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Low Pressure Injection System for Small Liquid Propellant Rocket Engines

H.S. Couto[1], A P. Pimenta[2] and D. Bastos-Netto[1]
[1]INPE, Combustion and Propulsion Laboratory,
Rod. Presidente Dutra km 40, Cachoeira Paulista, 12630-000, São Paulo, Brazil
[2]ITA, Dept. of Aeronautical Engineering
Centro Técnico de Aeronáutica, São José dos Campos, São Paulo, Brazil
[1]Email: demetrio@cptec.inpe.br

ABSTRACT

This work discusses a low pressure injection system to be employed in small rocket engines fueled by environmentally correct liquid propellants to be used in reentry systems and reusable vehicles. It consists of a conventional pressure swirl duplex atomizer feeding a gasifier generating an oxidizer rich gaseous mixture which is used as pressurizing gas of an array of Y-Jet atomizers (well known devices which generate small droplets while under fairly low operating pressures) which make up the main injection plate. It discusses the equipment performance for a LOX-Kerosene mixture.

Keywords: Atomizers, Y-Jet atomizers, Droplets and Sprays

1.0 INTRODUCTION

Small rocket engines with thrust between 200 and 1000N find their use as satellite apogee motors and space vehicle maneuvering engines as well as breaking engines for reentry vehicles. These engines usually are fed with hypergolic fuels, the most common pair in use nowadays being MMH and NTO. This procedure allows for small combustion chamber sizes as well as for operation reliability for there is no doubt on the effectiveness of these propellants. However, these chemicals are well known poisons which generate quite harmful combustion products. Although there is no harm in using these engines in orbital heights and keeping them there, this is not the case with returnable systems be them reusable or not. Therefore, it is of interest today the use of environmentally correct propellants such as, for instance, those partially cryogenic pairs consisting of LOX and a kerosene or another hydrocarbon. However the use of these propellants injected in the combustion chamber in liquid phase, lead to longer chamber residence times as droplets have to evaporate and burn prior to reaching the nozzle.

Therefore, it is obvious that these engines require atomizers able to generate droplets as small as possible to perform as desired. Typical atomizers employed in conventional bi-propellant rocket combustion chamber engines (in this area) are usually of impinging jets or pressure swirl kinds. However, the use of impinging jet atomizers to generate droplets within 10 - 20μm range will require fairly high injection pressures, leading to undesirably heavier fuel and oxidant tanks. Same goes for pressure swirl atomizers, whose well known low discharge coefficient will penalize the propellants pressurizing system. An injection unit capable to generate droplets in the above size range while still operating in a reasonable injection pressure range is the Y-Jet atomizer. To our knowledge these apparatus have never been used in rocket engines, possibly because they require the use of gas (such as air or steam) to achieve the atomizing process. Therefore, if one could build a light gas generator unit to effectively provide the atomization gas for the Y-Jet atomizer, this problem should be solved. This work presents a scheme to use associations of Y-Jet atomizers in environmentally correct bi-propellant small rocket engines. The idea consists in using a conventional pressure swirl duplex atomizer feeding a gasifier generating an oxidizer rich gaseous mixture which is used as pressurizing gas of an array of Y-Jet atomizers (well known devices which generate small droplets while under fairly low operating pressures) which makes up the main injection plate. It discusses the equipment performance for a LOX-Kerosene mixture.

2.0 SYSTEM DESCRIPTION

Consider the sketch shown in Figure1: Small fractions of both oxidizer (o) and fuel, (f), (such as LOX and kerosene, respectively), are injected into the gasifier (A) through a pressure swirl duplex atomizer (parallel injection, co-rotation, fuel inside), (B). This mixture is ignited by a spark plug (C). The combustion gases are then either:

(a) mixed with a parallel stream of LOX, vaporizing it, and this mixture used as pressurizing gases in the array of Y-Jet fuel atomizers (D) in the main injection plate (E) providing the bulk of the injection of fuel and oxidizer into the main combustion chamber (F) or,
(b) acting as pressurizing gases for an array of Y-Jet Liquid fuel atomizers and Y-Jet LOX atomizers both.

It can be seen that in both suggested options, i.e., in the only Y-Jet fuel atomizing array or in the Y-Jet LOX atomizers and Y-Jet fuel atomizers combination, the sprays generated in any of these Y-Jet atomizers will present droplets with SMD within a 10-20μm range under injection pressures below 10 bar.

Notice that, for case (a), the gases obtained from the LOX – Kerosene mixture burning just outside the pressure swirl atomizer must yield sufficient energy to gasify the remaining parallel stream of LOX being injected around the atomizer. This is not so for case (b), although, for both arrangements, they must be able to ensure the proper pressurization on the Y-jet arrays.

This choice of atomizer for the gasifier input was due to the fact that pressure swirl duplex atomizers provide an immediate contact and mixture of oxidizer and fuel, despite of the low discharge coefficient (C_D), they usually display. To overcome this disadvantage it was built a special atomizer with two coaxial threads which brought the device within the range of $0.4 \leq C_D \leq 0.7$, thus requiring smaller injection pressure for proper operation.

As already suggested above, the injection plate consists of either:
a – one array of Y-Jet atomizers fed by liquid fuel and by the gaseous oxidant (which is a "vitiated oxygen", i.e., a mixture consisting mostly of oxygen and the combustion products obtained in the gasifier) and one array of holes through which the excess "vitiated oxygen" is led into the main combustion chamber for burning (in the desired O/F ratio) with the fuel droplets being generated in the Y-Jet atomizers (Figure 1, case a), or,
b – inter dispersed liquid fuel and LOX Y-Jet arrays, both pressurized by the "vitiated oxygen" generated in the gasifier, as shown in Figure 1 (case b).

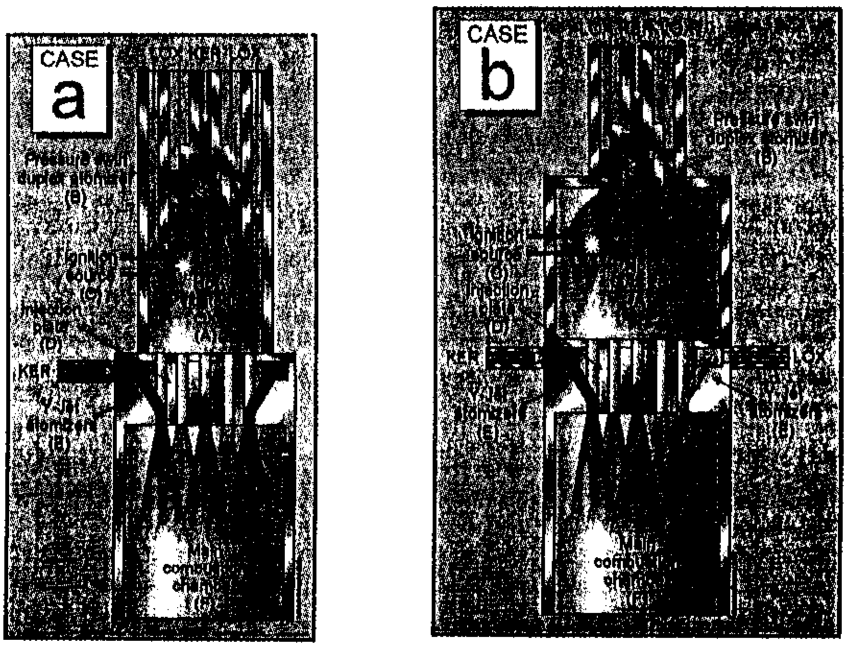

Figure 1. Schematics for proposed injection systems

3.0 GOVERNING MECHANISMS

If option (a) above is used, one should make sure that the gases (i.e., "the vitiated oxygen") will be hot enough to be the ignition source for the fuel/oxidant mixture streaming from the Y-Jet atomizers into the main combustion chamber. Therefore one of the input data to be used in the calculation of the gasifier pressure swirl atomizer is the fuel mass flow rate which will have to burn releasing enough energy per unit volume to keep the temperature level above the minimum required for the combustible mixture ignition in the main chamber. This can be done using a computer code such as NASA SP 273.

Hence, given the amount of LOX to be vaporized it will be enough to calculate the amount of kerosene to be burned with some of this LOX, in a process which might be stoichiometric or not, but whose energy being liberated is capable not only to vaporize the (whole) available LOX, but to bring it to a temperature level above the combustible mixture ignition temperature in the main chamber.

Actually this is a two-stage mechanism: 1st- LOX and liquid kerosene are injected simultaneously in the gasifier through a pressure swirl duplex atomizer, their droplets mixed and ignited; 2nd- The remaining LOX is injected co-axially parallel and externally to the flow of hot gases generated by the droplets combustion, being vaporized and heated as it approaches the main chamber injection plate.

In case (b) only a portion of the LOX is vaporized and burned, i.e., the amount needed as atomizing gases for the kerozene and LOX Y-Jet arrays assembled in the injection plate. Again, as in case (a), the calculation can be performed using commercially available combustion computer codes, and, as before, one has to guarantee that the burnt gases upon leaving these arrays can still be the ignition source for the combustible mixture in the main chamber.

The SMD (Sauter Mean Diameter) of droplets generated in a pressure swirl type of atomizer can be estimated using the correlation given by Couto et al [1]. These authors extended the results obtained by Dombrowski and Johns [2] to describe the mechanism through which a thinning plane viscous liquid sheet formed by a fan-spray atomizer disintegrated into fragments that contracted themselves by surface tension forming unstable ligaments that finally broke into droplets, finding that, for pressure swirl atomizers, the near conical rotating liquid sheet at its breakdown mode yields the following expression for d_L[cm], the diameter of the ligaments,

$$d_L = 0.9615\cos\theta\left(\frac{h_0^4\sigma^2}{U_0^4\rho_a\rho_L}\right)^{1/6}\left[1+2.6\mu_L\cos\theta\left(\frac{h_0^2\rho_a^4U_0^7}{72\rho_L^2\sigma^5}\right)^{1/3}\right]^{0.2} \tag{1}$$

where σ [dyn/cm] is the liquid surface tension, μ_L[cp] is the liquid dynamic viscosity, ρ_a [g/cm^3] is the density of the surrounding medium (assumed gaseous and quiescent) at pressure p_a[MPa], ρ_L[g/cm^3] is the density of the liquid, U_0 [cm/s] is the velocity of the liquid at the atomizer tip, h_0 [cm] is the film thickness within the atomizer final orifice and θ is the rotating conical sheet semi-angle [1].

Then, assuming that the collapse of a ligament produces a droplet of diameter d_d [cm], according to Rayleigh's mechanism [3], one can write

$$d_d = 1.89\, d_L \tag{2}$$

As for droplets generated in a Y-Jet type of atomizer Couto et al [4-5] found for the diameter of the ligaments at the sheet breakdown mode,

$$d_l = 0{,}9615\left(\frac{h_0^4\sigma^2\cos^6\theta}{\rho_a\rho_l U_f^2U_i^2}\right)^{\frac{1}{6}}\left[1+2{,}6\mu_l\sqrt[3]{\frac{h_0^2\cos^3\theta\,\rho_a^4U_i^8}{72U_f\rho_l^2\sigma^5}}\right]^{0.2} \tag{3}$$

where U_i [cm/s] is a velocity term which, in a general case, can be seen to be composed of three components: two of them relative to the gas flowing on both sides of the liquid sheet, the third one being the velocity of the sheet itself [6]. Therefore, one may choose a mean value for the velocity field as

$$U_i = \left[\frac{1}{3}\left[U_f^2 + \left(U_{1a} - U_f\right)^2 + \left(U_{2a} - U_f\right)^2\right]\right]^{\frac{1}{2}} \tag{4}$$

where U_{1a} and U_{2a} are the ambient velocities on either side of the sheet and U_f is the sheet velocity. As the gas velocity outside the liquid sheet is taken to be zero in this atomizer, one may write:

$$U_i = \left[\frac{1}{3}\left[2U_f^2 + \left(U_{1a} - U_f\right)^2\right]\right]^{\frac{1}{2}} \tag{5}$$

Y-Jet atomizers are designed so that the atomizing gas flow velocity, U_{1a}, reaches nearly the speed of sound so that, even with a small loss, this flow velocity remains high enough, and the larger this velocity is the smaller the droplets will be. In Laboratory tested Y-Jet atomizers, the droplets had their size in the range between 5 and 15 µm for low temperature (330K) atomizing gas, leading to sonic speeds of around 340 m/s. Therefore here, with hot gases, the sonic speeds will be much higher and so will be the flow velocities, leading to smaller droplets as desired.

The design procedure for case a set up can be termed as conventional for the only special condition required is that the gases (i.e., the "vitiated" oxygen) upon leaving the pre-chamber and entering the injection plate (part of it acting as pressurization element in the Y- Jet arrays) be hot enough to ignite the mixture in the main combustion chamber. This can be verified by checking the fuel ignition temperature range or by running a simulation with a software such as Chemkin II [7], assuming the well stirred reactor mode to check the flame stability behavior under the design conditions.

This is not so for case b. Here, according to Mullinger and Chigier [8], the atomization gas mass flow rate has to be at least equal to ten per cent the fuel mass flow rate so that the Y-Jet yield droplets with a minimum SMD.

Once this 10% requirement is fulfilled, the remaining hot gas can be injected in the main chamber through strategically positioned holes in the injection plate to act as ignition sources for the sprays generated by the Y-Jet arrays in the main chamber. As before, care should be taken to guarantee the full mixture ignition. In the design phase this can be done by running a Chemkin II [7] simulation in the well stirred reactor mode.

Choosing the Kerosene, $C_{13}H_{26}$ - Liquid Oxygen, LOX pair, with properties shown in Table 1, it can be seen that, within the working range of satellite bi-propellant thrusters the adiabatic flame temperature is quite insensitive to the chamber pressure (Figure2).

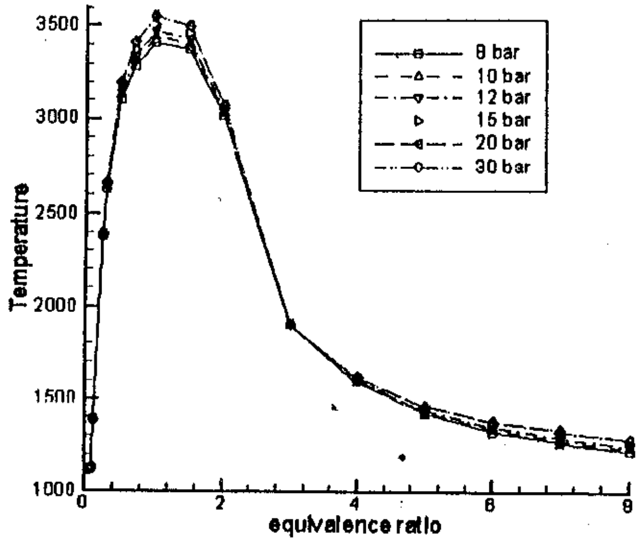

Figure 2. Adiabatic Temperature vs Equivalence ratio for Kerosene – LOX pair

Table 1. Kerosene – LOX properties

Substance	mol.wt. (g/mol)	Density (g/cm^3)	Viscosity (cp)	Surface tension (dyn/cm)	Heat of Formation (kcal/mol)
LOX @ -183°C	32	1.144	0.190	13.20	- 3.08
KER @20°C	182	0.824	1.85	26.00	-5.70

4.0 CONCLUDING REMARKS

Once the ignition temperature has been determined one can set the lower boundary for the design procedure. This leads to the maximum and minimum values for the equivalence ratio for which the minimum ignition temperature is attained. This operating temperature leads immediately to the speed of sound used in designing the Y-Jet Atomizers in the injection plates. A slightly smaller value will be the fluid atomizer velocity to be used in the calculation of the size of the fuel droplets leaving the Y-Jet atomizers arrays. Finally the use of the procedure presented by Couto et al [4], allows the dimensioning of the Y-Jet atomisers, i.e, for those in the array of Y- Jet atomizers with hot vitiated oxidizer and kerosene (case a) as well as for those in the arrays of Y-Jet atomizers with hot gases and Kerosene or LOX (case b).

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