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TRANSIENT THERMAL ANALYSIS & HOT TEST OF AN ABLATIVE COOLED THRUST CHAMBER OF SEMI CRYOGENIC ENGINE

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ABSTRACT

Semi cryogenic Engine is designed for high thrust level condition which works in Oxidizer Rich Staged Combustion Cycle (ORSCC) with a propellant combination of Liquid Oxygen (LOX) and Kerosene. The thrust chamber – the propulsion unit – of the engine is provided with multiple number of coaxial swirl injector elements arranged in concentric circles on the injector face plate. To characterize the injector element, a single coaxial element is chosen and an ablative cooled combustion chamber is designed for it by keeping the fundamental chamber parameters. Transient thermal analysis of Silica phenolic lined chamber for the selected Chamber pressure and mixture ratio condition is carried out prior to hot test. Hot test is successfully completed and the results are compared with the predictions along with identifying future course of experiments.

NOMENCLATURE

Dt	:	Throat diameter
μ	:	Dynamic viscosity
Cp	:	Specific heat at const. pressure
Pr	:	Prandtl number
Pc	:	Chamber pressure
g	:	Acceleration due to gravity
C*	:	Characteristic velocity
rc	:	Radius of curvature at throat
A*	:	Throat area
A	:	Area of the section

Twg	:	Gas side wall temperature
T0g	:	Nozzle stagnation temp
γ	:	Specific heat ratio
Ma	:	Mach number
m˚	:	Flow rate
L*	:	Characteristic Length

1. INTRODUCTION

Design and development of advanced propulsion systems like high thrust semi cryogenic engine, is a highly challenging task due to its complex systems and high level of heat flux. Liquid rocket engine comprises of thrust chamber, turbo pump, pre burner, igniters, control systems and components. The thrust chamber is the most key element of the propulsion system wherein the combustion of propellants takes place, which generates huge thermal energy with a hot gas temperature of 3800 K. The amount of heat release due to combustion is governed mainly by the injector element design and also by the combustion chamber design. The full scale engine thrust chamber will be provided with multiple coaxial injector elements arranged in an injector face plate and the combustion will be completed within the combustion chamber.

For the development of a high thrust full scale engine, all the above mentioned critical areas will be demonstrated in the scale down model hot tests. Design and development of a single injector element thrust chamber is intended to demonstrate the C* efficiency in the elemental level and the heat transfer to the chamber walls. This will substantially reduce the cost, time, effort and complexity of development.

During the design phase, flow and thermal design codes are generated for the prediction of hot gas mixing and the heat transfer using the analytical tools. Experiments are conducted with the scale down models and the critical parameters are analyzed for verifying the strength of the design codes and modify the tools based on the test results.

2. COMBUSTION PERFORMANCE

The combustion performance primarily depends on the injector design and the configuration of the chamber profile (fig1). For LOX/Kerosene combination, co-axial injector elements are preferred to achieve oxidizer gas shearing action with the Kerosene jet for the better atomization and mixing. Different configurations of coaxial injector elements are attempted by different designers depending on the experience and confidence. Injector with Swirling of liquid (Kerosene) at the outer side of the coaxial element and inner Oxidiser gas is chosen to perform combustion closer to the injector face plate which will enhance the Kerosene recirculation towards the face plate.

The chamber design also contributes for the combustion efficiency by providing proper length /volume for the completeness of the combustion, before it is expanded in the nozzle. The combustion efficiency of a thrust chamber is normally measured in terms of the characteristic velocity (C*).

$$C^* = \frac{p_c A^*}{\dot{m}}$$

Related to the maximum value of C*, that could be obtained at the nominal mixture ratio (O/F) and operating chamber pressure.

For an ideal, isentropic expansion process this is directly related to the stagnation speed of sound in the nozzle (αo).

$$C^* = \alpha_0 \frac{1}{\gamma}\left(\frac{\gamma+1}{2}\right)^{\frac{\left(\gamma+\frac{1}{2}\right)(\gamma-1)}{2}}$$

Any variations in the combustion mixture ratio will cause a reduction in the overall C*.

For calculation purpose, it may be assumed that each point in a given cross section of chamber has an individual C*, dependant only on the local mixture ratio, so that the overall C* achieved (η C*) is given by the integral mass flow across the cross section.

$$\frac{1}{\eta C^*} = \frac{1}{A}\int_A \frac{dA}{f\,(O/F)}$$

A	: `	Cross area (sqm)
O	:	Oxidiser flow F: fuel flow (kg/s)

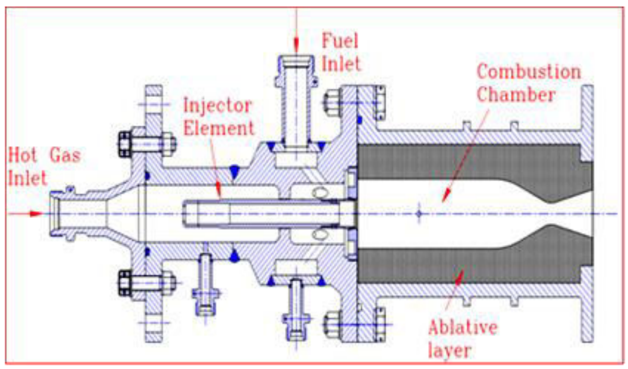

Fig 1 **Single Element Thrust Chamber**

Due to variations in local mixture ratio, the heat transfer is non-uniform around the circumference of the combustion chamber at any station downstream of injector. However the mere fact that the combustion will be incomplete due to the suboptimal injector and chamber design, which will reduce C*η. As a consequence, one must expect that there will be variations in the heat transfer rate around the periphery of hot gas jet. But the circumferential variation in heat transfer will tend to diminish as combustion progresses towards the throat. Single element chamber with coaxial injector head is shown in fig 1 and 2.

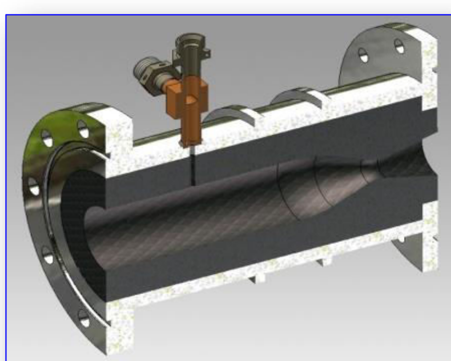

Fig 2 **Ablative cooled Thrust chamber**

3. CONVECTIVE HEAT FLUX

The principal process by which heat is transferred to the walls of a thrust chamber from the hot combustion gas is forced convection boundary layer.

Theoretical prediction of adiabatic flame temperature, the equilibrium composition of combustion products and the thermo physical & transport properties are the pre–requisite for the thermal design of the single element combustion chamber. The parameters are predicted by using software NASA SP–273 (COSMIC).

For the calculation of gas side heat transfer coefficient (hg), the modified Bartz equation has been used in the analysis.

$$h_g = \left[\frac{0.026}{D_t^{0.2}} * \left(\frac{\mu^{0.2} C_p}{Pr^{0.6}}\right) * \left(\frac{P_c g}{C^*}\right)^{0.8} * \left(\frac{D_t}{r_c}\right)^{0.1}\right] * \left(\frac{A_t}{A}\right)^{0.9} * \sigma$$

Where σ is

$$= \frac{1}{\left[\frac{T_{wg}}{2T_{0g}} * \left\{1 + \left(\frac{\gamma - 1}{2}\right) Ma^2\right\} + \frac{1}{2}\right]^{0.68} \left[1 + \left(\frac{\gamma - 1}{2}\right) Ma^2\right]^{0.12}}$$

4.RADIATION

Convective heat transfer from dissociated combustion gases has been thoroughly addressed from theoretical and experimental works, but few systematic attempts have been made to enlarge and enhance the understanding of thermal radiation occurring in high energy rocket thrust chambers; i.e. temperature up to 3800 K at a pressure from 10 to 200 bar. The radiative heat flux is computed from the equilibrium concentrations of the polar gas constitute and their respective emissivities.

The gas emissivity is defined as the ratio of the energy emitted by the gas to that of a black body. The radiative heat flux can be evaluated from the Stefan - Boltzmann equation

$$q_r = \sigma E_g {T_g}^4$$

Where

σ	:	Stefan - Boltzmann constant
Eg	:	appropriate gas emissivity
Tg	:	Absolute temperature of gas

5. EXPERIMENTAL WORK & ANALYSIS

An injector element which is designed for a high thrust LOX/Kerosene semi cryogenic engine (Thrust : 2000 kN) is adapted as the injector element for the performance evaluation programme. The configuration of injector element comprises of GO2 injector compartment, Kerosene injector compartment and injector face plate. The design of combustion chamber is carried out in line with that of the full scale chamber

Fig 3 **Single element Thrust chamber for hot test**

The design parameters like L*, contraction ratio and semi convergent angle for the configuration design of the chamber are maintained same as that of full scale chamber.

Unlike the full scale chamber, it is a ablatively cooled chamber with Silica Phenolic liner material which is a work horse chamber (fig:3) which can be useful to evaluate the performance of any injector configuration

5.1. Specification

Propellants	:	GO2/KEROSENE
Chamber pressure	:	40 bar
Mixture ratio (O/F)	:	2.3
Fuel flow	:	104 g/s
Oxidiser flow	:	260 g/s

5.2. Modeling and Prediction

The single element injector performance and thermal predictions are carried out prior to hot test so that the hot test duration can be fixed based on the limiting throat wall charring and erosion limits. (Fig:4).

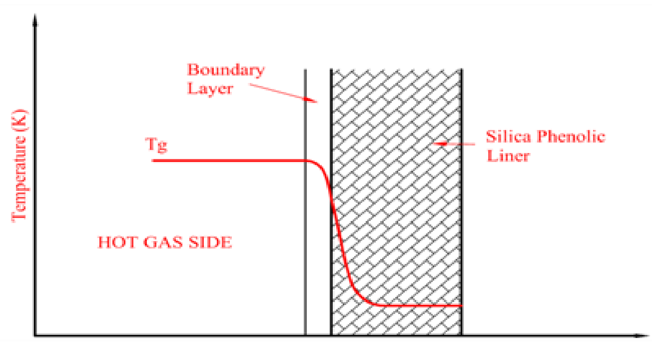

Fig 4 Thermal model for the ablative cooled chamber

5.3. Axi- symmetric transient Conduction model

During the engine firing, the inner surface directly exposed to combustion gases will receive heat by convection and radiation. The inner surface will transmit the heat energy to the next outer layer and so on. The cooling effect is obtained by the sinking of heat 3 dimensionally (radial, circumferential and axial) within the silica phenolic lined chamber.

5.4 Method of analysis

The two dimensional FE model is generated for the injector and chamber in ANSYS version 12 and the element solid 55 is taken for the analysis (fig 5).Which is the appropriate element for thermal analysis.

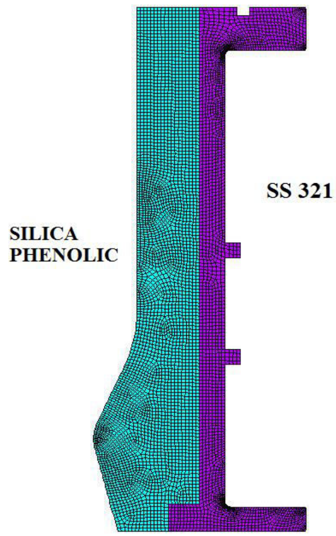

Fig 5 **Model for thermal analysis**

Hence to determine the temperature mapping at each instant; transient conduction analysis must be performed. Even though the heat flow is 3 dimensional, the main features of the thruster body thermal response can be captured with two dimensional (axi- symmetrical) model. The transient heat conduction equation in cylindrical coordinates is written as:

$$\frac{dT}{dt} = \nabla\alpha\nabla T = \frac{l}{r}\frac{\partial}{dr}\left(\alpha\frac{dT}{\partial r}\right) + \frac{\partial}{dZ}\left(\alpha\frac{\partial T}{\partial Z}\right)$$

where T is the temperature, t is the time, α is thermal diffusivity, r is the cylindrical co-ordinate and z is the co-ordinate along the chamber wall.

While solving the above equation numerically, the equation is discretized spatially using central difference scheme and temporarily using implicit scheme. The use of implicit scheme instead of explicit scheme prevents numerical instability. Then, the descretized equation is obtained as

$$\frac{\mathbf{T}^{n+1} - \mathbf{T}^{n}}{\Delta\, \mathbf{t}} = \Delta\, \alpha .\, \Delta\, \mathbf{T}^{n+1}$$

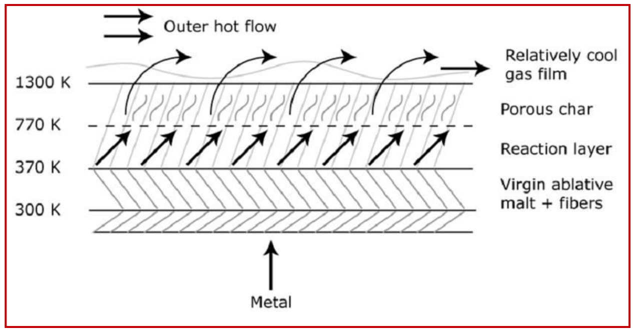

Fig:6 **Ablative cooling process during hot test**

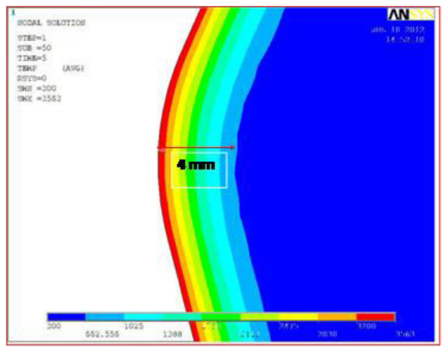

Fig 7 **Temperature distribution at throat region**

The ablative liner is fabricated from a phenolic resin, impregnated high silica fabric which is wrapped in a tape form on a mandrel at the required ply orientation.

Thermal conductivity of Silica phenolic material depend on the ply arrangement, ie conductivity is more along the ply and less, across the ply. Depends on the selected SP material configuration, results of analysis will be varying. As the SP temperature reaches 700 K, an endothermic reaction – pyrolysis - takes place ie, melting and vaporization of the bonding material which releases gas and forms a cool layer at the chamber wall. The char rate analysis is characterised by the formation of a char layer that progresses from the heated surface to the towards the metallic outer wall This process is called charring and the charred layer will remain as chamber wall material (fig 6). The virgin Silica phenolic material is possessing low thermal conductivity where as the charred layer posses higher thermal conductivity by one order (Fig 7 and 8).

5.5 Measurements on the Thrust Chamber

Measurements to capture the injector performance and thermal evaluation are provided on the thrust chamber. Chamber pressure, Injection pressures and flow rates on both oxidizer and fuel side, chamber outer wall temperature etc are the major parameters required for performance evaluation.

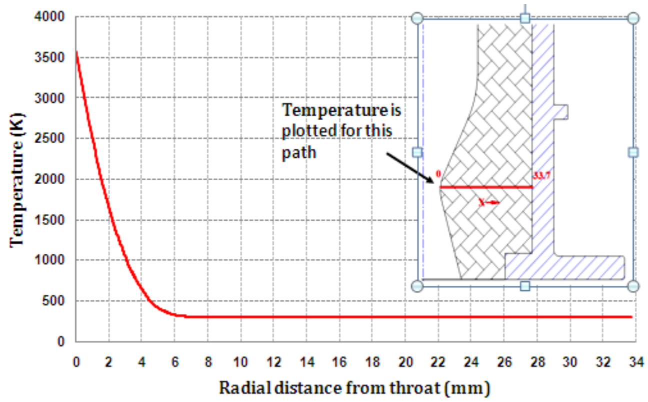

Fig 8 wall Temperature along the thickness of the SP liner

5.6 Hot Tests of Single element Chamber

The hypergolic slug igniter (Tri Ethyl Alumina- TEA) is used for the hot test which itself is a fuel highly reactive with oxidizer to initiate smooth combustion.

The hot test is carried out by evolving proper start and shutdown sequence generated through calibration of feed systems for the smooth ignition and sustained combustion with the required mixture ratio.

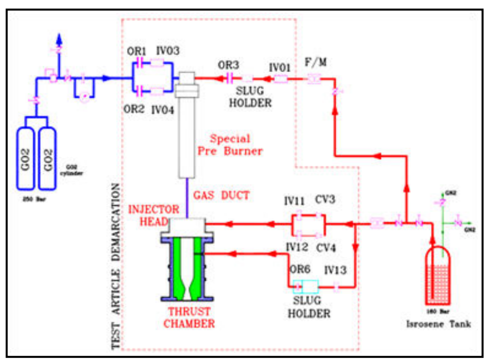

Fig:8 schematic of circuit feed

6. RESULTS

The Single Element Thrust Chamber hot test is carried out successfully and the flow rates of fuel and oxidizer were steady during the test (fig:10 and 11). The chamber pressure obtained was lower than the estimated value due to the derated (lower injector pressure drop) test conditions (22% of rated pressure) of the injector element. Since Kerosene is in the liquid form, sufficient pressure drop is required for the adequate atomization and droplet formation. The throat portion of the combustion chamber is eroded more than the prediction (fig:12). The erosion rate predicted was 0.4 mm where as the observed rate was 1.5 mm at throat section which is expected to be due to higher combustion temperature. This may be due to the higher hot gas temperature experienced by the silica phenolic liner. However the erosion was uniform and hence it can be taken that the combustion efficiency was steady during the hot test. The experiment also reveals that film cooling with liquid kerosene from the injector end is essential for minimising the erosion rate of throat portion of the chamber.

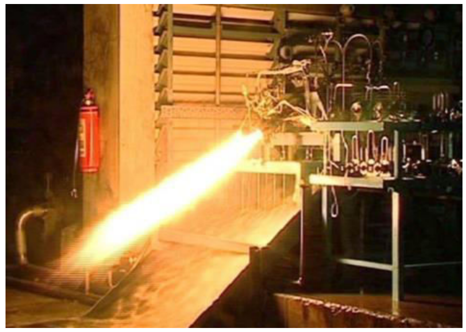

Fig 10 Single element Thrust chamber hot test

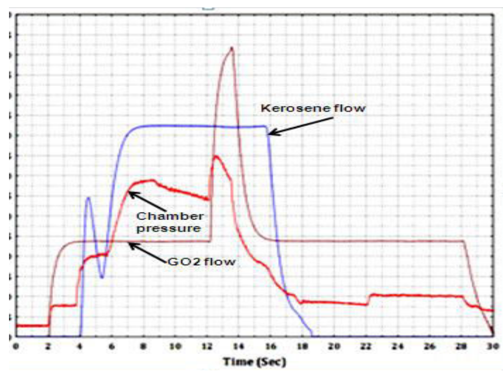

Fig 11 Chamber pressure measured during hot test

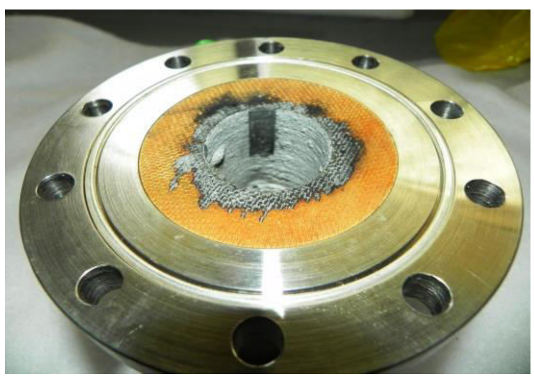

Fig 12 Silica Phenolic liner with charred material

7. CONCLUSION

- Ablative cooled chamber can be used as combustion chamber liner material only with introduction of film cooling which will reduce the gas temperature near the wall and there by the heat flux also.
- Heat flux generated at throat during the test was 450 kW/sq.m
- Outer shell was at ambient temperature only during the test, which confirms the integrity of the hardware
- Hot test results are encouraging and will be continued with better equipped hardwares.

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