Thermal Analysis on Regenerative Cooled Liquid Propellant Rocket Thrust Chamber Using ANSYS

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Abstract In this research work, thermal analysis has done on a rocket engine’s thrust chamber with four different shapes like, circular, rectangular with greater breath (b>d), rectangular with greater depth (d>b) and rectangular with greater depth with edges filleted coolant channel models to establish perfect suitable shape for the coolant channels in order to maintain the entire thrust chamber within the melting point of its materials. Finite Element Method (FEM) has adopted to establish the thermal behaviour of the coolant channel’s materials such as Nickel, Copper and Zirconium under the specific boundary conditions. Temperature distribution with respect to the nodal distances at thrust chamber’s inlet, throat and outlet portions with four different shapes of coolant channel models under Nickel, Copper and Zirconium materials were attained and compared with each other. Finite element results reveals that the successful configuration for generatively cooled rocket thrust chamber must have the coolant passage shape of rectangular cross section with greater depth (b>d).

1 Introduction

Liquid fuelled rocket engine’s performance is based on the huge value of thrust for its higher propulsion rate. Higher propulsion rate can be achieved by means of proper mixing, effective burning and regulated ejection of the fuel in the rocket engine’s thrust chamber [1]. The reliability of the liquid fuelled rocket engine’s thrust chamber is purely based on the exact prediction of its wall temperatures and amount of combustion gases heat flux [2]. Due to the usage of the liquid propellant in a liquid fuelled rocket engine, distribution of the temperature is not even in all wall sides of the combustion chamber. Temperature values are very higher at the nozzle end and very lower at throat portion of the nozzle [3]. Elevated temperature and pressure levels, and thrust chamber materials capable of withstanding high heat fluxes are necessary to meet these requirements [4]. Need of regenerative cooling methods are significantly increased to obtain the superior performance in the liquid fuelled rocket engine’s combustion chamber. Analysis of the rocket engine’s thermal behaviour
is well defined with related to the coupled heat transfer problem burning gas, combustion chamber wall and the liquid coolant [5, 6]. Life cycle of the combustion chamber can be considerably improved, when the side wall temperature is minimal [7]. In the thermal design of cooling systems for the thrust chambers of rocket engines, reliable estimation of the coolant heat transfer coefficients is of great importance [8]. In general, cooling systems design for the thrust chamber is playing a vital role during the liquid propellant rocket engine’s overall design [9]. Combustion process optimization, combustion chamber’s integrity and forecasting of heat flux moving between the combustion gages and the engine wall can be ensured using inclusive thermal analysis [10]. Liquid propellant rocket engine with high pressure thrust chamber reveals the superior performance operation during the regenerative cooling process. It can be used frequently used in huge and small size thrust chambers [11]. The life of the rocket engine is purely depending upon the active and proficient cooling system. The distinctive thermal analysis is much needed to explore the effect of cooling in the thrust chamber to maximize the combustion gases power in a rocket engine [12]. An upright physical perception on the rocket engine mechanism, special effects of geometrical changes calculations on the heat transfer and cooling necessities are the basic needs for the pioneering cooling approaches of the liquid propellant rocket engines [13]. Extreme and active cooling approaches are accomplished in the thrust chamber of the rocket engine by flowing a liquid propellant into the suitable cooling channels [14, 15]. In a high-pressure liquid rocket engine, unique circuit regenerative cooling is extensively used to enhance coolant enthalpy also diminish the thrust wall temperature [16]. In this research work, a distinctive thermal analysis has been conceded on a regenerative cooled liquid propellant rocket thrust chamber to establish perfect suitable shape for the coolant channels in order to maintain the entire thrust chamber within the melting point of its materials.

2 Materials and Methods

In general, thrust chamber wall should be designed to withstand the enormous heat expelled by hot combustion gas, which comes out of combustion chamber. The two important material properties such as thermal conductivity and melting point were considered for this analysis. Based on the above said properties, three materials were chosen to serve the purpose of reducing the temperature along the thickness of thrust chamber wall. At the same time it should be viewed seriously, the temperature should not exceed the melting point of the materials. The three materials namely Copper (Cu), Nickel (Ni) and Zirconium (Zr) were selected in the design of thrust chamber wall and the thermal properties of that materials were considered to carry out the analysis using ANSYS. At room temperature, high electrical and thermal conductivity has observed in Copper material among the pure metal. Copper has been placed between the inner layer Zirconium and outer layer Nickel. High polish is available in Nickel material, because it is a silvery white metal. It be in the right place to the changeover metals, and is rigid and flexible. It is the outermost layer of thrust chamber. Zirconia or Zirconium dioxide (ZrO2) is a white translucent oxide of Zirconium. Zirconia is an enormously intractable material. The thermal properties of the selected materials such as Copper, Nickel and Zirconium were given in table.1.

| Rocket thrust chamber wall material | Density (kg/m$^3$) | Thermal conductivity (W/mK) | Specific heat (J/kgK) | Melting point (K) |
|-----------------------------------|--------------------|----------------------------|-----------------------|-------------------|
| Copper                            | 8900               | 410.00                     | 401.90                | 1540              |
| Nickel                            | 8890               | 90.70                      | 456.39                | 1666              |
| Zirconium                         | 6000               | 120.75                     | 418.00                | 2500              |

Table 1 Physical and thermal properties of rocket thrust chamber wall materials
Coolant plays an important role in the generatively cooled rocket engine. In general, rocket engine nozzle and other parts are cooled using the liquid nitrogen before mixed with an oxidizer. The different Thrust chamber’s wall geometry configurations, which are used in this analysis were given in table 2. Before doing the finite element analysis, calculation of heat transfer coefficient and bulk heat transfer is much needed to establish the heat transfer behaviour between the propellant and the combustion chamber respectively. Though the formula is available, it is very difficult to determine the heat transfer coefficient of combustion gas as its temperature is in terms of 2800 K. At this enormous temperature, the liquid hydrogen dissociates into steam and it is very difficult to find heat transfer coefficient of steam. The heat transfer coefficient and bulk heat transfer for the rocket thrust chamber’s inlet, throat and outlet portions were derived from an existing equation and it has given in table 3 respectively. The different physical properties of the liquid hydrogen are shown in table 4.

### Table 2 Thrust chamber’s wall geometry configurations

| Model | Inlet geometry of thrust chamber wall |
|-------|-------------------------------------|
| Model - A | Circular |
| Model - B | Rectangular with greater breath (b>d) |
| Model - C | Rectangular with greater depth (d>b) |
| Model - D | Rectangular with greater depth with edges filleted |

### Table 3 Calculated heat transfer coefficient and bulk temperature at various portions in the combustion chamber

| Portion of combustion chamber | Heat transfer coefficient (W/m²K) | Bulk temperature (K) |
|-------------------------------|----------------------------------|----------------------|
| Inlet                         | 50000                            | 2500                 |
| Throat                        | 70000                            | 2400                 |
| Outlet                        | 40000                            | 2200                 |

### Table 4 Physical properties of liquid Hydrogen

| Property                  | Value          |
|---------------------------|----------------|
| Density (kg/m³)           | 9.46           |
| Velocity (m/s)            | 20             |
| Viscosity (Ns/m²)         | 1.3×10⁻⁵       |
| Specific heat (J/kg)      | 7200           |

3 Finite Element Analysis (FEA) on thrust chamber’s half-cooling channel models

An inclusive finite element analysis package (ANSYS) is used to accomplish the entire thermal analysis on the liquid propellant rocket engine’s thrust chamber. Initially half-cooling channel section had to be drawn before it was analysed. The drawing part was done in CATIA, a CAD package. Throughout the analysis, the mass flow rate had to be kept constant. The only way to do that while trying out different shapes was to keep the area of the coolant channel constant. Hence, the area of coolant slots was maintained uniform throughout the investigation, irrespective of the shape of it. In this analysis, SHELL 57 element is used to mesh the entire geometry of the half-cooling channel. The complete finite element models, which have meshed with the SHELL 57 elements of the four different thrust chamber’s half-cooling channels (Model-A, Model-B, Model-C and Model-D), have depicted in figure 1 (a) to figure 1 (d) respectively. In this investigation it is very important to know the various modes of heat transfer that were involved at the time of analysis. The following heat transfer conditions such as, convection from combustion gases (hot-gases), convection from the coolant, convection from the atmosphere and three-dimensional conduction within the wall were fed
during the heat transfer analysis. In this current heat transfer analysis, only half of the cooling section was taken the heat flux across the edge of the coolant channel was restricted by making it zero.

![Image of mesh geometry](image)

**Figure 1.** Mesh geometry of rocket thrust chamber half coolant channel inlet for (a) Model-A (b) Model-B (c) Model-C (d) Model-D

In the graphical plot, distributions of temperature with respect to the nodal distance were depicted clearly. It has observed from the graphical plot, distribution of temperature from the gases to the thrust chamber’s inlet portion has increased with respect to the increasing nodal distance. From the temperature distribution and nodal distance plot that has represented in figure.7 (a), it has observed that the cooling wall, which has analysed with Nickel material, can withstand the maximum temperature of 1666 K at the thrust chamber’s inlet, whereas this maximum temperature value is lower than that of its melting point of 2500 K. The analyses were carried out at inlet, throat and outlet sections of the thrust chamber wall. At each section, four analyses were done to establish the better geometrical shapes (table.2) of coolant passage. The four different geometry of thrust chamber wall was drawn by using CATIA software and the same geometries were imported to ANSYS software to analyse the temperature distribution under the three different cooling channel materials. The four different thrust chamber-cooling wall’s geometries like, Model-A, Model-B, Model-C, Model-D with different material properties assigned, and boundary conditions applied configurations were illustrated in figure.2 (a) to 22 (d) correspondingly. After these applied boundary conditions and the suitable material properties on the four different models of the combustion chamber cooling wall’s inlet were analysed in ANSYS software by using the solver option to establish the temperature behaviour between the cooling channel walls under the three different materials.

![Image of material properties and boundary conditions](image)

**Figure 2.** Material properties and boundary conditions applied rocket thrust chamber half coolant channel model’s geometry for (a) Model-A (b) Model-B (c) Model-C (d) Model-D
4 Results and discussions

A distinctive heat transfer analysis have been made on an existing rocket combustion chamber’s cooling wall at its inlet, throat and outlet portions by changing its geometry and material to expose the suitable shape of cooling wall geometry for the effective heat transfer between the produced gases and the cooling wall. Temperature distribution over the inlet portion of the thrust chamber’s cooling wall surfaces for the four different cooling passage geometry by changing the cooling wall’s material were illustrated in figure.3 (a) to figure.3 (d) correspondingly.

![Temperature distribution at rocket thrust chamber’s half coolant channel inlet](image)

**Figure 3.** Temperature distribution at rocket thrust chamber’s half coolant channel inlet for (a) Model-A (b) Model-B (c) Model-C (d) Model-D

Detailed colour plots, that have attained through heat transfer analysis from ANSYS software for the combustion chamber’s cooling passage geometry with four different shapes like, Model-A, Model-b, Model-C and Model-D have depicted in figure. 4 (a) to figure.4 (d) respectively. It has observed from the detailed colour plots temperature distributions were found maximum at the inner surface of the combustion chamber’s cooling passage wall.

![Detailed temperature distribution contour plot](image)

**Figure 4.** Detailed temperature distribution contour plot for rocket thrust chamber’s half coolant channel inlet with (a) Model-A (b) Model-B (c) Model-C (d) Model-D

Conversely, the temperature distribution over the combustion chamber’s wall has found minimum with respect to the increasing distance from the gas inlet portion. Similarly, distribution of temperature in a thrust chamber with respect to the nodal distance at coolant channel inlet in model-A for Nickel, Copper and Zirconium materials were shown in figure.5 (a), 5 (b) and 5 (c) respectively.
Figure 5. Temperature distribution with respect to the nodal distance at coolant channel inlet in model-A for (a) Nickel (b) Copper (c) Zirconium material

In the graphical plot, distributions of temperature with respect to the nodal distance were depicted clearly. It has observed from the graphical plot, distribution of temperature from the gases to the thrust chamber’s inlet portion has increased with respect to the increasing nodal distance. From the temperature distribution and nodal distance plot that has represented in figure 5 (a), it has observed that the cooling wall, which has analysed with Nickel material, can withstand the maximum temperature of 1666 K at the thrust chamber’s inlet, whereas this maximum temperature value is lower than that of its melting point of 2500 K. From the temperature distribution and nodal distance plot which is represented in figure 5 (b), it has observed that the cooling wall, which has analysed with Copper material, cannot withstand the maximum temperature of 1540 K at the thrust chamber’s inlet due to the exceeding its melting point of 1500 K. In the temperature and nodal distance graphical plot for copper material, regions marked by red ellipse are the nodes exceeding the melting point of copper. From the temperature distribution and nodal distance plot that has represented in figure 5 (c), it has observed that the cooling wall, which has analysed with Zirconium material, can withstand the maximum temperature of 2500 K at the thrust chamber’s inlet, whereas this maximum temperature value is lower than that of its melting point of 2899 K. Distribution of temperature in a thrust chamber with respect to the nodal distance at coolant channel inlet in model-B for Nickel, Copper and Zirconium materials were shown in figure 6 (a), 6 (b) and 6 (c) correspondingly. In the graphical plot, distributions of temperature with respect to the nodal distance were depicted clearly. It has observed from the graphical plot, distribution of temperature from the gases to the thrust chamber’s inlet portion has increased with respect to the increasing nodal distance. From the temperature distribution and nodal distance plot that has represented in figure 6 (a), it has observed that the cooling wall, which has analysed with Nickel material, can withstand the maximum temperature of 1666 K at the thrust chamber’s inlet, whereas this maximum temperature value is lower than that of its melting point of 2500 K. From the temperature distribution and nodal distance plot which is represented in figure 6 (b), it has observed that the cooling wall, which has analysed with Copper material, cannot withstand the maximum temperature of 1561 K at the thrust chamber’s inlet due to the exceeding its melting point of 1500 K. In the temperature and nodal distance graphical plot for copper material, regions marked by red ellipse are the nodes exceeding the melting point of copper. From the temperature distribution and nodal distance plot that has represented in figure 6 (c), it has observed that the cooling wall, which has analysed with Zirconium material, can withstand the maximum temperature of 2500 K at the thrust chamber’s inlet, whereas this maximum temperature value is lower than that of its melting point of 2899 K. Distribution of temperature in a thrust chamber with respect to the nodal distance at coolant channel inlet in model-C for (a) Nickel (b) Copper (c) Zirconium material.
distance at coolant channel inlet in model-C for Nickel, Copper and Zirconium materials were shown in figure.7 (a), 7 (b) and 7 (c) correspondingly. In the graphical plot, distributions of temperature with respect to the nodal distance were depicted clearly. It has observed from the graphical plot, distribution of temperature from the gases to the thrust chamber’s inlet portion has increased with respect to the increasing nodal distance.

![Graphs](image)

**Figure 6.** Temperature distribution with respect to the nodal distance at coolant channel inlet in model-B for (a) Nickel (b) Copper (c) Zirconium material

![Graphs](image)

**Figure 7.** Temperature distribution with respect to the nodal distance at coolant channel inlet in model-C for (a) Nickel (b) Copper (c) Zirconium material

From the temperature distribution and nodal distance plot that has represented in figure.7 (a), it has observed that the cooling wall, which has analysed with Nickel material, can withstand the maximum temperature of 1666 K at the thrust chamber’s inlet, whereas this maximum temperature value is lower than that of its melting point of 2500 K. From the temperature distribution and nodal distance plot which is represented in figure.7 (b), it has observed that the cooling wall, which has analysed with Copper material, can withstand the maximum temperature of 1315 K at the thrust chamber’s inlet, whereas this maximum temperature value is lower than that of its melting point of 1358 K. From the temperature distribution and nodal distance plot that has represented in figure.7 (c), it has...
observed that the cooling wall, which has analysed with Zirconium material, can withstand the maximum temperature of 2500 K at the thrust chamber’s inlet, whereas this maximum temperature value is lower than that of its melting point of 2899 K. Distribution of temperature in a thrust chamber with respect to the nodal distance at coolant channel inlet in model-D for Nickel, Copper and Zirconium materials were shown in figure 8 (a), 8 (b) and 8 (c) correspondingly.

**Figure 8.** Temperature distribution with respect to the nodal distance at coolant channel inlet in model-D for (a) Nickel (b) Copper (c) Zirconium material

In the graphical plot, distributions of temperature with respect to the nodal distance were depicted clearly. It has observed from the graphical plot, distribution of temperature from the gases to the thrust chamber’s inlet portion has increased with respect to the increasing nodal distance. From the temperature distribution and nodal distance plot that has represented in figure 8 (a), it has observed that the cooling wall, which has analysed with Nickel material, can withstand the maximum temperature of 1666 K at the thrust chamber’s inlet, whereas this maximum temperature value is lower than that of its melting point of 2500 K. From the temperature distribution and nodal distance plot which is represented in figure 8 (b), it has observed that the cooling wall, which has analysed with Copper material, cannot withstand the maximum temperature of 1415 K at the thrust chamber’s inlet due to the exceeding its melting point. From the temperature distribution and nodal distance plot that has represented in figure 8 (c), it has observed that the cooling wall, which has analysed with Zirconium material, can withstand the maximum temperature of 2500 K at the thrust chamber’s inlet, whereas this maximum temperature value is lower than that of its melting point of 2899 K. Temperature distribution over the throat and inlet portion of the thrust chamber’s cooling wall surfaces for the Model-C by changing the cooling wall’s material were illustrated in figure 9 (a) and figure 9 (b) respectively. Temperature distribution over the outlet portion of the thrust chamber’s cooling wall surfaces for the Model-C by changing the cooling wall’s material were illustrated in figure 9 (b). It has observed from the detailed colour plots, temperature distributions were found maximum at the inner surface of the combustion chamber’s cooling passage wall. Conversely, the temperature distribution over the combustion chamber’s wall has found minimum with respect to the increasing distance from the throat portion.
Figure 9. Temperature distribution in rocket thrust chamber’s half coolant channel for Model-C at (a) throat portion (b) outlet portion

Detailed colour plots, that have attained through heat transfer analysis from ANSYS software for the combustion chamber’s cooling passage geometry at its throat portion for Model-C have depicted in figure 10 (a) to figure 10 (c) respectively. Similarly, distribution of temperature in a thrust chamber with respect to the nodal distance at coolant channel throat in model-C for Nickel, Copper and Zirconium materials were shown in figure 10 (a), 10 (b) and 10 (c) respectively. In the graphical plot, distributions of temperature with respect to the nodal distance were depicted clearly. It has observed from the graphical plot, distribution of temperature from the gases to the thrust chamber’s throat portion has increased with respect to the increasing nodal distance. From the temperature distribution and nodal distance plot that has represented in figure 10 (a), it has observed that the cooling wall, which has analysed with Nickel material, can withstand the maximum temperature of 1666 K at the thrust chamber’s throat portion, whereas this maximum temperature value is lower than that of its melting point of 2500 K. From the temperature distribution and nodal distance plot that has represented in figure 10 (b), it has observed that the cooling wall, which has analysed with Copper material, can withstand the maximum temperature of 1269 K at the thrust chamber’s throat portion, whereas this maximum temperature value is lower than that of its melting point of 1358 K. From the temperature distribution and nodal distance plot that has represented in figure 10 (c), it has observed that the cooling wall, which has analysed with Zirconium material, can withstand the maximum temperature of 2500 K at the thrust chamber’s throat portion, whereas this maximum temperature value is lower than that of its melting point of 2899 K.

Figure 10. Temperature distribution with respect to the nodal distance at coolant channel throat in model-C for (a) Nickel (b) Copper (c) Zirconium material

From the temperature distribution and nodal distance plot that has represented in figure 10 (c), it has observed that the cooling wall, which has analysed with Zirconium material, can withstand the maximum temperature of 2500 K at the thrust chamber’s throat portion, whereas this maximum temperature value is lower than that of its melting point of 2899 K. Detailed colour plots, that have attained through heat transfer analysis from ANSYS software for the combustion chamber’s cooling
passage geometry at its outlet portion for Model-C have depicted in figure.11 (a) to figure.11 (c) respectively. It has observed from the detailed colour plots, temperature distributions were found maximum at the inner surface of the combustion chamber’s cooling passage wall. Conversely, the temperature distribution over the combustion chamber’s wall has found minimum with respect to the increasing distance from the outlet portion. Similarly, distribution of temperature in a thrust chamber with respect to the nodal distance at coolant channel outlet portion in model-C for Nickel, Copper and Zirconium materials were shown in figure.11 (a), 11 (b) and 11 (c) respectively. In the graphical plot, distributions of temperature with respect to the nodal distance were depicted clearly. It has observed from the graphical plot, distribution of temperature from the gases to the thrust chamber’s outlet portion has increased with respect to the increasing nodal distance.

Figure 11. Temperature distribution with respect to the nodal distance at coolant channel outlet in model-C for (a) Nickel (b) Copper (c) Zirconium material

From the temperature distribution and nodal distance plot that has represented in figure.11 (a), it has observed that the cooling wall, which has analysed with Nickel material, can withstand the maximum temperature of 1666 K at the thrust chamber’s outlet portion, whereas this maximum temperature value is lower than that of its melting point of 2500 K. From the temperature distribution and nodal distance plot that has represented in figure.11 (b), it has observed that the cooling wall, which has analysed with Copper material, can withstand the maximum temperature of 1269 K at the thrust chamber’s outlet portion, whereas this maximum temperature value is lower than that of its melting point of 1358 K. From the temperature distribution and nodal distance plot that has represented in figure.11 (c), it has observed that the cooling wall, which has analysed with Zirconium material, can withstand the maximum temperature of 2500 K at the thrust chamber’s outlet portion, whereas this maximum temperature value is lower than that of its melting point of 2899 K.

5 Conclusion

After the series of thermal analysis, which has conducted to optimize the better coolant shapes in a rocket engine thrust chamber, the following conclusions were made. Coolant shapes of circle, rectangle with greater breadth (d>b) and rectangle with filleted edges fail in the copper region due to the inability of coolant to reach the maximum copper region. Later, rectangle shape was considered with greater depth (d>b) so that the coolant could reach the copper region to the maximum extent as only copper was the area of concern analysis. Analysis results showed the successful configuration for generatively cooled rocket thrust chamber must have the coolant passage shape of rectangular cross
section with greater depth (b > d). This shape will have the greater influence of coolant to suppress the heat conduction along thrust chamber wall, especially in copper region.

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