Effect of Different Materials and Coolant Channel Configurations on the Performance of Actively Cooled Panels

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Abstract: ***The combustor liners of high speed combustion chamber are subjected to high thermal loads. Active cooling of such liners is seen as a viable option and research in this area is currently underway in many countries due to the advantages it offers. The main method of heat transfer is the regenerative cooling, where in coolant is passed through the channels provided in the combustion liner. But, the configuration of such liners has to be optimized in terms of providing desired cooling efficiency with the given mass flow rate of the coolant, so as not to carry the coolant more than required and keep the weight per unit area under control. The cooling efficiency is mainly dependent on several factors, which include the properties of material, dimensions of the cross-section of the flow, shape of the channel, mass flow rate of the coolant. For the current investigation different candidate high temperature materials and channel shape combinations are investigated for their thermal performance to effectively remove the high heat flux. The comparison brings out the most efficient material cum configuration suitable for application to the high speed combustion chamber. In the initial study, various configurations are verified based on minimum weight per unit area with the help of 1D MATLAB program and the results are further validated for the suitable configurations using ANSYS CFX. It was found that at high heat fluxes Nb-Cb752 can serve at lower mass flow rates.GRCop-84 material is found to compete with Nb-Cb752 in terms of the mass flow rate required. For a given mass flow rate, Inconel X-750 has the lowest weight per unit area compared to the other materials. Parabolic shape has been found to effective followed by Trapezoidal and rectangular shapes. So, it is important that the combination of the material and channel configuration play a significant role in the design of efficient heat exchanger of a high speed combustion chamber.***

Keywords: active cooling, channel configuration, high speed combustion chambers, high temperature materials

1.Introduction

The cooling of a high speed combustion chamber used in aerospace applications is quite a challenge. The major constraint is the weight which rules out the use of traditional cooling options. Thus active cooling technique is a viable option. In active cooling, hydro-carbon fuel is used as a coolant and hence no additional coolant is required to be carried on board. The coolant is passed through a narrow channel inside the combustor panel to absorb the combustion heat. Use of hydrocarbon fuel as coolant has the advantage of augmenting the heat sink capacity. Additional heat is absorbed as the fuel undergoes endothermic reaction known as thermal cracking. In this at elevated temperatures long chain free molecules are broken into smaller ones. The major challenge is the design of the cooling channel configuration, which can effectively transfer the heat at low coolant flow rates and has the lowest metal weight. Many proposals have been made, to arrive at a suitable configuration which can effectively cool the high heat fluxes encountered during the combustion.

Valdevit et al. [1] have shown that the geometry of the coolant channel, the thermo-physical properties of the coolant, material of the combustor and the conditions prevailing in the combustion chamber influence the heat transfer rates. They have carried out parametric studies for different materials for rectangular channels, over a range of geometric parameters, heat transfer coefficients and various coolant flow rates inside the channel. Here the cooling strategy mainly focused on the usage of sensible heat of the fuel to cool the panel. Thermal Barrier Coatings (TBCs) are also used to reduce the heat load reaching the surface of the panel.

The purpose of the present paper is to study the influence of thermo-physical properties of different materials and the geometric parameters of various geometric shapes on the cooling efficiency. The objective is to identify the combination of material and cooling channel shape, which minimizes the coolant flow rate required and reduce the overall weight. The objective set above is achieved by investigation of cooling efficiencies for the combination of material and channel shapes through a 1D heat transfer MATLAB program developed using fin analogy considering the walls of the channel as fins. With the help of this program various shapes and materials combinations are verified to arrive at the optimal dimensions for each shape and material combination. The approach for writing this program is similar to that of Valdevit et al [1]. Once the optimal material and shape configurations are selected, rigorous 3D CFD analysis is performed to validate the results. The hydrocarbon fuel JP-7 is used as a coolant throughout this investigation.

The structure of the paper is as follows:

- An overview of different high temperature materials chosen for study is presented.
- An overview of the MATLAB program written for 1D analysis for various channel shape configurations.
- Results from MATLAB program are presented and design graphs created for the combination of shapes and materials for minimum weight per unit area and coolant flow rates.
- For the selected material and channel configurations, 3D CFD analysis is carried out to validate the MATLAB results using ANSYS-CFX.
- The above analysis is followed by the conclusion and discussion.

Overview of High Temperature Materials

Material temperature limit for high temperature applications plays an important role. Some of the important aspects while considering the materials for high temperature application include metallurgical stability at elevated temperatures, resistance to oxidation and creep resistance. Majority of the applications involving high temperature materials are for the aerospace domain, where the weight is premium. Hence, some of the alloys such as Tungsten alloy, which can withstand high temperatures but are not suitable, as they are heavy. On the other hand the refractory materials do not have sufficient strength to withstand the loads which are encountered during the operation. Research is undergoing in many countries for developing better materials which are lighter and stronger at elevated temperatures. The materials listed in Table I are considered for investigation in this paper due to their widespread consideration for high temperature applications and the availability of the material properties in the literature.

Below is the short summary of these materials used in the present work.

- GRCop-84 (Cu-8 at.% Cr-4 at.% Nb): It is a copper-based alloy. David [2] of NASA has investigated the properties of this alloy and found that it is particularly suitable for high heat flux applications due to excellent elevated temperature strength, good creep resistance, long low-cycle fatigue (LCF) lives and enhanced oxidation resistance. It is suited for applications up to approximately 973 K. Its manufacturability using standard techniques and not necessitating any special manufacturing process are noteworthy.
- Nickel based super alloy – Inconel X-750: NICKEL-BASED super alloys [3] [4] are metallic materials with an exceptional combination of high temperature strength, toughness, and resistance to degradation in corrosive or oxidizing environments. These materials are widely used in aircraft and power-generation turbines, rocket engines, and other challenging environments, including nuclear power and chemical processing plants. Intensive alloy and process development activities during the past few decades have resulted in alloys that can tolerate average temperatures of 1050°C with occasional excursions (or local hot spots near airfoil tips) to temperatures as high as 1200°C, which is approximately 90% of the melting point of the material. The underlying aspects of microstructure and composition also play an important role in the strength of the Nickel based super alloys.
- Nb-Cb752: It is a Niobium alloy which has good strength at high temperature.

2. Overview of 1D MATLAB program

The thermal resistance network shown in the figure 1 is considered for obtaining the temperatures at various point on the channel. The 1D MATLAB evaluates the temperatures based on the fin analogy with the boundary condition that one end of the fin is insulated. MATLAB code is used as a tool to compare the material and shape configurations. The figure 2 shows the flow chart for MATLAB program. For the given geometry parameters, boundary conditions such as adiabatic wall temperature, heat transfer coefficients on the coolant side and combustion side, the amount of the coolant mass flow required to keep the maximum temperature of the metal within the material temperature limit is obtained. Predictably maximum temperature occurs at the combustion side of the channel and hence this temperature is an important measure to check, in the design of a suitable configuration. The MATLAB program is adapted to incorporate the resistances of various fin shapes such as rectangular, triangular and parabolic so that different material and channel configuration can be compared. Due to the incorporation of the above mentioned fin shapes totally four channel shape geometries viz., rectangular, Trapezoidal, parabolic and triangular, are obtained as shown in figure 3. The analysis is done for a single channel of length 0.7 m. The inputs required are the realistic adiabatic wall temperature (Taw), wall temperature on the combustion side (Tw), heat transfer coefficient on both combustion side (hG) and the coolant side (hc), coolant flow rate per unit width (Veff), inlet temperature of the coolant (Tfuelinlet) as encountered in experimental test conditions.

Table 1: Material Properties

Material	*Usage Temperature (K)*	*Density (Kg/m3)*	*Coefficient of thermal expansion (10-6 / K)*	*Coefficient of thermal conductivity (W/m2K)*
GRCop-84	973	8756	19	285
Nb-Cb752	1470	9030	7.4	50
Inconel X-750	1100	8276	16	23

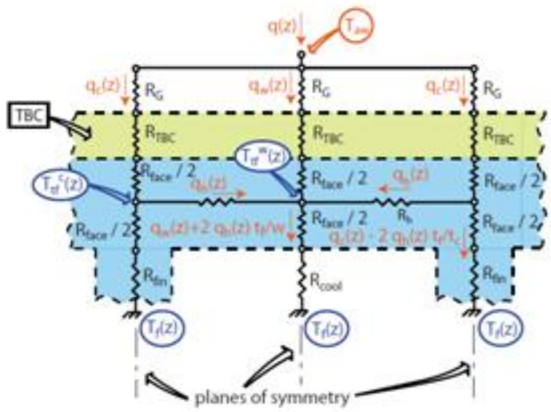


Figure 1: Thermal resistance network used for evaluation of temperatures (Courtesy: Valdevit et al. [1])

The convective and conductive thermal resistances are given below:

$$RG = \frac{1}{hG}$$

$$Rface = \frac{tf}{Ks}$$

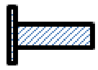
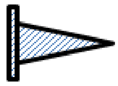
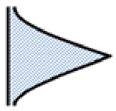
$$Rh = \frac{(w + tc/2)}{4Ks}$$

$$Rcool = \frac{1}{hc}$$

$Rfin$ = Resistance of fin is based on the shape of the fin from [5] are given in Table 2

RTBC = Resistance due to the thermal barrier coating is not considered for the current investigation.

Table 2: Fin Resistances of different shapes

Fin Type	*Resistance of Fin (Rfin)*	*Area of fin (Af)*
Rectangular fin 	$\text{Rfin} = \frac{ml}{hc\ Af \tanh(ml)}$ $m = \left[\frac{2\ hc}{k\ tc}\right]^{0.5}$	$Af = 2l;$
Triangular fin 	$\text{Rfin} = \frac{[ml\ I0(2ml)]}{hc\ Af\ I1(2ml)}$ $m = \left[\frac{2\ hc}{k\ tc}\right]^{0.5}$	$Af = 2w\left[\left[l^2 + \left(\frac{t_c}{2}\right)^2\right]^{0.5}\right]$
Parabolic fin 	$\text{Rfin} = \frac{[(4m\ l^2+1)^{0.5}+1]}{2\ hc\ Af}$ $m = \left[\frac{2\ hc}{k\ tc}\right]^{0.5}$	$Af = \left[\left[1+\left(\frac{t_c}{l}\right)^2\right]^{0.5} l + \left[\frac{l^2}{tc}\log\left(\frac{t_c}{l}\right) + \left[1+\left(\frac{t_c}{l}\right)^2\right]^{0.5}\right]^{0.5}\right]$

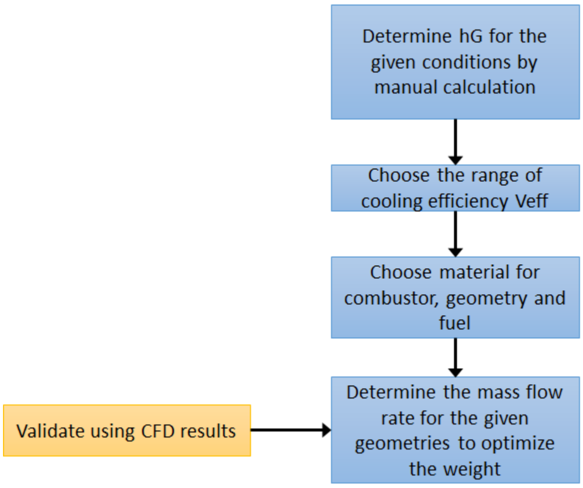


Figure 2: Flow chart of 1-D Matlab program

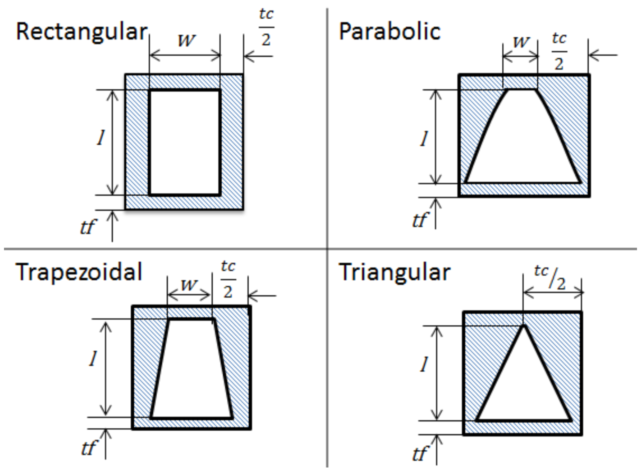


Figure 3: Different channel shapes used in the investigation

The heat transfer coefficient on the combustion side 'hG' is calculated using Eckert's Reference Enthalpy method [6]. The conditions considered on the combustion chamber side are that of prevailing in the actual scenario. On the coolant side the inlet temperature is 300 K. The heat transfer coefficient inside the coolant channel is obtained from the Gnielinski correlation. For any given channel configuration, the mass flow rate required is calculated such that the temperature of the channel is within the material temperature limit for a given length of the channel (Z).

The Matlab results are obtained for a range of values based on the manufacturing constraints. The channel width 'w' is varied from 0.00125 m to 0.0035 m except in case of triangular channel where channel width is zero, core thickness 'tc' is varied from 0.00125 m to 0.0025 m. The rest of the geometric parameters such as face thickness 'tf', flow channel height 'l' are maintained at 0.0015 m and 0.005 m respectively. The coolant flow rate per unit width of the combustor is varied between 0.002 m^2/s to 0.007 m^2/s.

Then the results are compared for the minimum weight per unit area. The minimum weight corresponds to the combined weight of the channel and fuel. This is in contrast to the graphs generated by Valdevit et al [1] shown in figure 6, where only the metal weight is considered for optimum weight comparison. The consideration of the weight of fuel is made since, the fuel weight adds up to the significant weight penalty. Hence the analysis is carried out by considering weight of the fuel and the metal. The section below describes how the weight per unit area is calculated in this paper. If a panel of width 'B' is considered, the width of the each channel is b = w+tc and length of the channel is 'Z'. Figure 5 shows the typical combustor panel and explains the notations described above. Number of channels for the given width of the panel are N = B/b. The number will be rounded off to the nearest integer. Then metal volume of the panel is calculated. The weight of the panel (WPanel) is volume times the density. The weight of the fuel (Wfuel) is the fuel required for the given duration of operation, say t seconds. Then the total weight of the fuel required is mass flow rate times the duration.

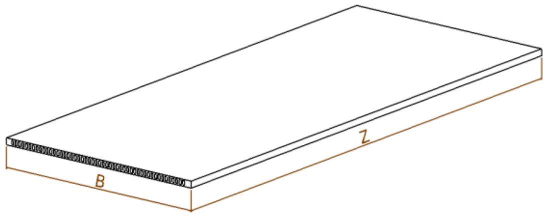


Figure 5: Combustor panel

The two quantities WPanel and Wfuel are summed up to obtain the total weight (Wtotal). The surface area is calculated by the product of B and Z. Weight per unit area is obtained by dividing the total weight by the surface area = Wtotal / (B*Z).

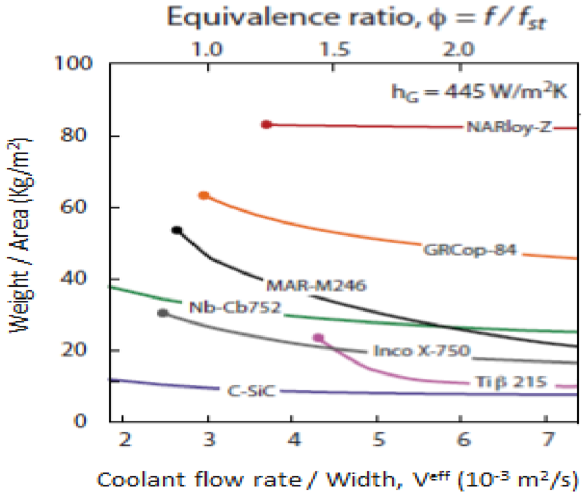


Figure 6: Minimum Weight comparison at hG = 445 W/m2K (Courtesy: Valdevit et al.[1])

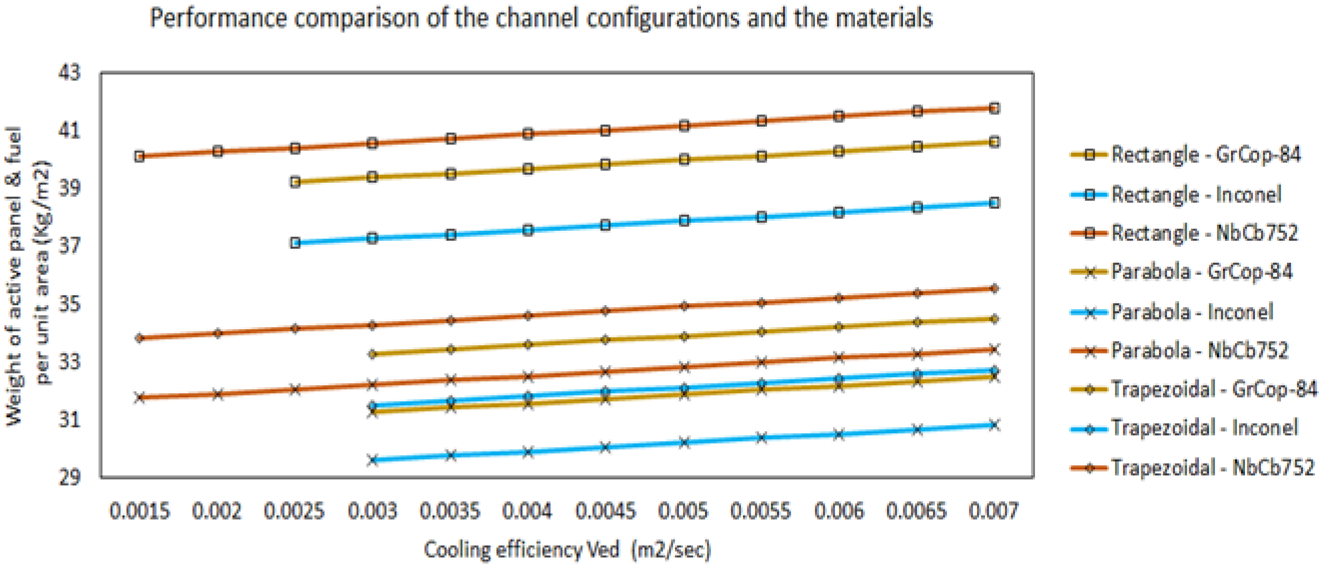


Figure 4: Minimum weight comparison at the heat transfer coefficient hG = 697.5 W/m2K for the different channel configurations viz., Rectangular, Trapezoidal, Parabolic (only heat transfer considerations)

2.1 MATLAB Results

The graph in figure 4 shows the comparative analysis of the minimum weight per unit area of different material and channel shapes combinations.

- The acceptable configuration in case of Nb-Cb752 has started at a very low flow rate. That implies that even at lower flow rates the cooling efficiency is sufficient to keep the temperatures below the material temperature limit. This is mainly attributed to the high material temperature limit of the Nb-Cb752 material.
- In case of GRCop-84 the material temperature limit is 973K, which is much lesser than the Inconel and Nb-Cb752. But, the coolant flow rate required is starting from Ved = 0.0025 m^2/s, which is comparable to that of Inconel X-750. This could be due to the high thermal conductivity of GRCop-84 which is allowing it to conduct more heat at lower mass flow rates.
- It can be observed that Inconel X-750 and GRCop-84 have been found to serve better at lower heat fluxes, while Nb-Cb752 is better at higher heat fluxes.
- For a given mass flow rate, Inconel X-750 has been found to be advantageous over other two, when compared in terms of the weight per unit area. This might be because, the given flow rate is in excess of the coolant required to keep the metal just below the temperature limit, which can be observed in the case of Nb-Cb752. Therefore, it cannot be concluded that Inconel X-750 is the best choice among the materials and choice should be made based on the coolant availability and the heat fluxes that are encountered during the operation.
- When it comes to shape, parabolic shaped fin has been observed to have the lowest weight per unit area followed by Trapezoidal and rectangular channel configurations.
- In terms of both material and channel configuration InconelX-750 has the lowest weight per unit area among the three shapes followed by GRCop-84 and Nb-Cb752 materials. This could be due to the use of mass flow rate in excess of the required fuel.
- When comparison is made between the figure 4 and figure 6, it can be observed that, while making a choice based on the weight per unit area, it can be seen that coolant flow rate is also an important component and that weight of the metal

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alone cannot be taken as a criteria. At higher coolant flow rates and longer duration of operation overall weight increases adding up to the weight penalty.

- The triangular configuration does not figure in the graph as it requires more coolant flow rate than the specified range to achieve the cooling efficiencies comparable to the other configurations. Hence, triangular configurations is discarded for further study.

The above result helps to give an overview of the comparative performance of different materials and channel configurations. Moreover, the above comparison is based on the thermal performance, but in reality, structural performance is also to be considered. The thermo-structural performance will be dealt with in the subsequent papers.

3. CFD Analysis

To extend the analysis and validate the above results, 3D CFD analysis is performed using ANSYS CFX. Analysis is carried out for the rectangular and Trapezoidal configurations. The parabolic configuration is excluded, even though it has the highest performance due to its complicated shape and manufacturing constraints. The triangular configuration was discarded due to its non-viability at mass flow rates in the given range. The channel configurations are chosen such that they have constant width of the (w + tc) and has the same area of cross section (same volume of metal) for both rectangle and trapezoidal configurations, in order to make the channel configurations comparable. The simulations are performed such that minimum mass flow rate required to keep the metal temperature just below the material temperature limit as highlighted in Table III.

Boundary Conditions:

- Inlet Boundary condition:
  - Mass flow inlet
  - Temp = 300 K
  - Pressure = 3e6 Pa
- Outlet Boundary Condition:
  - Pressure Outlet
- Combustion side of the channel
  - Heat transfer coefficient(hG)- 697.5 W/m2K
  - Adiabatic Wall Temperature – 3297 K

Materials:

- Channel Material - Inconel X-750, Nb-Cb752 , GRCop-84
- Coolant - JP-7

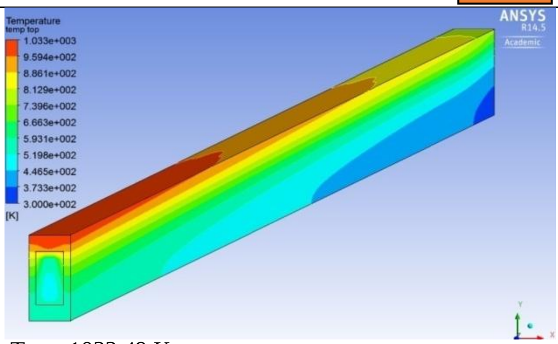
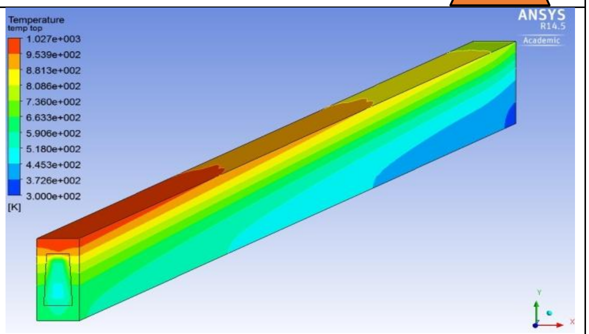
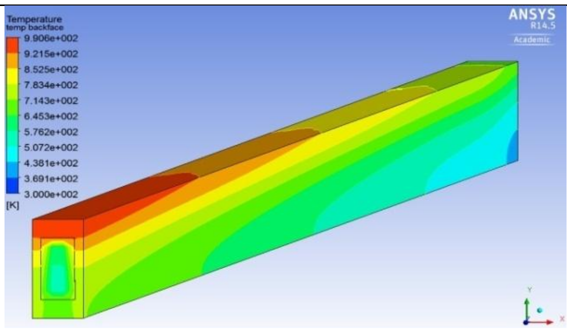
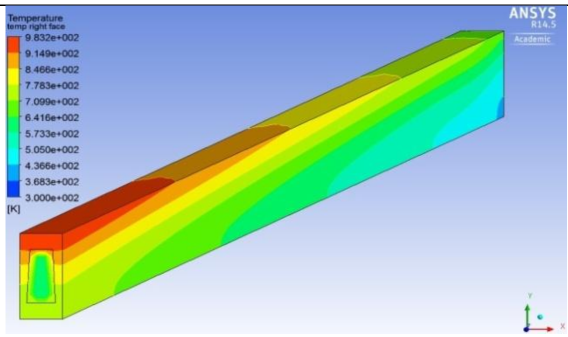
Turbulence Model: K-Є Turbulence model is used

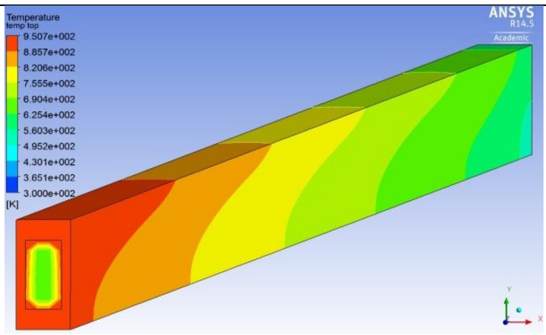
Type of analysis: Transient analysis

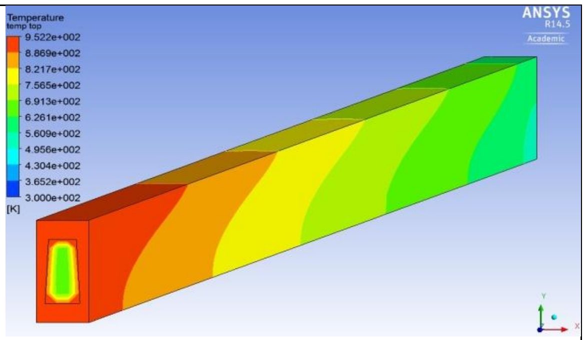
3.1 Results and Discussion

The following section describes the results obtained from the CFD simulation. In order to make the results comparable weight per unit area is obtained by considering the same width of the panel 'B' as that of considered for generating the weight per unit area in the MATLAB program and for operation time of 30seconds. It has been observed that all the configurations are achieving steady state by 30seconds.

Table 3: CFD results for different material and channel shape combinations

Material Description	Rectangular Configuration 	Trapezoidal Configuration 
Inconel X-750	 Tm = 1033.49 K ṁ = 0.0075 Kg/s Tf = 948.96 K	 Tm = 1025.94 K ṁ = 0.007 Kg/s Tf = 944.26 K
NbCb-752	 Tm = 990.5 K ṁ = 0.006 Kg/s Tf = 948.6 K	 Tm = 983.1 K ṁ = 0.005.7 Kg/s Tf = 948.14 K

<table>
<tr>
<td>GRCop-84</td>
<td>

Tm = 950.72 K
ṁ = 0.0049 Kg/s
Tf = 940.9 K</td>
<td>

Tm = 952.16 K
ṁ = 0.0047 Kg/s
Tf = 946.48 K</td>
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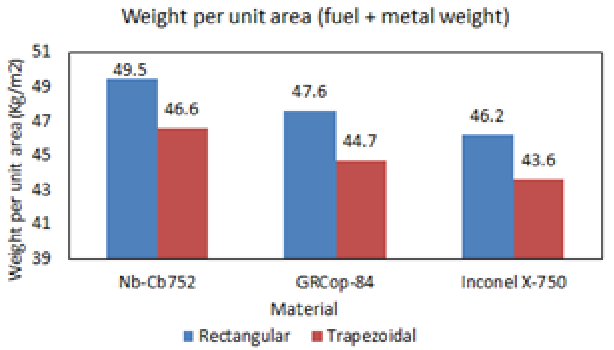

Figure 7: The graph compares the weight per unit area of rectangular and trapezoidal channel configurations for the three different materials Inconel X-750, Nb-Cb752, GRCop-84.

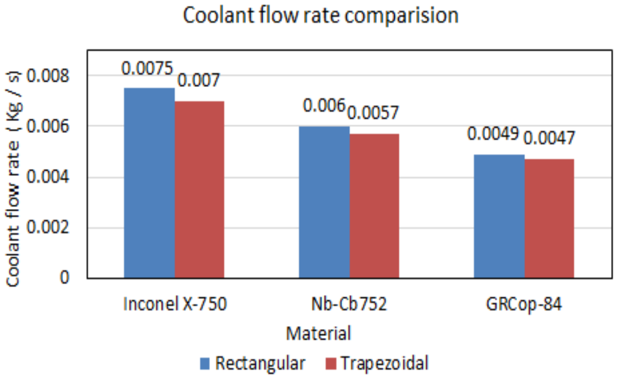

Figure 8: Graph compares the coolant flow rate of rectangular and trapezoidal channel configurations for the three different materials Inconel X-750, Nb-Cb752, GRCop-84.

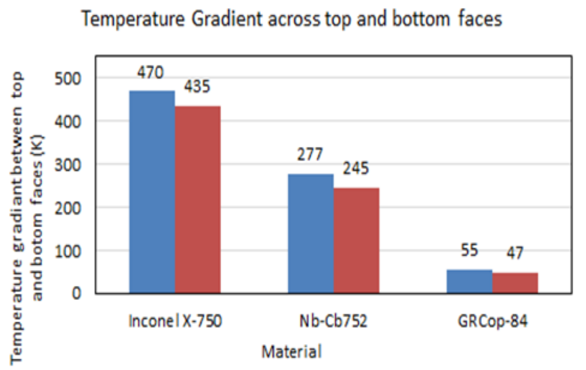

Figure 9: The graph compares the temperature gradient between top and bottom faces at the outlet section of the channel.

Effect of shape: Between rectangular and trapezoidal shapes, latter has the advantage across all the materials as it requires low coolant mass flow as shown in figure 8. This is due to the higher contact surface area available for Trapezoidal shape than the rectangular shape. Thus aiding to remove more heat. The Trapezoidal with GRCop-84 combination requires lowest mass flow rate among all the combinations investigated. Thus contributing to the lowest weight per unit area. These results confirm the results obtained from MATLAB, that trapezoidal channel has better performance than that of rectangular channel in terms of weight per unit area in all materials considered as shown in figure 7.

Effect of materials: As shown in figure 7 Inconel has the lowest weight per unit area for the given operation time, which corroborate the MATLAB result. But, when the results are extrapolated for longer operation times, a reverse trend is observed and that GRCop-84 is found to have the lowest weight per unit area followed by Nb-Cb752 and Inconel X-750 because in case of GRCop-84 requires lower mass flow rates when compared to other materials. Thus for longer duration, weight of the fuel plays an important role. These results highlight the importance of considering the weight of the fuel when comparing the performance of different material and channel shape combinations.

From figure 9, it can be observed that the temperature gradient across the top and bottom faces is minimum for GRCop-84. The gradient is taken at end of the channel, where temperatures of both material and fuel are the highest. This aspect is important as thermal stresses are proportional to the gradient across the panel. Lower temperature gradient contributes to lower thermal stress.

4. Conclusions

The combination of the channel configuration and the material has a profound effect on the cooling efficiency and that coolant flow rate along with operation time plays a vital role to arrive at the minimum weight configurations.

- GRCop-84 requires 34% less coolant flow rate and Nb-Cb752 requires 32 % less coolant flow rate when compared to the Inconel X-750. It leads to the observation that while Nb-Cb752 and GRCop-84 are viable alternatives at lower coolant mass flow rates.
- Among the configurations compared, the Trapezoidal with GRCop-84 material has the best performance and requires 37% lesser mass flow rate than the Inconel X-750

rectangular configuration which needs the highest coolant flow rate among all the configurations compared.

The above analysis provides an insight on the impact of the material and the shape of the channel to effectively design actively cooled panel.

References

[1] Lorenzo Valdevit, Natasha Vermaak, Frank W. Zok and Anthony G. Evans, "A materials selection protocol for light weight actively cooled panels," Journal of applied mechanics, vol. 75, pp. 061022-1 – 061022-15, 2008.
[2] Tresa M. Pollock, Sammy Tin, "Nickel-Based Superalloys for Advanced Turbine Engines: Chemistry, Microstructure, and Properties," Journal of propulsion and power, (22) No. 2, pp. 361-374, 2006.
[3] David L. Ellis, "GRCop-84: A High-Temperature Copper Alloy for High-Heat-Flux Applications", NASA/TM—2005-213566, 2005.
[4] www.specialmetals.com INCONEL® alloy X-750 (UNS N07750/W. Nr. 2.4669)
[5] Heat and Mass Transfer by Frank P. Incropera, David P DeWitt, Fifth edition, John Wiley & Sons, Inc., pp.141
[6] Robert D. Quinn and Leslie Gong, "Real time aerodynamic heating and surface temperature calculation for hypersonic flight simulations," NASA technical memorandum, 4222, 1990.