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Material Selection and Structural Integration of Actively Cooled High Speed Combustion Chamber☆

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Abstract

Thermal management in the supersonic combustion chambers subjected to high heat fluxes is vital for maintaining their integrity. At high temperatures ordinary materials cannot sustain the high heat loads. On the other hand, the prevailing high temperature gradients, necessitates the provision for expansion to avoid build of thermal stresses for the integration. Hence, thermal management needs a holistic approach encompassing the areas of material selection, heat transfer and structural integration. The current state of art research is focused on achieving this by active cooling through endothermic fuel, which is used as a coolant due to the advantages such as reduced weight and improved heat sink capacities. Particularly the space applications pose serious limitations on the weight. 1D thermo-structural hand calculations can be easy point to start with to arrive at the optimized shape of the single actively cooled channel. But the underlying assumptions and owing to the 1D nature of the such calculations, pose limitation towards understanding the behavior of the active panel as a whole and achieving the practical integration strategy. Therefore, there is need to perform 3D CFD and FEA thermo-structural analysis of the active panel structure. This paper extends upon the approach of 1D analytical material selection methodology through weight optimization followed by rigorous CFD and FEA analysis to understand and device ways for structural integration for long duration flight of about 600 seconds.

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Keywords: Active Panel Cooling; Combustoin Chamber; Material Selection; Structural Integration;

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1. Introduction

High speed travel by supersonic vehicles need effective thermal management. The combustion gases inside the combustion chamber impose high heat fluxes on its walls. Active cooling, is proposed to be a suitable solution for effective thermal management wherein the endothermic fuel is used as coolant. The use of endothermic fuel, provides additional heat sink capacity in the form of chemical heat sink due to cracking apart from the physical heat capacity of the fuel. Hence, it can reduce the amount of coolant to be carried on board and thus the overall weight of the vehicle. In the active cooling, channels of suitable shape are provided inside the panel through which the coolant is passed as shown in Fig. 1. As the coolant passes through the channel, it absorbs the heat impinging on the surface of the chamber. Thus providing the necessary cooling for the combustion chamber.

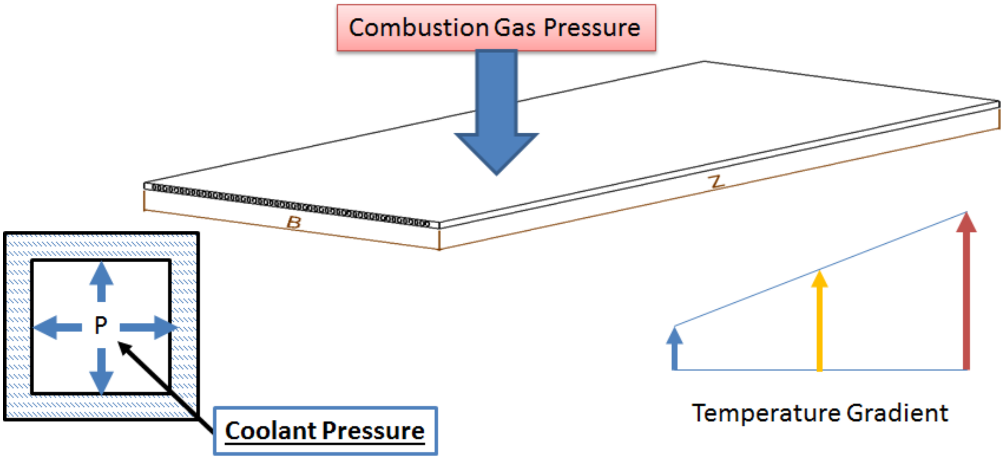

Fig. 1. Actively Cooled Panel

The purpose of the present paper extends on the approach of the 1D analytical model to arrive at the suitable material and shape of the active cooling channel, followed by 3D CFD and FEA thermo-structural analysis to gain further insights. This analysis is important since the assumptions underlying the 1D analytical approach do not capture accurately the transient response of the structure to the thermal and structural loads for long duration flights. This limitation has to be overcome before going for practical implementation.

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 all influence the heat transfer rates. Parametric studies of rectangular channels were performed, for a range of geometric parameters and heat transfer coefficients. Thermal Barrier Coatings (TBCs) were also found to be beneficial to increase the feasibility of the actively cooled panel. Young et al. [2] optimized the cooling panel satisfying hydrodynamic, thermal and Mach number constraints.

Siva Karthik et al. [2-4] have compared different high temperature materials such as Inconel X-750, NbCb-752 and GrCop-84 with two different geometric shapes viz., rectangular and trapezoidal to identify the most suitable material cum shape of the active cooling channel suitable for the application. It was observed that NbCb-752 with rectangular channel configuration was found to be more suitable in terms of overall panel plus coolant weight per unit area and the coolant flow rate required for the given heat loads and duration of the time.

Young et al. [5] optimized the cooling panel satisfying hydrodynamic, thermal and Mach number constraints.

2. 3D Numerical Analysis

The combustion chamber of the hypersonic vehicle is attached to the belly of the vehicle as shown in the Fig. 2. In the work, so far, the active cooling channel geometry was optimized based on the 1D analytical calculation corroborated with 2D numerical thermo-structural analysis assuming plane strain conditions [3] [4]. The optimized channel geometry is used to construct the active panel, which forms the combustion chamber. The 1D and 2D approaches are a quick way to arrive at the suitable configuration for the actively cooled panels. It evaluates the temperatures based on the fin analogy with the boundary condition that one end of the fin is insulated and the stresses due to the thermal and pressure loads are evaluated based on plane strain condition. MATLAB program is used to verify various configurations based on the manufacturing constraints, to obtain the amount of the coolant mass flow required to keep the temperatures of the metal and coolant within the material limit and the Von-Mises stresses are within the yield limit of the given material.

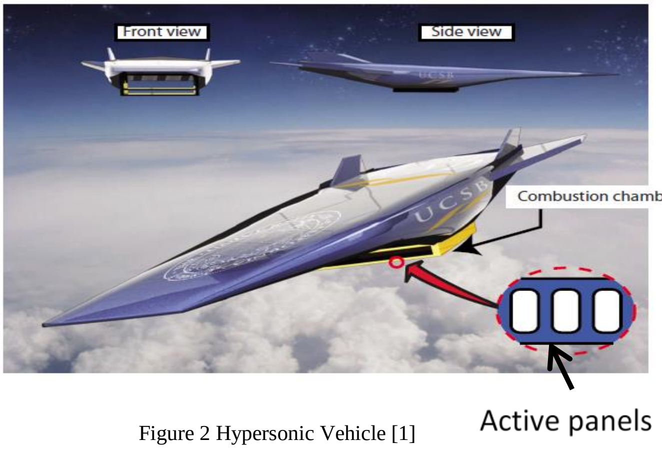

Figure 2 Hypersonic Vehicle [1]

Fig. 3. provides the performance maps derived from the 1D MATLAB analytical calculations for the materials Inconel X-750 [6] & NbCb-752 [1] and the shapes such as rectangular and Trapezoidal channels. From the graph it can be observed that the NbCb-752 is most suitable for the application. Also, among the rectangular and trapezoidal configurations the former is found to be more suitable due to the lowest coolant flow requirement and the lowest overall weight per unit area. Considering the optimized material cum configuration of the coolant channel a combustion chamber is modelled with the actual dimensions as per Fig. 4. Full scale 3D combustion chamber is shown in Fig. 5.

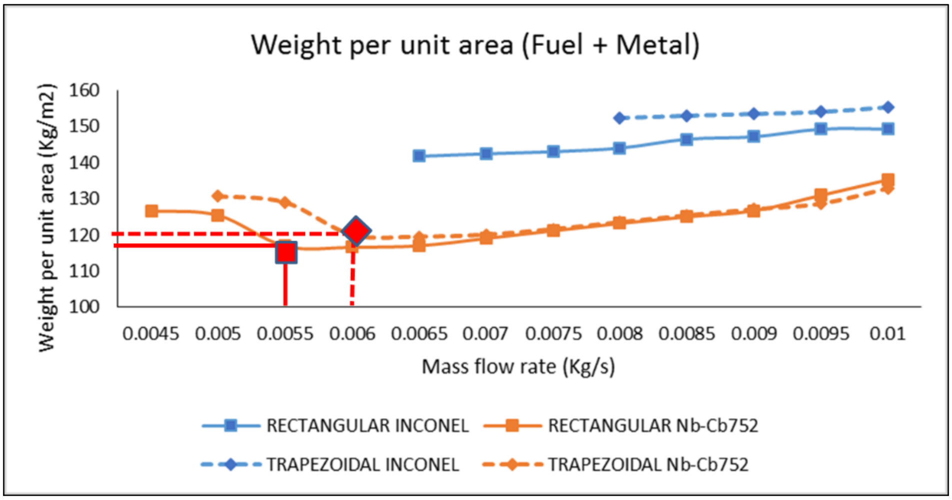

Fig. 3. Overall Weight per Unit Area Vs Mass Flow Rate

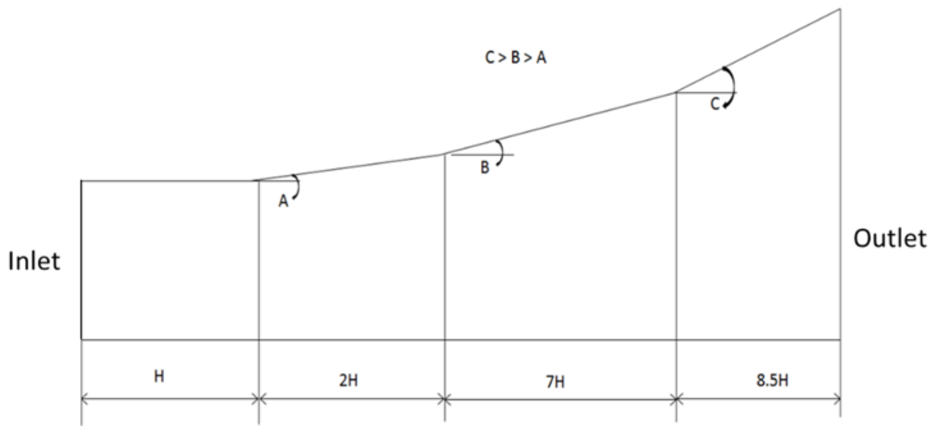

Fig. 4. Combustor Flow Path

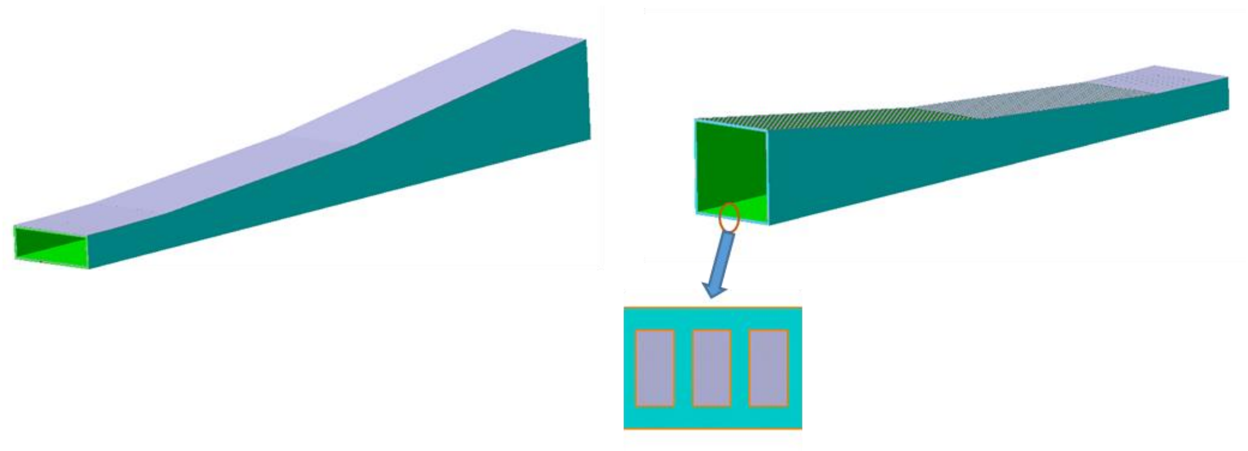

Fig. 5. Combustion Chamber with optimized cooling channel

3. Thermo-Structural Analysis:

The top panel is simulated with displacement boundary conditions since this portion is expected to form the integration interface between the engine and the vehicle as shown in the Fig. 2.

3.1. Thermal Analysis

To estimate the temperatures across the combustion chamber, the following heat transfer coefficient and adiabatic wall temperatures are needed to define the convective boundary conditions in Fluent. Fig. 6. represents a general distribution of both these variables on the top of the panel.

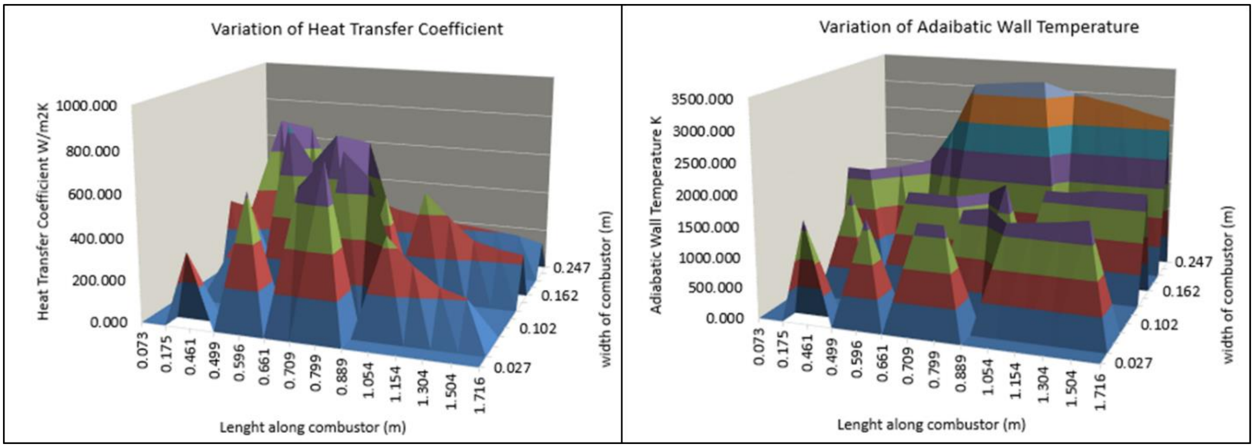

Fig. 6. Heat Transfer Coefficients and Adiabatic Wall Temperatures

Considering the optimized mass flow rate obtained from the 1D analytical calculation, 3D CFD run is given to arrive at the temperature distribution on the panel. The temperature profile obtained from Fluent CFD software for the panel is shown Fig. 7. The combustion chamber reached a maximum steady state temperature of 828 K, after 30 seconds, which is below the material temperature limit of 1400 K for NbCb-752. Also, the coolant has attained the temperature of 700 K which is below it coking limit of 950 K at the outlet. Here the chemical heat sink capacity is ignored as it comes into play after 850 K. But in reality the presence of chemical heat sink can further reduce the coolant mass flow rate and thus lowering the overall weight of the vehicle. The temperatures obtained in the CFD analysis serve as the thermal boundary condition for obtaining stresses during structural analysis.

3.2. Structural Analysis:

The stresses are mainly contributed by the high temperature gradients. Therefore the supports for integration are to be provided to accommodate the thermal expansion. Initially, various set of boundary conditions are tired out to verify various schemes of integration such that the stresses are within the material limits and also allow for thermal expansion. It was expected that the thermal expansion is highest in the longitudinal direction, since, along this direction the thermal gradient is highest and thus any restriction in this direction can lead to build up of stresses leading to the failure of the structure. Based on the FEA analysis the integration scheme which keeps the stresses with in the material limit is chosen for further study. These displacement boundary conditions forms the basis for arriving at the optimum integration scheme. The degrees of freedom are restricted in all the three directions to hold the panel optimally in position. As expected, it is observed that the integration strategy needs to allow for free expansion in the longitudinal direction, while respecting the boundary conditions as shown, in order to keep the structure safe and the stresses within the material limit. The stresses obtained are due to the temperatures obtained at the steady state, which are the highest. The maximum Von-Mises Stress observed is 137 MPa which is well below the yield limit of the material thus keeping the combustion chamber safe. By keeping the stresses below the yield, the flight can be used for multiple number of cycles of operation. Hence, the combustion chamber is safe and suitable for long duration flights. From hand calculation, elongation of the panel subjected to the given thermal gradient:

Length of the panel * coefficient of thermal expansion * thermal gradient

$= l*\alpha*\Delta T = [1.85 * 7.4e\text{-}6* (827 - 337)] = 0.00671$ m (for free thermal expansion).

The maximum displacement from FEA was found to be 0.003 m, which is less due to the restricted movement against free thermal expansion due to the supports. Thus the combustion chamber by proper thermal management constituting the aspects of the material selection, proper integration strategy can maintain the integrity for the given length of operation and sustain for number of cycles of operation.

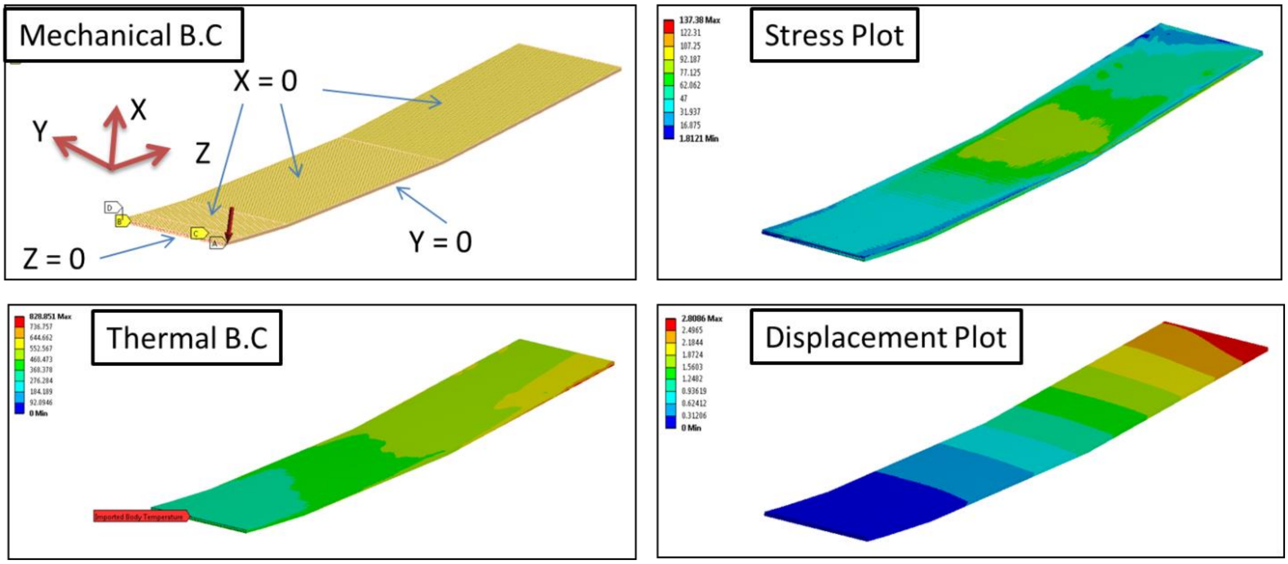

Fig. 7. Idealized Boundary Conditions

Similar analysis was carried out with Inconel X-750 and it was found that the amount of coolant required to keep the structural integrity is 30 % higher than that of NbCb-752. Addition of thermal barrier coatings (TBCs) are also found to lower the coolant flow requirement by as much as 20%.

4. Conclusions

The analysis showed that the integration strategy should take into account the thermal expansion to avoid build-up of stresses due to thermal gradients. Simple 1D and 2D simulation serve to provide a rough approximation, which should be verified by the 3D CFD and structural analysis to understand the behaviour of the structure for a particular integration strategy. Based on 3D simulation, the realistic boundary conditions have to be evolved before the practical implementation. Nb-Cb752 material is found to withstand the heat loads with lower coolant flow rates compared to Inconel X-750. The stress levels on the combustion chamber for the given boundary conditions were found to be within yield limit of the material, indicating that the combustion chamber can be reused for long duration flights of 600 seconds and for multiple cycles.

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