Computational Study of Metal Foam Heat Transfer Efficiency in Scramjet Engines

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ABSTRACT

Hydrocarbon fuel has been widely used in air breathing scramjets and liquid rocket engines as coolant and propellant. However, high heat flux area in scramjet needs active panel cooling with enhanced heat transfer to protect the panel from high temperature. In the present study different candidate high temperature materials and porous medium combinations are investigated for their thermal performance to effectively protect the panel from high heat flux. 3D numerical simulation is carried out to study different schemes of heat transfer enhancement based on type of channel material and porous media in a tube. Both porous medium cases and non porous medium cases are analyzed and compared. The porous medium in the channel decreased the temperature gradient of the fuel across the channel. The porous medium increased the heat transfer coefficient in the channel. Results the heat absorption of the fuel is increased. The results show that heat transfer in the nb-cb 752 with porous medium enhanced at least 4.5 times with the current configuration compared to the clear tube

I. INTRODUCTION

Thermal protection in high speed air-breathing vehicles is the crucial issue. Heat generation is extremely high due to combustion and high Mach number. Active cooling, using circulating hydrocarbon fuel has been considered as the most promising cooling method for the scramjet. Before going to the combustor the fuel flows through the active cooling channel and it absorb the heat from the combustor panel. Enhancement of the heat transfer efficiency of the coolant is a key factor in reducing the material temperature. Heat flux in the scramjet varies between 2 to 220 MW/m^2. Hence, thermal protection is very serious problem. As a result, proper heat transfer enhancement techniques of the active cooling system are of urgent need. Increasing the heat exchange area and surface heat transfer coefficient of the coolant are the valid rules in heat transfer enhancement. Porous medium has tremendous specific area. Hence, it shows an excellent capability in heat transfer enhancement. The effective thermal conductivity of the panel material can be highly increased by a porous medium, like metal foam. Thus, heat transfer enhancement using a porous medium gives beneficial advantage.

Valdevit et.al.[1] shown that the heat transfer characteristics of the coolant effects by the geometric parameters, thermo physical properties of the channel and also Valdevit *et al*. [1] recommended that rectangular channel with hydrocarbon fluid shows much effect on cooling efficiency of the fluid. Many authors studied the effect of porosity on heat transfer analysis in the channel. Jiang *et al*. [6] have conducted the numerical analysis of hydrocarbon fuel with partially filled steel porous medium with 0.8 to 0.9 porosity range with 20 PPI (Pores per unit inch) in steel circular tube and fuel n-decane is the coolant medium. The authors [6] concluded that proper porosity value enhance the heat transfer characteristics. Dukhan *et al*. [7] have conducted the experiment with aluminium metal foam with porosity of 0.876 and 20 PPI with water as medium. Dukhan *et al*. [7] have concluded that fully developed flow with metal foam shows effect on Nusselt number. Results from Vafai and Kim [8] and Mohamad *et al*. [9] found that thickness of the momentum boundary layer depends on both the Darcy number and the inertia parameter.

The purpose of the present paper is to study the heat transfer analysis of the hydrocarbon fluid in the metal foam channel. The objective is to find the efficient material and metal foam combination for a range of porosity values. Comparison is set between considering and without considering metal foam. Investigation starts with 1D analytical analysis (MATLAB) by adapting the approach of Valdevit *et al*. [1]. The programme is used for the range of geometric parameters for different materials and metal foams such as nb-cb 752, Inconel X-750 and Niobium foam respectively. Based on the geometric parameters finalized from 1D analysis, 3D CFD analysis is taken into consideration for a wide variety of porous ranges (range from 0.8 to 0.9) and materials combinations. Hydrocarbon fluid for the present analysis is taken as n-decane.

The procedure followed in the present analysis for 3D analysis is summarized below:

- Select suitable metal foam, material, porosity range and coolant
- Write the MATLAB programme for a range of geometric parameters by adopting Valdevit *et al*. [1]

- Based on the output from 1D analysis, 3D CFD analysis is carried out for different range of porosity values.
- Compared the heat sink values for different material and metal foam combinations.

II. MODEL DESCRIPTION

The Scramjet combustion chamber surrounded with number of active cooling channels is shown in the Fig. 1. The numbers of rectangular channels are calculated based on the width of the panel and thickness of the panel. Number of channels N_c=$\left(Z/_{(w+tc)}\right)$ where Z is the length of the panel, w is the width of the panel and t_c is the core thickness. Single rectangular channel is used for the present study. Heat transfer coefficient h_G in combustion side is calculated using Ginesauki correlation [10]. Heat transfer coefficient (h_c) in coolant side is calculated using Eckerts enthalpy method [11]. Based on these conditions the heat flux considered as 220W/cm^2.

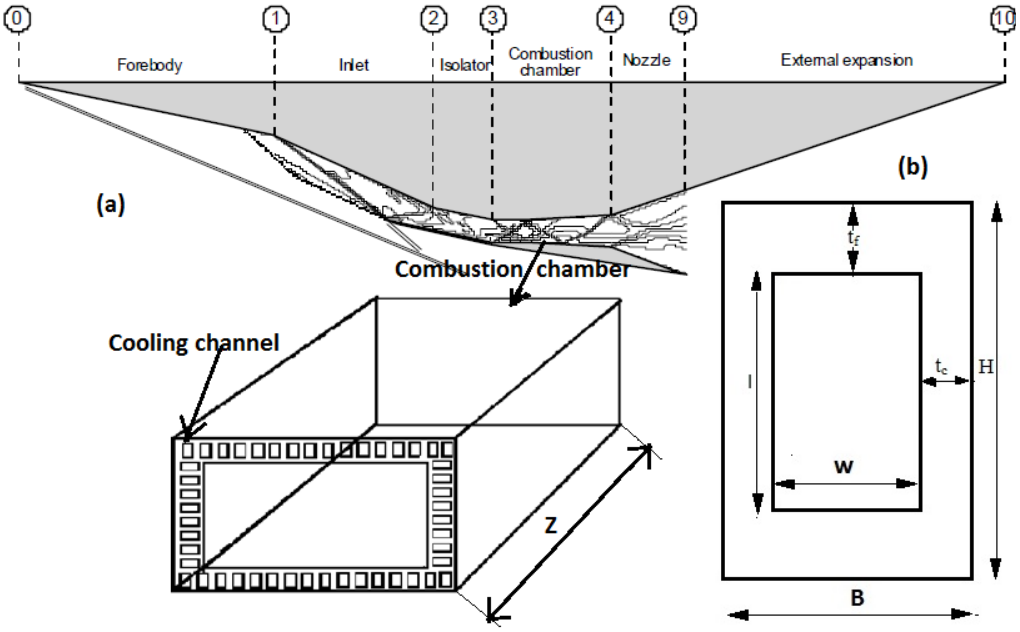

***Figure 1 (a)** Hypersonic scramjet vehicle with actively cooled panels (b) Active panel geometric parameters*

III. METHODOLOGY

In the present study, optimal channel dimensions are analysed with 1D and 3D analysis. Initial approximate dimensions are obtained from 1D calculation. The input conditions such as inlet temperature(T_o), inlet pressure (P_o), h_c, and h_g are given to the 1D analysis. High temperature alloy nb-cb 752 is considered for channel material. Hydrocarbon fuel n-decane is considered as coolant in the channel. Based on Valdevit et.al [1] Range of dimensions t_c, w, l, and t_w *are considered and optimized the channel dimension in the 1D analysis.* Bases on two critical considerations, geometric parameters of the channel are optimized in both 1D and 3D analysis. . (1) The exit temperature of the coolant should be below the coking limit of the fuel. (2) The stresses developed in the channel should be less than von-mises stress value must be less than or equal to 2. A 3D geometry is created based on the approximated dimensions from 1D analysis. The fluid zone of the thus satisfied optimal channel is assumed as porous medium. The 3D analysis is repeated for different materials.

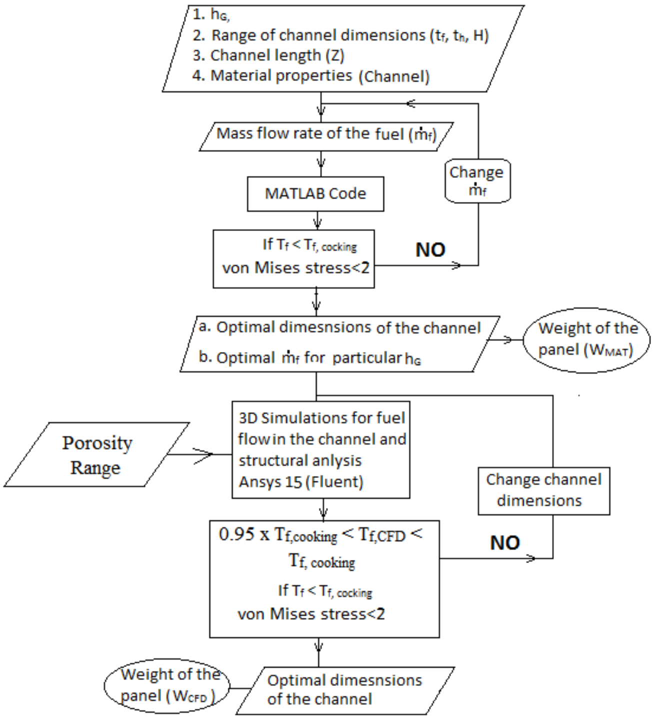

Figure 2 Flow chart for numerical methodology

IV. BOUNDARY CONDITIONS

Boundary conditions for the single channel are shown in Fig. 3. Pressure based solver is used. Mass flow inlet ($\dot{m}_f$) and pressure outlet boundary conditions are given for fuel in the channel. The heat flux is applied at the top of the channel set as 220 W/cm^2. The remaining sides of the channel are set to be adiabatic wall condition. The turbulence in the channel is modelled with $k - w \;\; SST$. Porous condition is enabled. Inertial resistance ad viscous resistance values applied to the fluid flow. The inlet temperature of the fuel is 300 K and mass flow rate is 11 g/s. The inlet pressure and outlet back pressure P_b is set to 3 MPa which is supercritical for n-Decane.

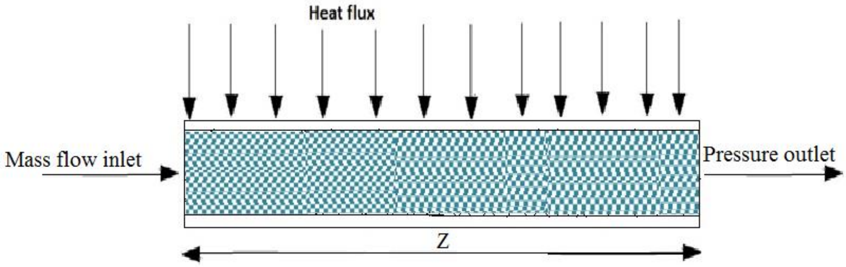

Figure 3 Boundary conditions for the channel

Governing equations

Mass Conservation equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0 \qquad (1)$$

Conservation of energy:

$$\frac{(\partial_{\rho Cp}\, T)}{\partial t} + \nabla \cdot (\rho Cp\, TV) = \nabla \cdot k \nabla T \qquad (2)$$

Conservation of momentum:

$$\frac{\partial \rho V}{\partial t} + \nabla \cdot (\rho VV) = \nabla \cdot \sigma + \rho g \qquad (3)$$

Permeability of the porous material [2]

$$K = a_1 \; exp b_1 \in \qquad (4)$$

$a_1 = 9\times10^{-12}$ m^2 and $b_1 = 0.1$

$$c = \frac{2C_f \epsilon^3}{\sqrt{K}} \quad (5)$$

Friction factor f can be calculated from the following equation:

$$D\mu\vartheta + \frac{C}{2}\rho\vartheta^2 = \frac{f}{2}\vartheta^2\rho\sqrt{D} \quad (6)$$

$$D = \frac{\epsilon^2}{K} \quad (7)$$

$$f = \frac{2\mu D}{\rho\vartheta} + \frac{C}{\sqrt{D}} \quad (8)$$

$$\lambda_e = \epsilon\lambda_f + (1-\epsilon)\lambda_s \quad (9)$$

Nb foam properties [4]:

Foam	∈	PPI	Pore diameter (mm)	Viscous resistance	Inertial resistance
Nb foam	0.876	20	1	3×10^7	1042

V. RESULTS AND DISCUSSIONS

Active cooling using hydrocarbon fuel has been considered to be the most promising cooling method for a scramjet. In the present analysis mass flow rate 0.01Kg/s and heat flux 220W/cm^{2}set to be constant for all the cases. However, the properties of hydrocarbon fuel vary with temperature dramatically, which affects the heat transfer in turn. To account this properties variation with temperature is considered in this study. Niobium foam is used as the porous media and set in this zone as illustrated in Fig. 3. The thermal conductivity of metal foam of q_w = 220 W/cm^2 is set for all the following cases.

5. EFFECT OF POROUS MEDIUM

The variation of heat transfer coefficient for nb-cb 752, Inconel X-750 materials are shown in Fig. 4. When compared to the non porous channel, porous zone channel heat transfer coefficient is increased. At an axial length of 0.6 m, heat transfer coefficients of nb-cb 752, Inconel X-750 materials with porous consideration are pp and qqq respectively, these values are 4.5 and 2.5 times than the case of non-porous of same materials. This happened because of the porous material in the channel increases the heat exchange area, results the effective thermal conductivity of the fluid increases greatly. The thermal conductivity of nb-cb 752 is higher than Inconel X-750, same trend is observed for porous materials also.

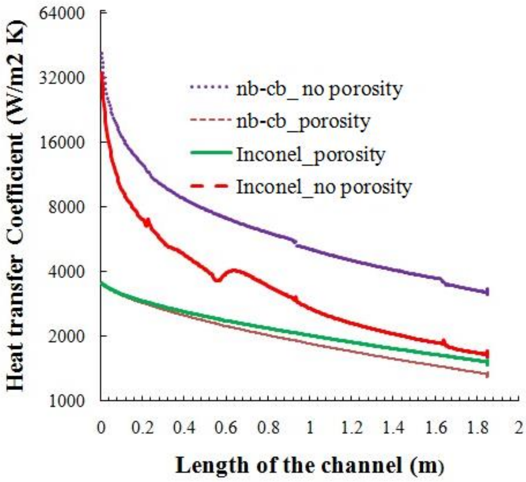

Figure 4 Heat transfer coefficient of cleat channel and porous medium for nb-cb 752 and Inconel X-750

Temperature variation at the top of the channel along the length is observed and plotted in Fig 5. The porous media of the material helps in increases the heat transfer from top plane to bottom of the channel. Hence the temperature at top plane of the channel is less for porous channels. The average temperature of the fuel increases along the channel and the temperature gradient decreases across the channel. Hence, the temperature difference between porous and non-porous is decreased along the length of the channel.

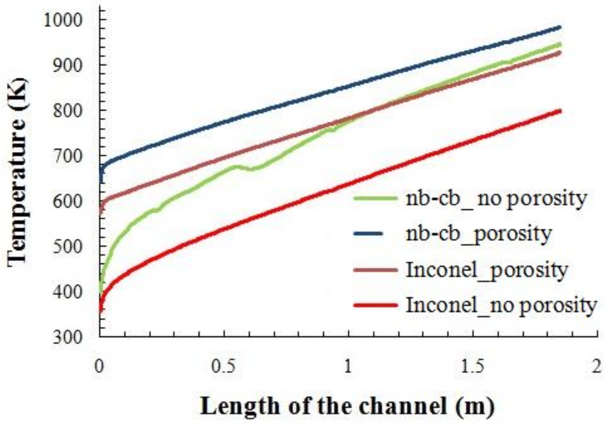

Figure 5 Wall temperature of Inconel and nb-cb 752 materials for without and porous medium

The heat transfer is enhanced about 3 times for nb-cb 752 and 2.01 times for Inconel X-750, which proved the effect of a porous media. The thermal conductivity of nb-cb 752 is high hence, the heat transfer coefficient in the porous channel is increases. Results the heat gain of the fuel in nb-cb 752 with porous channel is higher than Inconel porous channel. Variation of heat absorption of fuel for both porous and nonporous material cases are shown in Fig. 6. From the perspective of velocity and turbulence kinetic energy, it can be explained as follows. Clear region decreases the effective flow area.

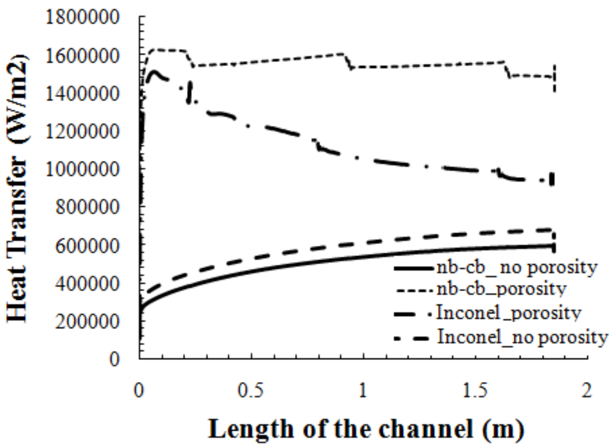

Figure 6 Heat transfer for nb-cb 752 and Inconel X-750

As a result, in Fig. 7 (a) and Fig. 8(a) it's seen that the velocity in the clear region is little higher. Porous medium intensifies the turbulence of fluid region. The turbulence kinetic energy increases due to the flow disturbance of the porous media. Moreover high effective thermal conductivity of the fluid and channel metal helps to transfer the heat. Increase of turbulent kinetic energy and heat transfer coefficient in the fluid part becomes the main reasons of reinforces the heat transfer. From Fig. 7(b) and Fig. 8 (b) it is observed that InconelX-750 and nb-cb 752 with porous medium shows the little higher turbulent kinetic energy compared to without porous medium cases.

Inconel X-750 with porous medium has less heat transfer compared to the nb-cb 752 with porous medium. However, the thermal conductivity is less for the Inconel X-750. As a result, the heat transfer is better enhanced with nb-cb 752 with porous media (Nb foam). Nevertheless, the pressure drop increase is not that obvious when compared to the supercritical pressure of hydrocarbon fuel. Cooling channels of a scramjet are not that sensitive to pressure drop as the supercritical pressure is usually maintained to avoid the boiling heat transfer deterioration. Hence, pressure drop is not considered.

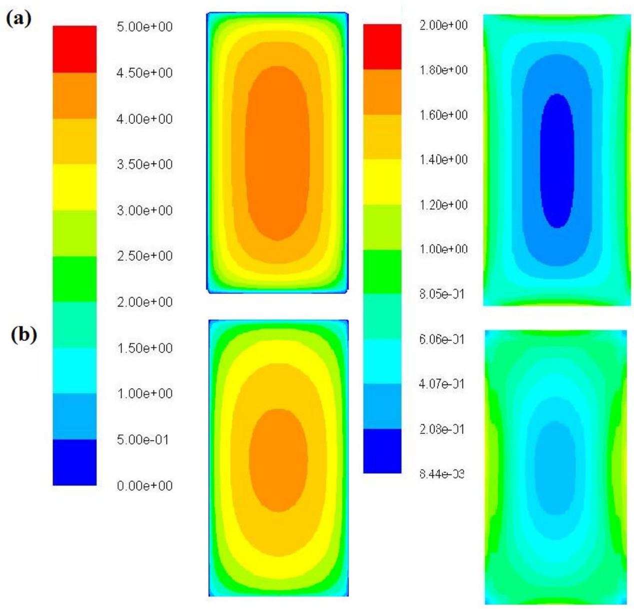

Figure 7 (a) Inconel without porosity velocity profile (m/s) and turbulent kinetic energy (m^2/s^2) (b) Inconel with porosity velocity profile (m/s) and turbulent kinetic energy (m^2/s^2)

The main effect of gradient porous media is the increase of the turbulence kinetic energy shown in Fig. 8(b). The heat transfer is only changed compared with the clear active channel condition. Therefore, from Fig. 6 it is observed that the heat transfer is enhanced by about 67% increase in case of nb-cb 752 and 50% increase in case of Inconel X-750. This is concluded in a turbulence flow. However, in laminar flow without turbulence, velocity variation due to the change of effective area becomes the key factor. The results are accordant with conclusion of this work.

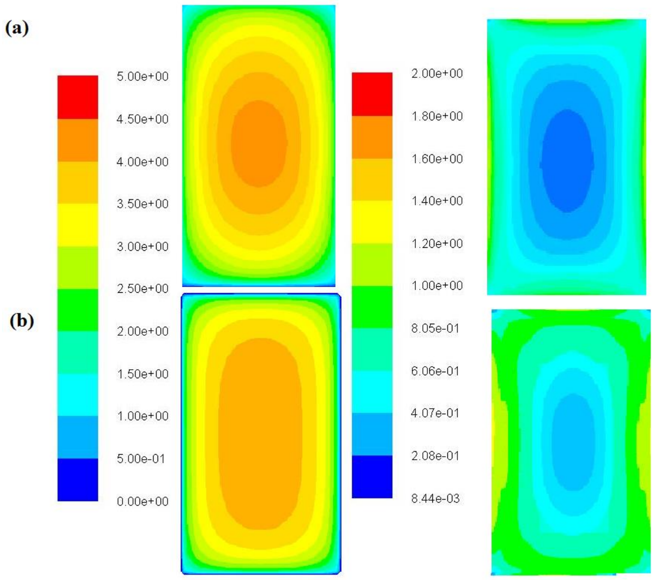

Figure 8 (a) Nb-cb 752 without porosity velocity profile (m/s) and turbulent kinetic energy (m^2/s^2)(b) Nb-cb 752 with porosity velocity profile (m/s) and turbulent kinetic energy (m^2/s^2)

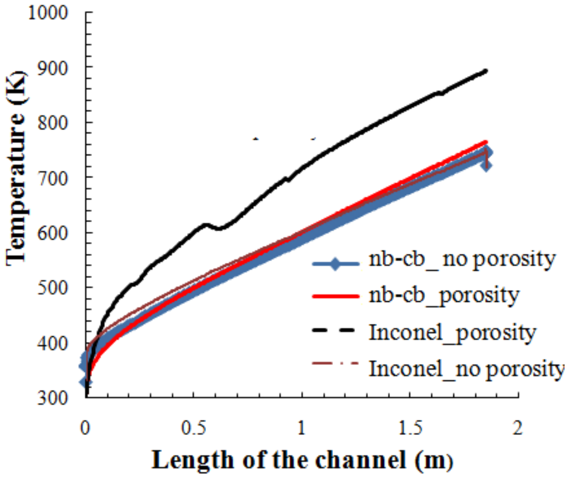

Figure 9 Fluid temperature along the length for nb-cb 752 and Inconel X-750 with and without porous medium

VI. CONCLUSIONS

In this work, a 3D numerical simulation is carried out to investigate the heat transfer in a porous media in a rectangular channel with hydrocarbon fuel under supercritical pressure. The effect of homogenous porous medium on different materials is studied. The results show that:

1. Heat transfer is enhanced with homogeneous porous media. The heat transfer coefficient and thermal conductivity is higher in Nb-cb 752 material, both contribute to increase in heat transfer coefficient, results the heat transfer enhancement.
2. The effect of homogenous porous media is better with nb-cb 752 material, while heat transfer coefficient increases about 4.5 times in the porous medium case. This is because the effective thermal conductivity of porous zone contributes to the convection with wall directly.

3. Nb-cb752 with porous medium enhances 67% heat transfer and Inconel X-750 with porous medium enhances 50 % heat transfer when compared to the clear tube. It leads to the observation that porous medium is the viable option for enhance the heat transfer.
4. Among the configurations compared, nb-cb 752 with Niobium foam has the best performance than remaining cases.

VII. NOMENCLATURE:

K=permeability (m^2)
$\in$= Porosity of the material
C = Inertial resistance (m^{-1})
D = Viscous resistance (m^{-2})
V_r = Reduced velocity (m/s)
ρ =Density of the fluid (Kg/m^3)
μ =Viscosity of the fluid
D_p = Diameter of the open pores.
$f = friction\ factor$
ϑ = velocity of the fluid
λ_e = Effective thermal conductivity of the fluid (W/m k)
λ_s = Solid thermal conductivity (W/m k)
C_f= Forchheimer Coefficient

VIII. REFERENCES

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