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Experimental Characterization of a Liquid Oxygen Isrosene Based Single Element Injector for a Liquid Rocket Engine

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ABSTRACT:

Mixture formation is one of the most important process in liquid rocket engine combustion devices because it determines combustion efficiency, stability and heat transfer characteristics, this process is implemented through the use of a suitable propellant injectors. In order to study the performance of injector on hydrocarbon fueled cost effective engines for future space transportation with respect to engine operating conditions a swirl coaxial bi-swirl injectors has designed for Lox/Isrosene(kerosene) propellant combinations, based on the principle of maximum flow postulated by G.N. Abramovich. Methodology has been verified by single element cold flow characterization test using air and water as analogy media. A high resolution sector patternator has been developed for the cold flow characterization test for analyzing the equivalent spray pattern. It has been shown that increasing the liquid injection pressure increases the equivalent spray angle and improves the patternation. Mass flow rate, droplet size (SMD),liquid film thickness for fuel and oxidizer injectors are also arrived at for different pressure drop, Reynolds number and Weber number. The results of the Lox/Isrosene (kerosene) cold flow experiment show the design is successful.

Key words: Coaxial injector, Sauter mean diameter (SMD),spray cone angle, mass flow rate, liquid film thickness

I. INTRODUCTION

The performance and stability of a liquid engine is strongly influenced by the type of propellant used, injector design, combustion chamber design and its operating conditions. The important element that often controls the success or failure of the liquid rocket engine is the injector. Even though there are various type of injectors are used depending on the propulsion cycle and mission requirements, the commonly used injectors in the ISRO's launch vehicles programmes are shear co-axial injectors, swirl co-axial injectors, and impinging type injectors. In order to understand the performance of the injector and the developmental challenges with respect to engine operating conditions, a single element swirl co-axial type of injector element with liquid oxygen and Isrosene as propellant is designed and characterized. The same engine can be used as a source of hot gas for material characterization and various heat transfer studies and combustion stabilities related to the qualification/performance improvement of semi cryogenic engine under development. The present report gives objective, preliminary design details of single element swirl co-axial injector element and results of the cold flow characterization using water.

II. OBJECTIVE

Design and cold flow characterization of single element swirl co-axial injector element realized for a desired operating condition.

III. DETAILS ON THE SWIRL CO-AXIAL INJECTOR

Basic geometry of swirl coaxial injector elements is described in figure1 and the various parameters involved in swirl injector design are given in Table1. It consists of a hollow casing (1), an axis symmetric vortex chamber (2), a nozzle (3), and tangential passages (4) connected upstream with the propellant feed system.

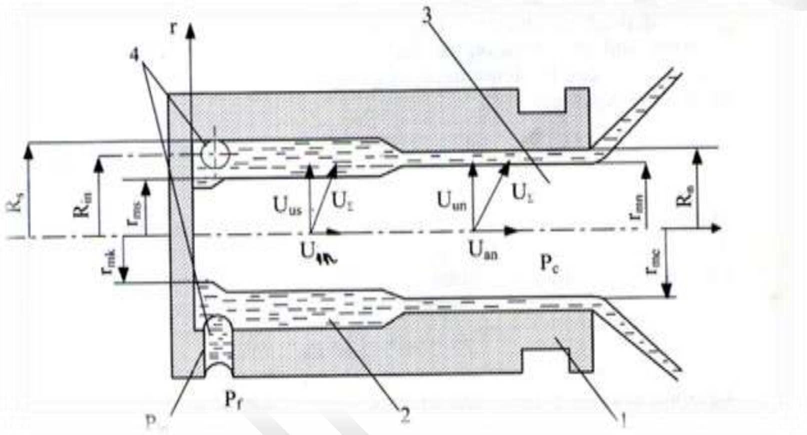

Figure 1: Schematic diagram of swirl injector and liquid flow in the injector; 1-injector casing; 2-vortex chamber; 3-nozzle passage;4-tangential passages

A. Significant geometric parameters

Important geometric parameters determining swirl-injector characteristics are:

- ✓ nozzle radius **Rn**;
- ✓ cross-sectional area of the inlet flow passage **Ain**;
- ✓ swirling arm, i.e, the distance from the axis of the tangential passage to the injector axis, **Rin**

Table 1 : Parameters involved in swirl injector design

Parameter	**Definition**
m^0	Mass Flow Rate
P_t	Pressure In The Propellant Feed System
P_c	Combustion Chamber Pressure
P_{in}	Inlet Pressure In The Tangential Channel
A	Spray Cone Angle
u	Mass Flow Co-efficient
ϕ	Fractional Area Occupied By Liquid In The Nozzle
H	Liquid Film Thickness
$\sum U$	Total Velocity
U_{un}	Swirl Velocity In Nozzle
U_{an}	Axial Velocity In Nozzle
U_{rn}	Radial Velocity In Nozzle
U_{uk}	Swirl Velocity At Head End Of Vortex Chamber
U_{rk}	Radial Velocity At Head End Of Vortex Chamber
U_{in}	Velocity At Entrance In Vortex Chamber
R_{mk}	Radius Of Film At Head End Of Vortex Chamber
R_{mn}	Radius Of Film In Nozzle
A_n	Area Of Nozzle
R_{in}	Radial Location Of Center Of Tangential Channel
A	Geometric Characteristic Parameter

The geometric parameters can be grouped to form a dimensionless number known as the geometric characteristic parameter[3] defined by

$$A = \frac{A_n R_{in}}{A_{in} R_n}$$

It determines the injector flow co-efficient **u,** the nozzle filling co-efficient ϕ , the spray cone angle at the cylindrical nozzle exit, and other output parameters. In addition there are some secondary parameters, which are of importance in determining the liquid flow residence time and viscous losses in the injectors.

These include:

- The diameter and length of the vortex chamber.

- The nozzle length and the convergent angle of the vortex-chamber wall adjacent to the nozzle.

B. Fluid flow behaviour inside co-axial swirl injector:

The flow process in a real swirl injector can be described by taking into account viscous effects with navier stokes equations[3].when the fluid is fed into the tangential passage (4) (as shown in figure 2),the liquid is set in rotary motion in the vortex chamber (2) and form a liquid vortex with free internal surface whose radius smoothly changes depending on the magnitude of the tangential and axial velocity components along the length of the injector. In practice , the real conditions can be approximately taken into account by introducing the hydraulic loss coefficient **,** ε_i **,** which characterizes the total pressure loss in the ,the angular-momentum loss coefficient **K**:

Any change in the $\mathbf{U_i}$is invariably associated with a change in the liquid surface radius $\mathbf{r_m}$.

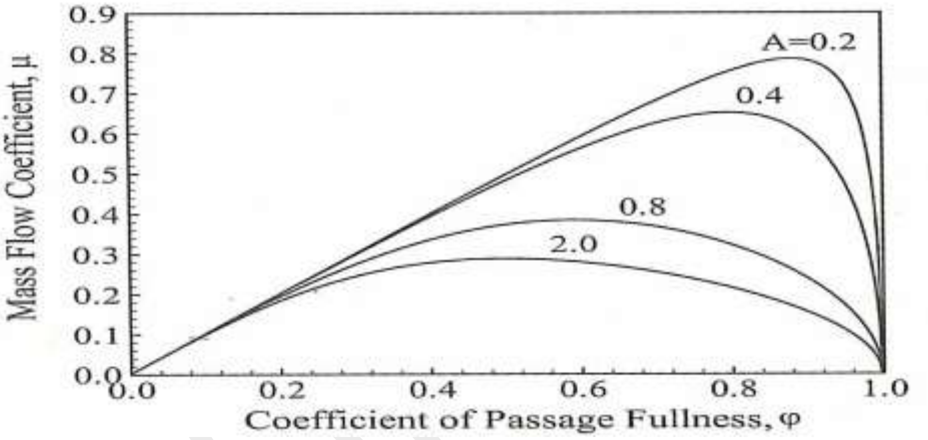

Figure 2: Flow Characteristics of the Swirl Injector with Various Geometries

Some of the known features of swirl injectors, have led to their predominant application in liquid rocket engines,

1. For the same pressure drop and liquid flow rate, the average median diameter of the droplets is 2.2 to 2.5 times smaller than that of jet injectors. This advantage prevails for very high flow rates and decreases when the counter pressure grows i.e the sum of the combustion chamber pressure and the centrifugal pressure created by swirl motion.
2. The flow passage areas of swirl injectors are not so sensitive to manufacturing errors such as deviation from prescribed diameter and surface misalignment.
3. The flow passage areas of swirl injectors are much larger than those of jet injectors with same flow rates, and consequently they are less susceptible to choking or cavitations.

Pressure drop across a swirl injector is shared between the tangential channels and the vortex chamber. During the engine start-up, when the vortex chamber is initially empty, the entire pressure drop is applied to the tangential channels and the velocity is much higher than its steady-state value. The vortex chamber begins to be filled with rotating liquid with simultaneous increase in the centrifugal pressure and the viscous losses decrease the pressure drop across the inlets passage and subsequently the mass flow rate prior to ignition. This self turning capability with variable flow resistance under transient conditions improves the engine start-up operation.

C. Operating parameters for a bi-swirl injector

The major specification needed for designing a single element injector is given below.

Table 2 : Operating Parameters

Single element injector Parameter	**Values**
Thrust , N	365
Chamber pressure ,bar	25
Total propellant flow rate ,kg/s	0.151
Total oxidiser flow rate , g/s	110
Total fuel flow rate , g/s	41.5
Mixture ratio	2.65
LOX inlet temperature ,K	100.0
Fuel temperature at the inlet , K	298
Injection pressure, bar	8

IV. DESIGN DETAILS OF THE SWIRL COAXIAL INJECTOR ELEMENT

The whole theory of an ideal swirl injector is based on three principles [3], namely, Bernoulli's equation, conservation of mass energy and angular momentum. The fundamental equations which relate the various parameters of the swirl injector, as given in Table1, can be inter-related based on the invoiced theory which are given below,

$$P_f = P_C + \frac{\rho U_{un}^2}{2} + \frac{\rho U_{an}^2}{2} + \varepsilon_i \frac{\rho U_{in}^2}{2} \underline{\qquad\qquad\qquad} (1)$$

$$U_{uk} r_{mk} = U_{in} R_{in} = U_{rn} r_{mn} \underline{\qquad\qquad\qquad} (2)$$

$$m^o = \phi \pi R_n^2 \rho U_{an} \underline{\qquad\qquad\qquad} (3)$$

$$m^o = u \pi R_n^2 \sqrt{2 \rho \Delta p_i} \underline{\qquad\qquad\qquad} (4)$$

$$u = \frac{\rho U_{an} A_n \phi}{\rho A_n \sum U} = \frac{U_{an} \phi}{\sum U} \underline{\qquad\qquad\qquad} (5)$$

$$\alpha = \tan^{-1}(U_{un} / U_{an}) = \tan^{-1} \sqrt{2(1-\phi)/\phi} \underline{\qquad\qquad} (6)$$

Table 3: Design details of the Lox post

Parameter (Lox post)	**Value**
Discharge Coefficient	0.8
Geometric characteristic parameter	0.212
Nozzle outlet diameter, mm	2
Tangential entry diameter, mm	1
Number of holes	4
Mass flow rate, g/s	110
Length of tangential entry mm	3
Liquid injection pressure drop, bar	8
Liquid film thickness, mm	0.34
Ratio of cross sectional areas (liquid film to injection tube)	0.9
Length of nozzle, mm	2
Length of the vortex chamber, mm	6.633
Diameter of the vortex chamber, mm	3.14
Swirl arm, mm	1.2

Table 4: Design details of the Isrosene(kerosene) post

Parameter (Isrosene post)	**Value**
Discharge Coefficient	0.1
Geometric characteristic parameter	6.2
Nozzle outlet diameter, mm	3.81
Tangential entry diameter, mm	0.42
Number of holes	4
Mass flow rate, g/s	41.5
Length of tangential entry, mm	2.52
Liquid injection pressure drop ,bar	8
Liquid film thickness, mm	0.049
Ratio of cross sectional areas (liquid film to injection tube)	0.26
Length of nozzle, mm	3.81
Swirl arm ,mm	2.3

V. RESULTS OF THE COLD FLOW CHARACTERISATION TEST

Detailed cold flow calibration experiments are conducted with de-ionized water to ascertain the intrinsic spray properties of the injector such as liquid film thickness, coefficient of passage fullness, discharge co-efficient and spray cone angle. Figure 3 and Figure 4 gives the mass flow rate variation in the LOx and kerosene post respect

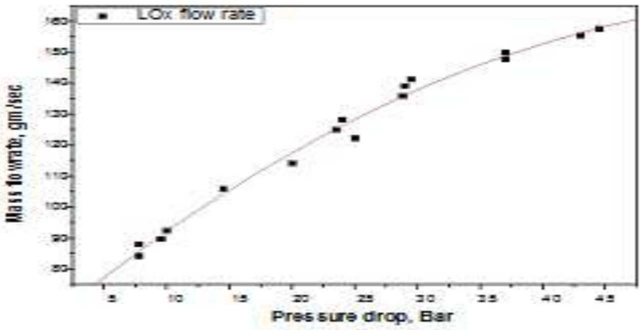

Figure3: Mass flow rate variation with pressure drop using LOx post geometry

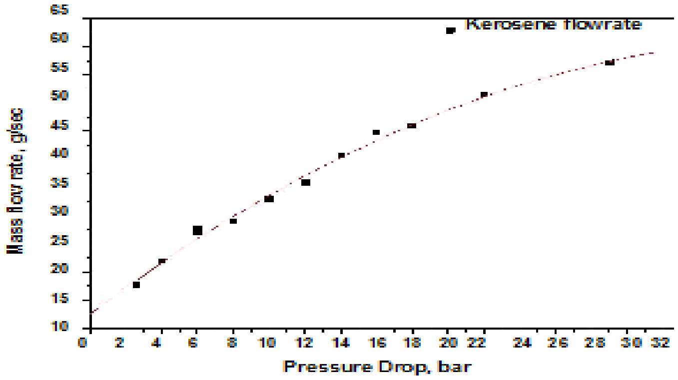

Figure4: Mass flow rate variation with pressure drop using Isrosene post geometry

VI. ESTIMATION OF SPRAY CHARACTERISTICS OF THE SWIRL CO-AXIAL INJECTOR

Preliminary estimate of the liquid film thickness in respective fuel and oxidizer post from the cold flow trials are carried-out using the co-relation given by Lefebvre et al. A detailed experimental study on the factors governing mean drop size using a range of atomizers and operating liquids, with differing viscosities and surface tensions for a normal case of nozzle spraying liquid into a slow moving or stagnant air are also carried out by Lefebvre et al. Co-relation for determining the SMD of the spray relating two non-dimensional numbers namely Reynolds number and Weber numbers are defined by these investigators on the basis of liquid film thickness and spray cone angle of the emanating spray for different pressure drops across the nozzle.

Reynolds number is given as: $R_e = \dfrac{\rho_L v_L t \cos\alpha}{\alpha_L}$

Figure 5 shows the liquid film thickness and the sauter mean diameter of the liquid oxygen spray emanating from oxidizer post. The calculations are based on the measured volumetric flow rate and average spray cone angle of 50 degrees since there is no much change in spray cone angle with increasing pressure drop around the design pressure drop.

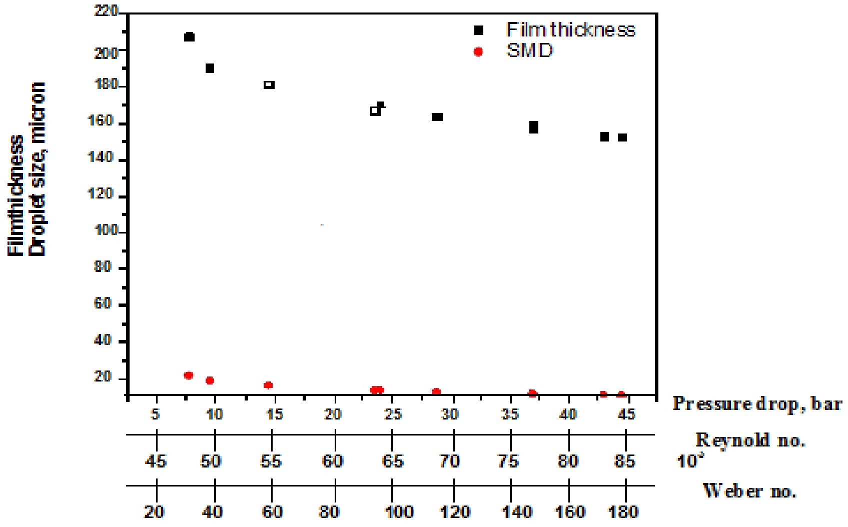

Figure 5: Variation of the liquid film thickness and SMD for oxidizer side.

Figure6 shows the liquid film thickness and the sauter mean diameter of the Isrosene spray emanating from fuel post of the injector. The calculations are based on the measured volumetric flow rate and average spray cone angle of 45 degrees since there is no much change in spray cone angle with increasing pressure drop around the design pressure drop

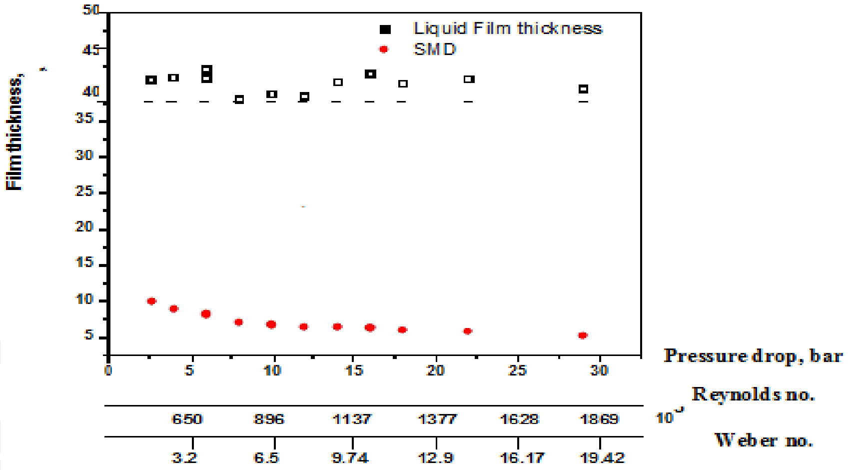

Figure 6 : Variation of the liquid film thickness and SMD fuel side.

VII CONCLUSION:

Design, realization and detailed flow characterization of a swirl co-axial single element injector is completed and the pressure drop across the injector via-a-vis mass flow rate as well as the droplet size (SMD) for the fuel and oxidizer side of the injectors are also arrived at for different pressure drop, Reynolds number and Weber numbers. In order to evaluate the combustion efficiency of the system, hot test are planned to be carried out at different mixture ratios.

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