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Design & Analysis of Regenerative Cooling for Liquid Propelled Rocket Engine

[1]Shahzeb Irfan, [2]Talha Bin Khalid, [3]Dr. Ihtzaz Qamar
Department of Aeronautics & Astronautics
Institute of Space Technology
Islamabad, Pakistan
[1]shahzeb.irfan93@yahoo.com
[2]talhakhalid2008@gmail.com
[3]ihtzaz.qamar@ist.edu.pk

***Abstract*— Development of MATLAB code enables producing conical shaped nozzle geometry with appropriate wall thickness, total length, converging and diverging angles considering propulsive performance characteristics of the engine. Along the nozzle axis, segmentation is done for determining area ratios and Mach number. Analysis of the preliminary design yields heat flux variation and temperature profiles of the gases and the coolant along the nozzle axis. Concept of multiple passages of coolant over the nozzle shifts heat transfer mechanism from a normal surface to heat transfer from an extended surface thus allowing more heat to be absorbed by the coolant to maintain inner wall temperature well below its melting point. The preliminary analysis is used for developing multiple passages of coolant walls, thus temperature profiles and heat flux variations for multi-passage configuration are determined. Technical limitations incorporation by considering manufacturing and weight constraints allows optimization of the number of coolant passages for increasing efficiency of the regenerative cooling system.**

Keywords—regenerative; coolant; nozzle; rocket

I. Introduction

Cooling of the thrust-chamber is an essential element for having maximum performance and stability of liquid propelled rocket engines[1]. Regenerative cooling utilizes propellant (fuel) as a coolant fed through multiple passages in the thrust-chamber wall for cooling before being injected into the combustion chamber[2], thus is the most suitable technique for the liquid rocket engines working under extreme conditions of chamber pressures and temperatures[3]. LOX/RP-1 (Kerosene) is considered as the liquid rocket propellants and RP-1(kerosene) as the coolant for analysis purposes. Exhaust gases are treated as an isentropic mixture for providing basis of preliminary analysis (single coolant passage over the nozzle). The heat transfer between the exhaust gases and the coolant has been analyzed axially through segmentation[4] along the nozzle axis.

II. Assumptions

For simplicity in calculations, initially some assumptions were made based on the experimental data from the literature. The flow was assumed to be isentropic in the nozzle. Combustion chamber properties (total pressure, temperature, characteristic velocity etc.) were pre-defined. Also, pre-defined wall material properties (thickness, conductivity etc.) were used.

III. Methodology

A. Design

The initial nozzle design (Fig.1) was developed on MATLAB, considering basic assumptions and pre-defined geometric properties. Enlisted below are the specified geometric parameters:

Total length:	0.500 mm
Inlet diameter:	0.160 mm
Throat diameter:	0.084 mm
Convergence angle:	30°
Divergence angle:	15°

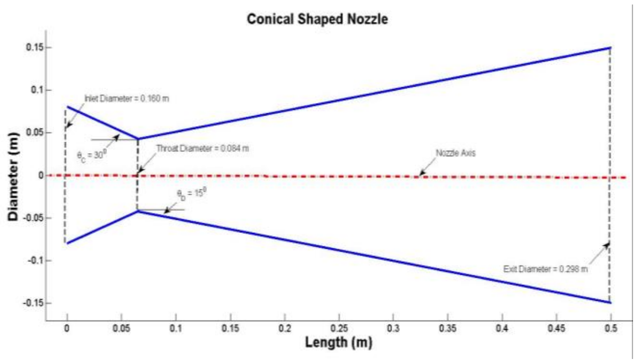


Fig. 1 2D conical nozzle design

The preliminary design (Fig.1) was used for the analysis of single-channel coolant design to check if this configuration will be able to cool the chamber or not. The single-channel coolant configuration could not satisfy the specified requirements for cooling. So, multiple-chamber coolant configuration was implemented. The preliminary analysis was used as a basis for determining local/axial diameters of the coolant chambers. Moreover, the isentropic relations were applied to determine variation of adiabatic wall temperature and the Mach number variation along the nozzle axis. The temperature constraints were also implemented during the design phase, i.e. the temperatures of the wall and the coolant were kept less than the melting point and the boiling point respectively, for the given pressure.

B. Analysis

Axial segmentation along the nozzle axis was done for the analysis of cooling parameters for each segment along the nozzle axis (Fig.2).

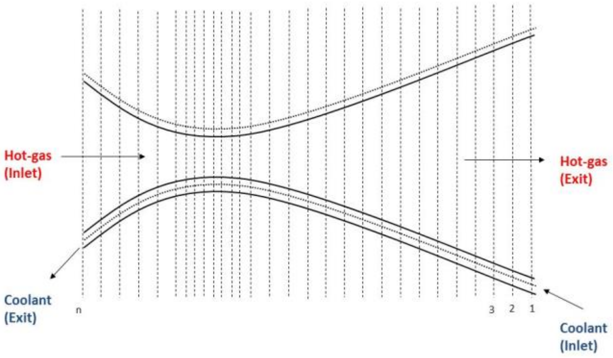


Fig. 2 Axial segmentation along the nozzle

These segments collectively yield the overall results of regenerative cooling along the nozzle. The most important parameter required for analysis of the regenerative cooling system is the convective heat transfer co-efficient (h_g) which was calculated using Bartz equation[5, 6].

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

Where:

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

Heat transfer equations were used for the calculation and determination of gas-side heat flux (q_g), required convective heat transfer co-efficient for coolant side (h_c) and heat flux (q) variation along the nozzle axis. The governing heat transfer equations used are as follows:

$$q_g = h_g\left(T_{aw} - T_{wg}\right) \text{ [7]}$$

$$h_c = \frac{0.029 C_p \mu^{0.2}}{Pr^{0.67}}\left(\frac{G^{0.8}}{d^{0.2}}\right) \text{ [8]}$$

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

Furthermore, the hydraulic diameter (d_H) of the coolant passages was determined for the desired number of channels (N), and the pressure drop (ΔP) for those channels was analyzed along the nozzle axis. The axial velocity profile of the coolant was also determined.

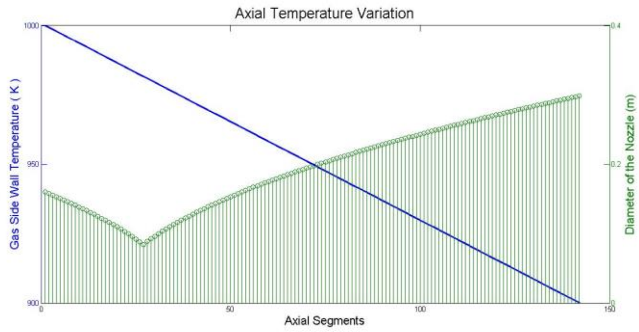
C. Optimization

The hydraulic diameters (d_H) of the coolant channels were optimized so as to provide maximum cooling with minimum number of channels. The manufacturing constraints were also considered for the coolant channels and a minimum diameter limit was determined, so that the channels can be manufactured with practically possible values of diameter. The safety margins/factors were incorporated for achieving values of gas-side wall temperature (T_{wg}) and coolant side wall temperature (T_{wc}) lower than the melting point and the boiling point respectively, by a safety margin of about 10% - 15%. Furthermore, the coolant channels were optimized so as to keep the velocity of the coolant within practical range.

IV. RESULTS

The temperature profiles for the gas-side wall and the coolant side wall are determined after the analysis. Gas-side wall temperature is cooled down from 1000K to 900K (Fig.3) and the coolant side wall temperature goes from 900K to 1000K (Fig.4), both the temperature profiles are well within the desired range of wall temperatures.

Fig. 3 Gas-side wall temperature variation



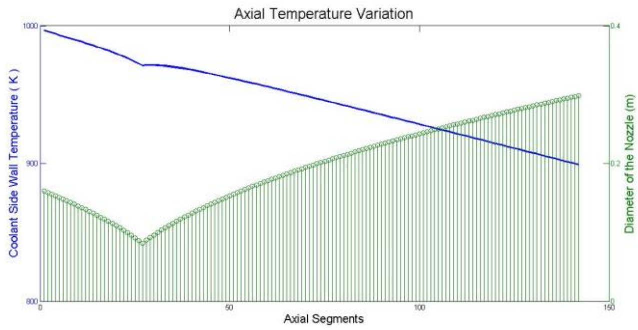


Fig. 4 Coolant-side wall temperature variation

The variation of heat transfer coefficients along the nozzle is also analyzed. The gas-side heat transfer coefficient (h_g) does not exceed the maximum value of 90 W/m^{2}K (Fig.5), whereas the value of coolant side heat transfer coefficient (h_c) goes as high as 340 W/m^{2}K (Fig.6). Both these results are the indications for efficient regenerative cooling.

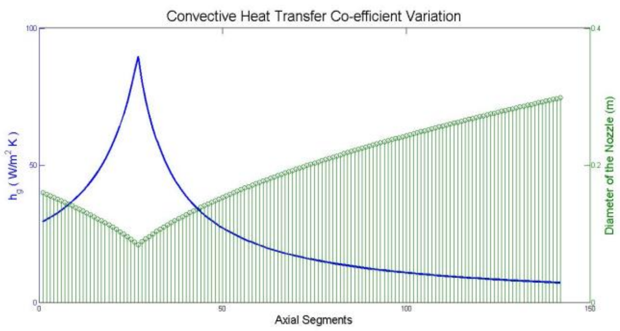


Fig. 5 Gas-side heat transfer coefficient variation

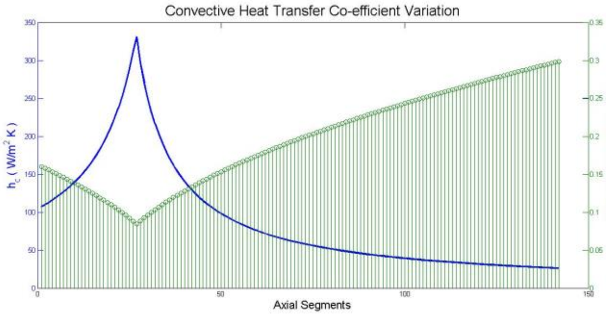


Fig. 6 Coolant-side heat transfer coefficient variation

The theoretical heat transfer data suggests that the values of heat flux (i.e q_g and q_c) for anti-parallel flow should be equal in order for the cooling to be possible. So, the results show the differences between q_g and q_c of the order of 10^{-11} (Fig.7), which is almost negligible and hence indicates that the cooling is quite efficient for the given nozzle profile.

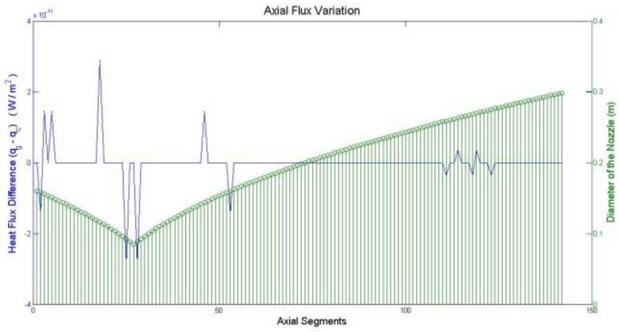


Fig. 7 Heat Flux Difference along the Nozzle

The cooling capacity (C_c) of the coolant along the nozzle has also been analyzed (Fig.8), which indicates that the capacity of the coolant to absorb heat is considerably more than the capacity of the exhaust gases to release heat, hence providing suitable grounds for regenerative cooling.

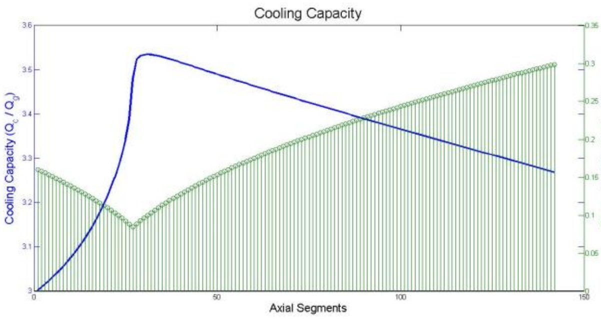


Fig. 8 Cooling Capacity

For efficient cooling, considering the limitations and constraints, keeping the number of coolant passages fixed to 60 channels, the hydraulic diameter variation of the coolant passages has also been determined (Fig.9).

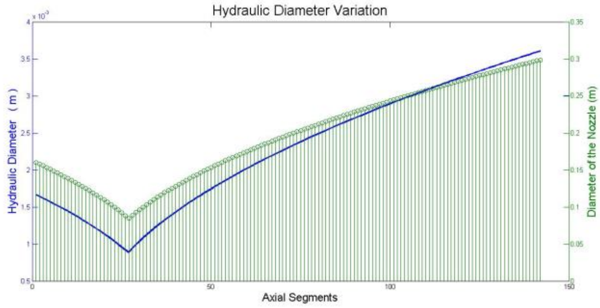


Fig. 9 Hydraulic Diameter variation along the Nozzle

For the given number of channels with varying hydraulic diameters, the velocity of the coolant through the coolant channels (Fig. 10) does not exceed 40 m/s which is well within the practical range. Also, the pressure drop because of those coolant passages along the nozzle (Fig.11) comes out to be quite low hence indicating that an efficient regenerative cooling system has been developed.

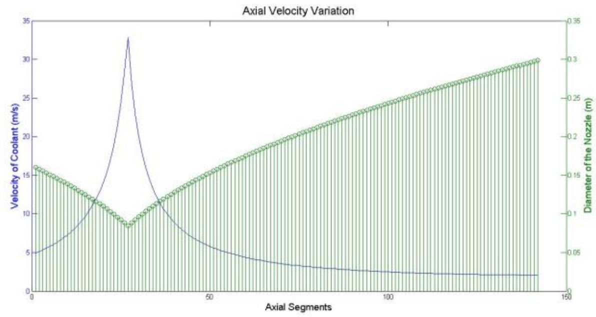


Fig. 30 Coolant Velocity Variation along the Nozzle

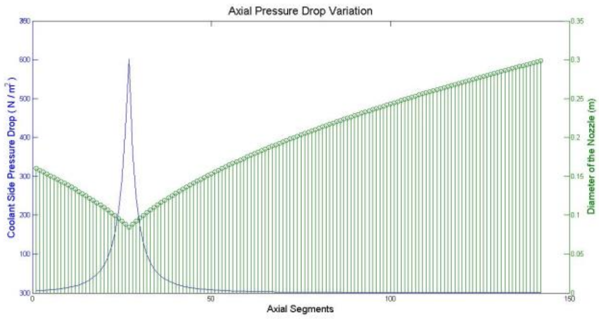


Fig. 4 Pressure Drop along the Nozzle

V. Conclusion

The regenerative cooling for the given nozzle design has been satisfied after the implementation of constraints. The MATLAB code has analyzed and generated reasonable values of heat transfer variables, which indicate that efficient cooling system has been developed after taking the pre-defined limitations and manufacturing constraints into consideration. Optimization of the coolant channels has yielded reasonable values of the coolant velocity, with minimum pressure losses.

VI. Acknowledgment

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