Thermal Design And Analysis Of Regeneratively Cooled Thrust Chamber Of Cryogenic Rocket Engine

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Abstract

The thrust chamber of the cryogenic rocket engine (liquefied gas at low temperature) requires optimum design and extensive thermal analysis to ensure the engine life. In liquid propellant rocket engine selection of cooling methods plays an important role to ensure the engine life. One of such cooling method is regenerative cooling, where the fuel itself acts as a coolant and is passed through the coolant channels provided in the periphery of the chamber wall. In this paper, the regenerative cooling of cryogenic propellant rocket engine thrust chamber is modelled to operate at a chamber pressure of 40 bar and thrust of 50KN with propellant combination of LOX/LH_2 where LH_2 itself acts as a coolant and it has been numerically studied with the in-house developed one dimensional thermal source code developed by C++ programming language and various parametric studies are done to achieve maximum chamber life.

Keywords— *Heat flux, cryogenic propellants, Regenerative cooling, heat transfer, chamber life*

1. Introduction

Only 0.5 to 5 % of total energy generated by combustion is transmitted to all internal surfaces of thrust chamber exposed to hot gases. Local heat flux values vary along the thrust chamber wall according to geometry and design parameters of thrust chamber. A typical heat flux distribution along the thrust chamber wall is given in Figure1.

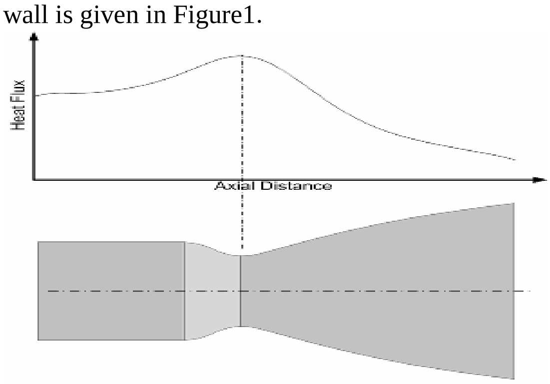

Fig 1 Heat Flux Variation at Thrust Chamber

The thrust chamber of a cryogenic rocket engine is exposed to extreme conditions during operation where pressures go as high as 20MPa and temperatures reach 3600K, this high pressure and high temperature leads to high heat transfer rates (100 to 160 MW/m^2) in thrust chamber. Under these harsh conditions, the combustor must incorporate active cooling to increase the thrust chamber life by depressing thermal stresses and preventing wall failure. Regenerative cooling is the most effective method used in cooling of liquid propellant rocket engines.

Regenerative cooling is done by building a cooling jacket around the thrust chamber and circulating one of the liquid propellants (usually the fuel) before it is injected into the injector. It has been effective in applications with high chamber pressure and high heat transfer rates. In regenerative cooling the heat absorbed by the coolant is not wasted, it augments the initial energy content prior to injection, increasing the exhaust velocity slightly (0.1 to1.5%).

2. Research Methodology

The methodology of the chamber design is centered on determining cooling channel baseline geometry, by studying a limited number of channel geometry parameters. The cooling channel geometry is a principal parameter, controlling the regenerative cooling thermal analysis. There are only two parameters which define the channel at any axial location along the engine, namely width and height and allowing these to vary with respect to axial location in the engine introduces a large number of independent parameters. A parametric approach is taken to understand the basic trends of varying the channel geometry parameters. In order to study the effects of varying the channel geometry on the regenerative cooling thermal analysis, a baseline case was required. Manufacturing limit plays an important role in realization of material. Similarly, thrust chamber design need some of the basic parameters to initiate the design work.

Those parameters are Selection of chamber pressure ratio, Selection of optimum mixture ratio, Selection of nozzle area ratio. The performance parameters are obtained from NASA-CEA code for O/F ratio of 6 and chamber pressure of 40 bar. Those values are tabulated below

Parameters	Values
Characteristic velocity(C^*)	2249 m/s
Specific impulse I_{sp}	376 s
Thrust coefficient, C_f	1.675
Molecular weight	13.37

Table 1 Parameters from NASA –CEA code

Total mass flow rate can be calculated from the following equation

$$F = I_{sp\ act} \times \dot{m}_{total} \times g$$

$$\dot{m}_{total} = \frac{50000}{350*9.81}$$

$$= 14.5 \text{ Kg/s}$$

$$\dot{m}_{total} = \frac{P_c \times A_t}{C^*_{act}}$$

$$\frac{\pi}{4} d_t^2 = 7.83 \times 10^{-3} \text{ m}^2$$

$$D_t = 100 \text{ mm}$$

2.1 Length of the Convergent and Cylindrical Portions

The convergent length of combustion chamber is the sum of the axial length of the portion between the cylindrical chamber & the Nozzle cone (X1), length of the conical portion (X2) & the length between conical potion and the throat (X3), these three lengths are calculated as follows.

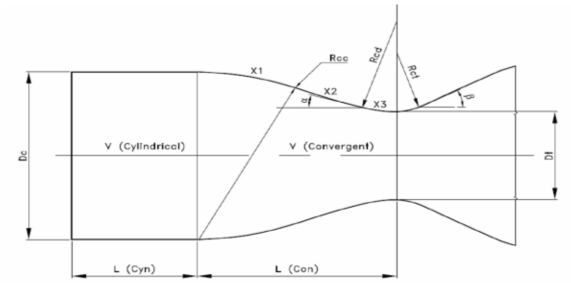

Fig 2 A schematic of length of the convergent and cylindrical portion

$$X_1 = R_{cc}\sin\alpha$$

$$= 68.4 \text{ mm}$$

$$X_3 = R_{cd}\sin\alpha$$

$$= 100\sin 20$$

$$= 34.2 \text{ mm}$$

$$X_2 = \frac{\frac{D_C}{2} - \left[R_t + R_{cc}(1-\cos\alpha) + R_{cd}(1-\cos\alpha)\right]}{\tan\alpha}$$

$$= 87.67 \text{ mm}$$

$$L_{con} = X_1 + X_2 + X_3$$

$$= 190 \text{ mm}$$

Combustion chamber volume (V_c) $= L^* \times A_t$

$= 635 \times 7.83\text{E-3}$

$= 4987278 \text{ mm}^3$

$$V_{con} = \frac{\pi}{3} \times L_{con} \times \left[R_c^2 + R_t^2 + R_c R_t\right]$$

Volume of the cone V_{con}= 3481931.8 mm^3

Volume of the cylindrical portion = V_c - V_{con}

= 4987278-3481931.8

V_{cyl} = 1505346 mm^3

Length of the cylindrical portion

$$L_{cyl} = \frac{V_{cyl}}{\frac{\pi}{4} d_c^2}$$

$$= 48 \text{ mm}$$

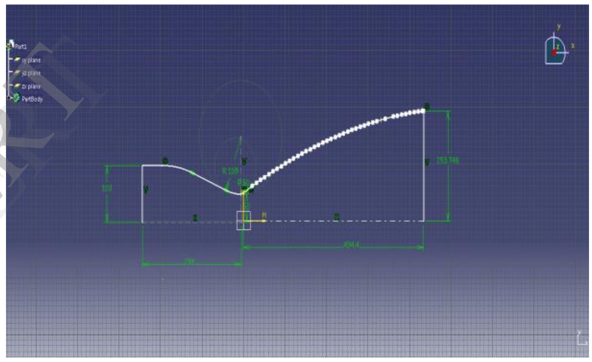

Fig 3. A line diagram of thrust chamber

3. Design of Regenerative Cooling System

An effective and efficient cooling system is crucial in extending the engine life. Thermal design includes the method of cooling, selection of coolant, flow rate of coolant, selection of configuration and dimensions of the channels and material selection. In order to analyze the thrust chamber cooling system, it is necessary to understand both dimensions and shape of the cooling system. Based on the cooling requirement any one of the basic cooling system duct can be selected as reported in literature by Carlies.

- The straight channel slot type
- Helical slotted duct

3.1 Straight Channel Design Calculation

Manufacturing limit plays an important role in the design of coolant channels. As reported in literature by Schuff, selected base line geometrical values are given below

Chamber thickness =1mm
Width of the rib =1.2mm
Channel height =1.5 mm

For this engine configuration, coolant channel with rectangular cross section has been preferred. Number of coolant channel is mainly decided by the value of perimeter at throat (i.e. minimum cross section of chamber).

$$N = \left(\frac{perimeterofthethroat}{C_w + R_w}\right)$$

Perimeter of the throat=π * equivalent diameter
Equivalentdiameter=(diameter+(2*shellthickness)+channel height)

Equivalent diameter =(100+(2*1)+1.5)
=103.5 mm

Perimeter of the throat =π*103.5
=314 mm

$$N = \left(\frac{314}{1+1.2}\right)$$

=142 channels

Serial no	Cross section area	Channel height (mm)	Channel Width throat (mm)	Number of channels
1	6	1.5	4	60
2	6	2	3	74
3	6	5	1.2	98
4	6	6	1	130
5	6	6	1	142

Table 2. Summary of Straight Channel Design

3.2 Helical Channel Design Calculation

In the case of helical channels, the channel width can be reduced by giving a proper helix angle. As the channel width is reduced, the coolant velocity is increased by the inverse function of cos θ component of the helix angle.

$$C'_w = \frac{C_w}{Cos\alpha}$$

The helical coolant channels are providing higher coolant velocity when compared to straight channels. While transferring from straight channel configuration to helical configuration it will experience the increase in channel length and decrease in number of channel with respect to the angle provided to the helical channel.

Let helix angle θ=15°

$$Cos\theta = \left(\frac{Rw}{Rw_1}\right)$$

$$Rw_1 = \left(\frac{1.2}{\cos 15}\right) = 1.24$$

$$Cos\theta = \left(\frac{Rw_1}{Rw_2}\right)$$

$$Rw_2 = \left(\frac{1.24}{\cos 15}\right) = 1.283$$

$$\text{Number of channel} = \left(\frac{314}{1+1.283}\right) = 137 \text{ channels.}$$

Serial number	Helix angle	Number of channels
1	15^0	137
2	20^0	133
3	25^0	127
4	30^0	120

Table 3. Summary of helical channel design

4. Development of One Dimensional Source Code

The heat transfer in a regeneratively cooled chamber can be described as the heat flow between two moving fluids, through the multilayer partition. The following fig 4 shows this process schematically. The general steady-state correlation of heat transfer from the combustion through the layers which include the metal chamber wall can be expressed by the following equations At steady state condition heat flux at these three locations will have the same value. The steady state heat transfer equations in the radial direction are given below.

$$q_g = h_g\left(T_{aw} - T_{wg}\right)$$

$$q = \left[\frac{k}{t}\right]\left(T_{wg} - T_{wc}\right)$$

$$q = h_c\left(T_{wc} - T_{co}\right)$$

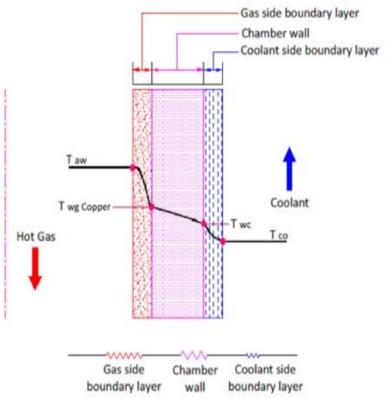

Fig 4 Heat Transfer Schematic of Regenerative Cooling System

For the thermal analysis, one full channel has been considered, in order to calculate the wall temperatures, heat flux and chamber pressure drop etc. The combustion gas properties, flow mach numbers and characteristic exhaust gas velocities for LOX/LH_2 propellant combination has been worked out using the "Chemical equilibrium & rocket performance" program.

4.1 Calculation of Gas Side Heat Transfer

Based on experience with turbulent boundary layer, Bartz Correlation is a well- known equation used for estimation of rocket nozzle convective heat transfer as reported in literature by Jerome.

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

$$h_g = \left[\frac{0.026}{D_t^2} \times \left(\frac{\mu^{0.2} C_p}{\Pr^{0.6}}\right) \times \left(\frac{P_c g}{C^*}\right)^{0.8} \times \left(\frac{D_t}{r_c}\right)^{0.1}\right] \times \left(\frac{A_t}{A}\right)^{0.9} \times \sigma$$

$$\sigma = \frac{1}{\left[\frac{T_{wg}}{2T_{og}} \times \left\{1 + \left(\frac{\gamma - 1}{2}\right) M_a^2\right\} + \frac{1}{2}\right]^{0.68} \left[1 + \left(\frac{\gamma - 1}{2}\right) M_a^2\right]^{0.12}}$$

The combustion temperature, Mach no and ratio of specific heats for the local points has been obtained from NASA CEA programme. The adiabatic wall temperature at different location is calculated from the above equation.

$$T_{aw} = \frac{1 + \left(\Pr^{0.33}\left(\frac{\gamma - 1}{2}\right) M^2\right)}{1 + \left(\frac{\gamma - 1}{2}\right) M^2} * Tog$$

4.2 Calculation of Coolant Side Heat Transfer

Heat transfer coefficient on coolant side is found out by following

$$h_c = \frac{0.029 C_p \mu^{0.2}}{\Pr^{0.67}} \left(\frac{G^{0.8}}{d^{0.2}}\right) \left(\frac{t_{co}}{t_{wc}}\right)$$

4.3. Coolant Channel Pressure Drop Estimation

The coolant pressure drop at each of the computing stations while marching forward in space is computed as reported in literature by Mustafa.

$$\Delta p = \frac{f.\Delta l.v^2.\rho}{2d_h}$$

The friction factor f is obtained iteratively as a function of coolant Reynolds number and roughness protrusion height, using the Colebrook equation

$$\frac{1}{\sqrt{f}} = 1.74 - 2\log_{10}\left[\left(\frac{2e}{d_h}\right) + \frac{18.7}{R_e\sqrt{f}}\right]$$

$$R_e = \left(\frac{\rho v d_h}{\mu}\right)$$

$$d_h = \left(\frac{4p}{A}\right)$$

In order to precede the thermal analysis thrust chamber has to be divided into many sections as shown in the Fig.5. The calculations start from the exit of the nozzle to injector end. Calculation was initiated by assuming the Twg = 300 K, with this assumption coolant side thermal conductivity calculated through Bartz equation. Then gas side heat flux is calculated by Equation after calculating heat flux coolant side wall temperature are calculated by equating equation. Once the gas side wall temperature is calculated, heat flux at the coolant section also can be calculated. At the steady state both the heat flux should be equal, if it is not equal Twg is increased by one until it reaches the steady state condition.

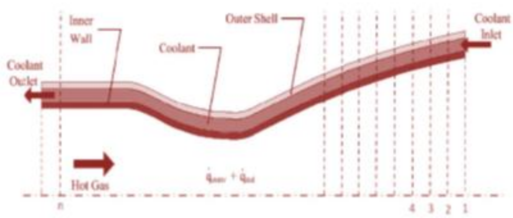

Fig 5 Numerical Design for Thermal Calculation

The heat flux at the coolant entry is iteratively computed by known coolant temperature at the one end and the adiabatic wall temperature. The intermediate wall temperatures have been encountered arrived through the iteration and the corresponding heat flux also obtained. From the first point (entry section) the coolant is moved to the next station by 1 mm axial distance. The heat flux has also been transferred to the coolant which absorbs the hot gas side flux and its temperature is increased.

The total heat transmitted to the coolant =q*perimeter of that section*L

Perimeter=π*diameter of that section

The total heat absorbed by the coolant=ṁ*C_p*ΔT

$\Delta T = T_{ci} - T_{co}$

At the steady state condition, heat transmitted to the coolant will be equal to heat absorbed by the coolant. Since the inlet coolant is known; the temperature ΔT gives the outlet coolant temperature.

This outlet temperature is taken as input to next section and similarly by computing the heat flux at the every location, a forward marching method is adopted up to injector end to generate the wall temperature profile along the length of the chamber. Once the base line parameter is obtained, all the results are plotted as curves.

4.4 Parametric Studies for Thermal Analysis

In this thesis parametric studies are the main objective. The following flow chart can be used to explain the different roots of parametric studies. From these studies, analytical results are focused to limit the throat wall temperature below 900 K and channel pressure drop below 30 bar, two values are considered as a design limit of the regenerative cooling system.

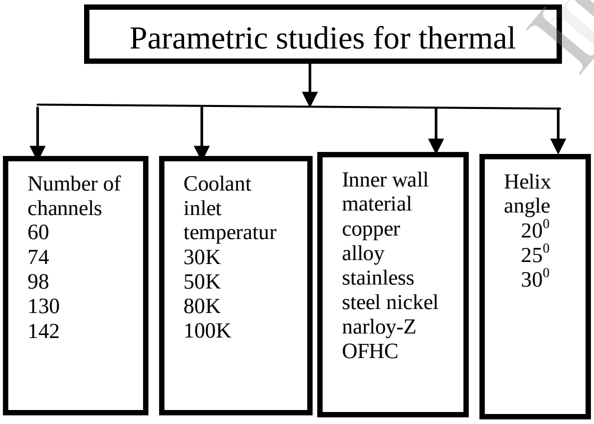

Fig 7 Flow Chart for Parametric Studies

5. Results and Discussions

The results of parametric studies are obtained from the one dimensional sourcecode written in C++ programming language, the results are tabulated below for the effect of coolant injection temperature, materials, helix angle, number of coolant channels, chamber inner wall thickness.

5.1 Effect of Coolant Inlet Temperature

The flow behavior of coolant inside the cooling channels is of great importance to improve design and performance of regeneratively cooled rocket engines. Lower coolant temperature at the injection point results in lowering the wall temperature since it also results in increase in coolant side heat transfer co-efficient.

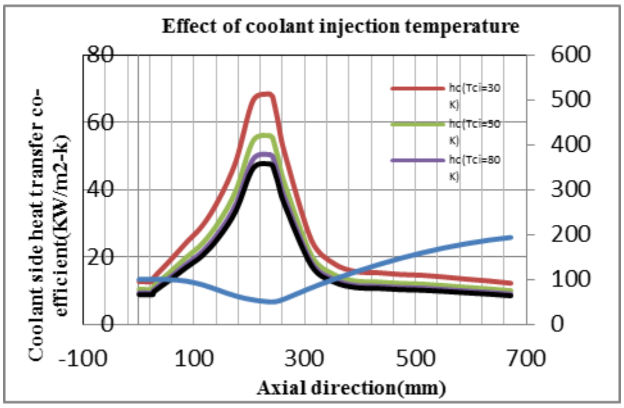

Fig 8 . Effect of Coolant Injection Temperature

In the current investigation coolant injection temperature has been varied from 30K to 100K. Another important factor to be noted is by lowering the coolant temperature leads to increase in specific heat of the coolant, this makes the LH2 is attractive substance for regenerative cooling. From the above result it is clear that LCH4 results in much lower specific heat at higher injection temperature than LH2 which as higher specific heat by lowering the coolant temperature.

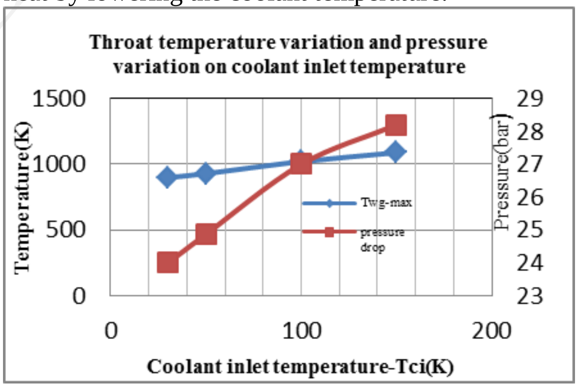

Fig9. Throat Temperature and Pressure Variation on Coolant Inlet Temperature

From the above graph it is clear evident that the lower injection temperature provides the favourable temperature at the throat point, pressure drop across the coolant channel also shows the considerable variation, this variation is because of the increase in temperature leads to lowering the coolant density. At the injection temperature on 30K gives the throat wall temperature of around 860K (i.e. well below the melting point of the copper).Higher injection temperature results in higher wall temperature at the throat. Coolant injection temperature of 30K have the wall temperature of 899 K and the pressure drop of 24 bar and increase in coolant injection temperature of 150 K have the throat wall temperature of 1089 K with the pressure drop of 28.2 bar. Through this increase in coolant injection temperature provides the unfavorable situation for both temperature & pressure drop conditions.

Parameter	**T_{ci} = 30K**	**T_{ci}= 50K**	**T_{ci}= 100K**	**T_{ci}= 150 K**
Inner wall temperature at throat(K)	899	930	1021	1089
Coolant heat transfer coefficient (KW/m2-K)	69	54	50	46
Gas side heat transfer coefficient (KW/m2-K)	89	72	66	55

Table 4. Summary of Effect of Coolant Injection Temperature

5.2 Effect of Material

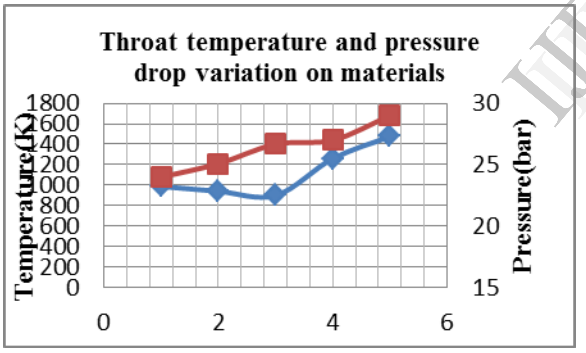

Fig 10.Temperature and Pressure Variation on Materials

Thermal conductivity value of Narloy-Z is 340W/m-K and Copper alloy holds the value in the range of 180 – 280 W/m-K. From the table 5 given below it is clear that among the copper materials OFHC is getting the throat temperature value of 890K which is 10.21% higher than copper alloy and 25.5% Narloy-Z (High strength copper alloy). OFHC result in lower gas side wall temperature of 890 K. High conductivity plays a major role on the more energy transfer (i.e. high heat transfer),which leads to the lowering the wall temperature on the inner wall of the thrust chamber. It is more visible that higher heat flux provides lower gas side wall temperature (i.e. more heat transfer). By considering the thermal management ability of the material along with the strength, OFHC seems to be the best option for the inner chamber wall material, pressure drop across the coolant channel also comes very much favorable to the required value of less than 30bar.

Based on this result OFHC (Oxygen Free High Conductivity Copper) has been selected for the current regenerative cooling system.

Materials	**Throat Temperature(K)**	**Pressure Drop(bar)**
Copper alloy	987	24
Narloy-Z	940	25.08
OFHC	890	26.67
Nickel	1260	27
SS	1476	29

Table 5. Summary of Effect of Inner Wall Material

5.3 Effect of Helix Angle

Helical channels can provide better cooling efficiency than the straight channels, with the penalty of higher pressure drop, but it has the manufacturing difficulty also. For this analysis three different helical angles are 20º, 25º and 30º are taken. Channel length will increase according to the helix angles but in this case increase in angle will results in decrease in number of coolant channel.

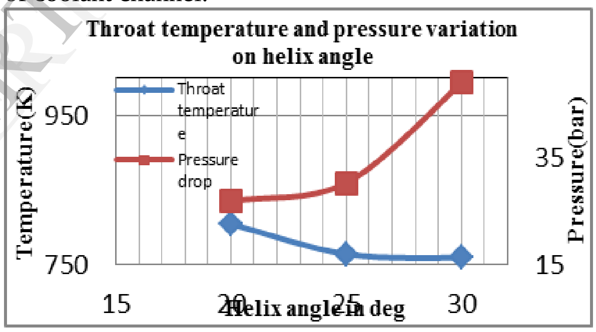

Fig12. Throat Temperature and Pressure Variation on Helix Angle

The above graph is drawn by taking the throat temperature and channel pressure drop across the chamber. By considering the boundary layer development on the helical channels it shows the effective heat transfer on the chamber wall. Boundary layer breakup leads to the more energy transfer across the thin boundary layer. Increasing the helix angle results in the lowering the wall temperature on the throat but penalty has been paid on the pressure drop increment, it can be clearly seen from the above graph, pressure drop moves to the 49bar from the 30 bar. With this consideration helix angle of low values are seems to be most favorable on the throat temperature as well as pressure budget within the limit (i.e. throat temperature of 940Kand pressure drop of 27 bar).

From this analysis helix angle of 20deg has been selected, because it gives the throat wall temperature of 940K (i.e.47K lower than the straight channel configuration) and channel pressure drop value of 27bar, which is 8% above the design value (i.e. 25 bar).

Helix angle	Throat temperature(k)	Pressure drop(bar)
20°	940	27
25°	981	30
30°	1260	49

Table 6. Summary of Effect of Helix Angle

5.4 Velocity Variation with Helix Angle

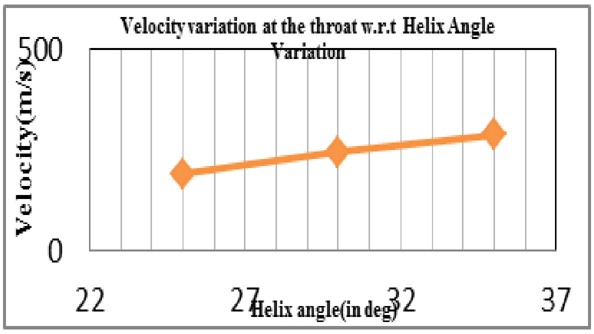

Fig 12. Velocity Variation at the Throat with Respect to Helix Angle

Velocity at the throat plays an important role in the carbon deposit at the coolant wall, which may act as an insulating layer. Insulating layer will be an unfavorable condition when its deposit grows in thickness; this reduces the amount of heat transfer to the coolant. Because of this effect gas side wall temperature go to the high value. In the regenerative cooled engine with the gaseous injection velocity at the throat should not exceed the value of 200 m/s. By taking all these into the consideration helix angle of 20-25deg is providing the favourable velocity.

Helix Angle	Velocity(m/s)
20°	176
25°	190
30°	245
35	287

Table 7. Summary of Velocity Variation With Respect To Helix Angle

5.5 Effect of Number of Channel

In a regenerative cooling system number of coolant channel plays an important role in transfer the amount of heat flux to the coolant which may result in lowering the inner wall temperature, but increasing the number of channel put the penalty in the mode of increase in pressure drop across the coolant channel.

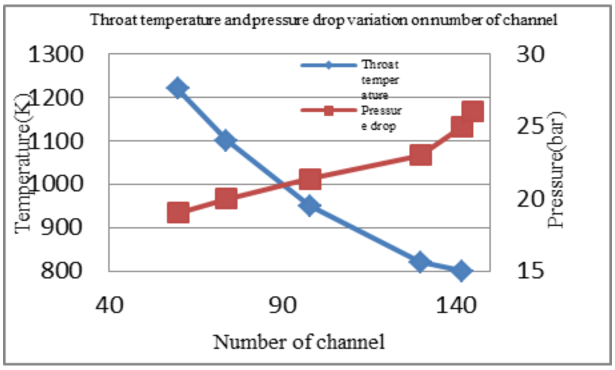

Fig13. Throat Temperature and Pressure Variation on Number of Channel

In the current analysis number of coolant channel has been varied between 60 to 142 among this cooling system with the 142 number of channel provides the favorable throat temperature of 800K as well as the pressure drop of 25bar. Cooling system with 142 coolant channels at the throat and 284 coolant channels at the exit (i.e 672 mm from the injector end) has been fixed as the baseline geometry for further thermal investigation.

Number of channels	Throat temperature(K)	Pressure drop(bar)
60	1220	19
74	1100	20
98	950	21.34
130	820	23
142	800	25

Table 8. Summary of Effect of Channels

6. Conclusion

In the present investigation an attempt has been made to analyze the thermal behaviour of hydrogen, in the design of regenerative cooling system for engine modelled to operate on a LOX/ LH_2 mixture at a chamber pressure of 40 bar for 5000 kg thrust.

Results obtained through the numerical coding were discussed. The following important observations were made from the results obtained through numerical and computational studies.

- Liquid hydrogen injection temperatures effects are studied between the temperature ranges of 30 to 150 K. At the injection temperature of 30K the throat wall temperature is found to be around 890K. Increase in coolant injection temperature of 150 K provides the throat wall temperature of 1089K. thus increase in coolant injection temperature results in unfavorable situation for both temperature and pressure drop and hence coolant injection temperature of 30 K is preferable.
- Number coolant channel study revealed that higher the number of coolant channel, lower

the inner wall temperature, with the penalty of higher pressure loss across the coolant channel. Based on this study regenerative cooling system with 142 number of channel configuration gave the favourable wall temperature of 800 K with the pressure drop of 25 bar across the coolant channel, which is less than a design limit.

- Different chamber inner wall materials were also studied in order to choose the suitable inner wall material, which can give lower inner wall temperature with higher strength at the elevated temperature. Nickel, Stainless steel, Copper alloy, Narloy- Z and OFHC were the materials considered for the thermal analysis. Among these Copper base material OFHC gave the inner wall temperature at the throat in the range of 890 K, because the higher thermal conductivity allowed more heat to transfer through the wall. This resulted in lower gas side wall temperature than other metals.
- Helical channel effects for 20°, 25° and 30° were studied in this analysis. Helical channels gave better cooling efficiency in the regenerative cooling system, than the straight channel, but with the penalty of higher pressure drop. Among these 25° and 30° angles gave the gas side wall temperature in the range of 980-1260K with pressure drop of 30 bar and 49 bar respectively. It shows that higher helix angles are not suitable for the favourable pressure drop in the coolant channel. Helix angle of 20° gave the wall temperature of 940 K with the pressure drop value of 27 bar.

From all parametric results it has been found that two channel configurations are optimized to provide the better cooling efficiency in the designed regenerative cooling system. First one is straight channel configuration using 142 numbers of channels with the channel height 1.5 mm, rib of width 1.2 mm, aspect ratio of 1.5 at throat and channel doubling at the distance of 672 mm from the injector. Second configuration is using the helical channels with 20 degree angle, 142 number of coolant channels.

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