \tag{10}$$

13. Recalculate the item 5.

14. Determine the diameter of the swirl chamber D_{cv} given by:

$$D_{cv} = 2R + d_e' \tag{11}$$

15. Determine the length of the swirl chamber L_{cv} given by at least:

$$L_{cv} = 2mm > d_e' \tag{12}$$

The L_{cv} should be slightly larger than the diameter of the tangential inlet orifice. Just to make a liquid from a quarter to a third of rotations, once a chamber determines the atomization conditions.

16. The lengths of the tangential inlet orifice l_e must have the proper length so that the jets enter the centrifuge chamber and not to be deflected from the tangential direction. It is recommended $l_e = (1.5\text{-}3)\ d_e'$.

17. The length of the discharge orifice l_s should not be too long so as not to decrease the angle α. For $K_{eq} < 4.5$, it is recommended $l_s = (0.5\text{-}1)\ d_s$ and $K_{eq} > 4.5$, $l_s = (0.25\text{-}0.5)\ d_s$.

18. Specify a transient cone angle β between 60 and 120 degrees based on the operating conditions of the injector. Note that smaller angles β cause an increase in discharge coefficient μ and decreasing the angle α.

For the case of external injector, the calculation is analogous, but it should be checked the thickness of the liquid film in the external chamber to avoid contact with the external wall of the inner chamber.

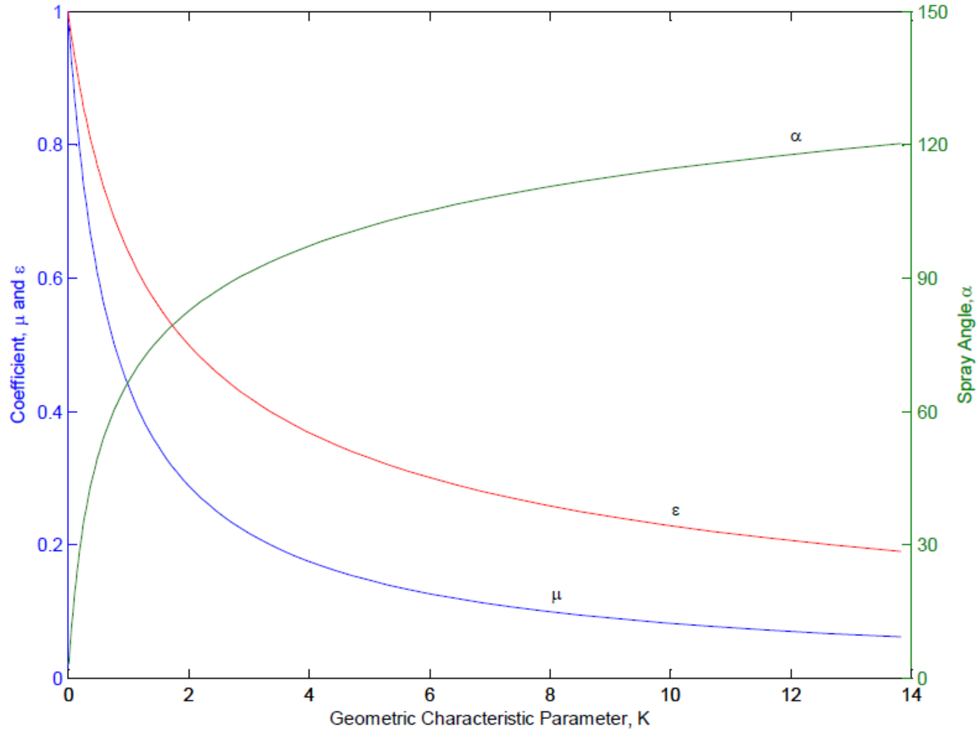

Figure 3. Behavior of geometrical parameters, discharge coefficient (μ), efficiency of filling of the injector (ε) and spray angle (α) on geometric characteristic parameter (K).

3 Results and Discussions

Table 2 shows the dimensions obtained for the design of a swirl injector for atomization of the propellants. An algorithm developed in Matlab language was used to obtain these results.

Table 2. Results.

Injector	Internal	External
Propellants	Ethanol	Hydrogen Peroxide
Mass flow rate - $\dot{m}$ (g/s)	10	40.2
Discharge orifice diameter - d_s (mm)	1.6	5.2
Discharge orifice length – l_s (mm)	9.4	1.4
Number of tangential inlet orifices - n	2	4
Diameter of the tangential inlet orifice - d_e (mm)	1.4	2.1
Length of the tangential inlet orifice – l_e (mm)	2.8	4.3
Radius of the center to the tangential inlet orifice – R (mm)	3.3	4.9
Diameter of the swirl chamber – D_{cv} (mm)	8	12
Length of the swirl chamber – L_{cv} (mm)	4.2	4.6
Transient cone angle (β)	90	90
Spray angle (α)	81.9	62.3
Pressure drop - ΔP (MPa)	0.253	0.253
Reynolds number (Re)	5654	10375
Injection velocity (m/s)	6.8	8.6

4 Conclusions

This paper presented the development of a procedure for designing pressure swirl injectors for mixing ethanol and hydrogen peroxide. The results were obtained through a program written in Matlab language.

Future work for this project will study the characteristic sizes of the droplets generated by internal and external injectors using variations in mass flow rate and operating pressures used for propellants.

5 References

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