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Thermal Design Methodology for Regenerative Fuel-Cooled Scramjet Engine Walls

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Scramjet engine wall experiences high heat transfer rates due to high temperature combustion products flowing with supersonic speed in the combustion chamber. Thermal protection of combustor wall for the long duration operation is one of the major challenges. Passive cooling of the combustor considering wall as a heat sink limits flight duration and it reveals the need for active cooling system. Regenerative cooling of the combustor walls using hydrocarbon fuel as a coolant is one of the best solution to withstand thermal load for the long duration. In such cases, before embarking on materials development and fabrication, it would be most beneficial to have a procedure that simultaneously selects the preferred material and design. Thermal design methodology of regenerative cooling system for hydrocarbon fueled air-breathing engine walls is presented in this paper. The main ingredient is three-dimensional heat transfer analysis coupled with fluid flow based on FEM that can be used for thermal management study of regenerative cooled panel configurations and selection of materials including Thermal Barrier Coatings (TBCs). The procedure is applied for a thermal design of fuel-cooled scramjet combustor walls exploiting physical heat sink of a hydrocarbon fuel. The major constraint of the design is to maintain coolant temperature within the thermal stability limit of the fuel during flow inside the channel. High temperature materials, viz., Cb-752, C-103 and C-SiC are considered as a candidate materials alongwith TBC. Results of several combinations of material, TBC with suitable bond coat, wall thicknesses and channel location are presented in this paper. It is inferred that TBC along with re-generative cooling is playing the major role in reducing the engine wall temperature thereby the maintaining fuel temperature inside the channel within desirable limit. The Cb-752 coated with Y_2O_3 TBC remains viable solution for thermal management of scramjet engine walls for long duration application.

***Keywords**: Thermal design, Scramjet Engine, Re-generative cooling, Material selection*

1. Introduction

Supersonic combustion ramjet (Scramjet) propulsion [1] is the option for hypersonic flight regime. Passive cooling of the engine as a heat sink results in high temperature and exceeds the allowable limit of materials within short duration, thereby limits the flight duration of hypersonic vehicle. High heat transfer rate due to high temperature combustion products flowing with supersonic speed inside the engine reveals the need for active cooling system. Although there are several literatures about the regenerative cooling in recent years, the studies considering physical (sensible) heat sink of the fuel combined with effect of TBC for scramjet engine are limited, especially for the hydrocarbon fueled scramjet engine. The purpose of this article is to describe the thermal design methodology of regenerative cooling of scramjet engine walls using physical heat sink of the fuel and material selection for long duration application.

Generic schematic diagram of regenerative cooling [2] of the scramjet engine is shown in Fig. 1. In a regenerative cooling system, the fuel is first pumped into the cooling channels to cool the thermal structure as a coolant and then the hot fuel is injected into the combustor as a propellant to generate the thrust. Furthermore, the fuel gets pre-heated after regeneration in the cooling channel can improve the combustion performance. The engine intake is subjected to air flowing with high velocity which gets compressed in the region. The scramjet combustor is subjected to high heat transfer rate due to high temperature and high speed combustion products flowing through the engine. Heat flux distribution of the scramjet combustor is shown in Fig. 2.

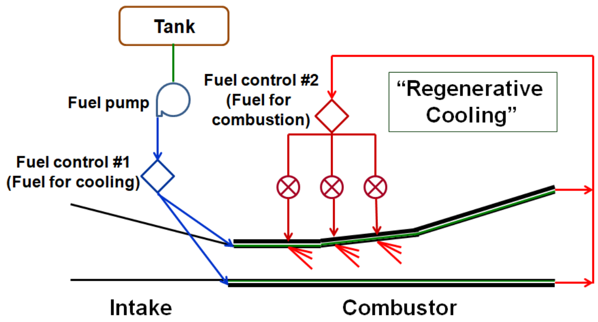

Fig. 1: Schematic diagram of regenerative cooling system for scramjet engine walls

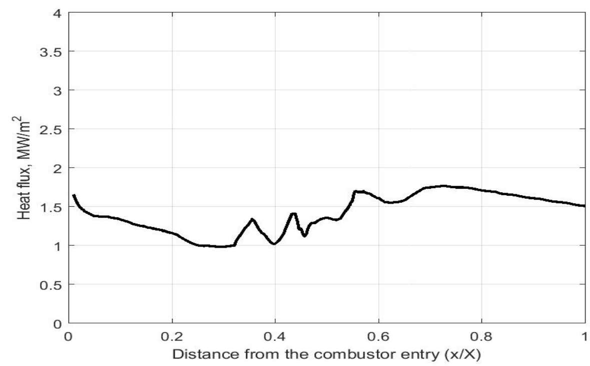

Fig. 2: Heat flux distribution along the length of the combustor wall

2. Scramjet combustor wall

Schematic diagram of two-module scramjet combustor with jacket of cooling channels on the walls and cross section detail of channel with combustor wall domain having periodic symmetry is shown in Fig. 3. The present study focuses on rectangular channels. Extension to other periodic shapes is elementary and is not expected to modify the main conclusions. The ratio a/b and Ch_w/b is 1.5 and 1 respectively. TBC along with suitable bond coat is also considered on inner surface of the combustor wall.

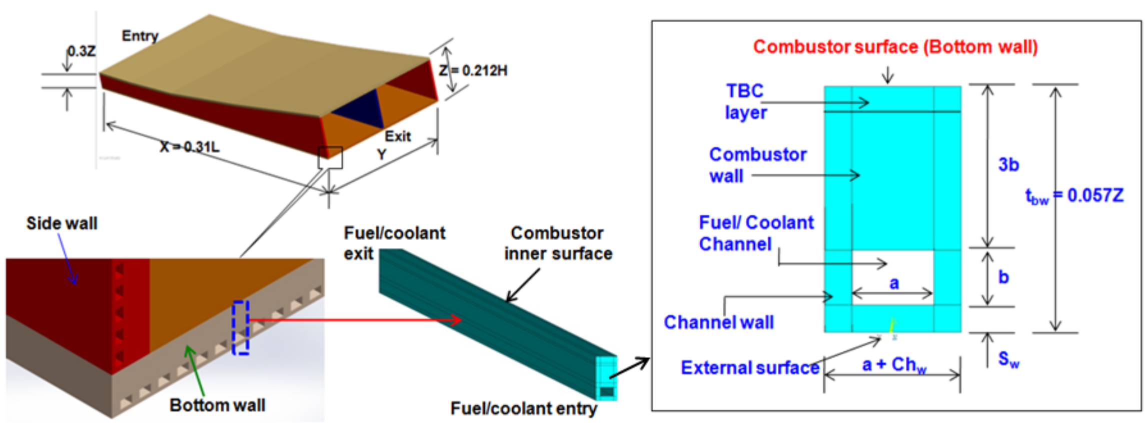

Fig. 3: Scramjet combustor wall with jacket of cooling channels and cross section detail of a channel with combustor wall

3. Heat transfer rate of the coolant channel

The coolant mass flow rate per channel is estimated from total fuel mass flow rate required for combustion, rate of heat to be removed and number of cooling channels. Number channels depend on geometry of the combustor wall and chosen channel dimension. A typical fuel flow rate of 0.325kg/s per combustor module for the flight regime Mach 6-7 is considered in the present study. Based on experience of earlier static tests as well as CFD simulations, it is assumed that amount of heat to be removed from the bottom wall is 30% of total amount of heat per combustor module. The mass flow rate of coolant per channel in the bottom wall of combustor is 0.001741kg/s. Convection heat transfer coefficient between coolant channel and regenerative coolant is evaluated using classical engineering method for fully developed turbulent flow through smooth pipes. Petukhov's expression [3] is used for the calculation of heat transfer coefficient considering various isothermal wall conditions.

$$Nu_d = \frac{(f/8)\,\mathrm{Re}_d\,\mathrm{Pr}}{1.07 + 12.7(f/8)^{1/2}(\mathrm{Pr}^{2/3}-1)}\left(\frac{\mu_b}{\mu_w}\right)^n$$

Where, $f = (1.82\log_{10}\mathrm{Re}_d - 1.64)^{-2}$
$n = 0.25$
Re is Reynolds number
Pr is Prandtl number
μ_b and μ_w are dynamic viscosity of the coolant corresponds to bulk temperature and wall temperature respectively.

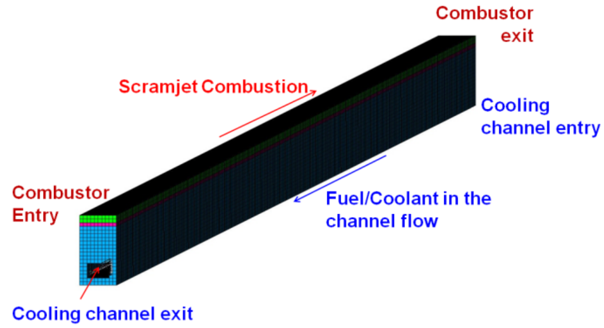

Fig. 4: Finite element grid of regenerative cooled scramjet combustor wall

The JP-7 is chosen as fuel in the present case due to its better thermal stability and the availability. Supercritical pressure condition of 50bar is considered inside the channel. The heat transfer coefficient is of the order of 1900W/m^2-K for the average fuel temperature of 645K. Thermo-physical and transport properties of the JP-7 fuel obtained from NIST data base are used in the analysis as a function of temperature and pressure. Thermal conductivity, specific heat capacity, density and dynamic viscosity of the JP-7 fuel at 300K is 0.134W/m-k, 1980J/kg-K, 763kg/m^3 and 9.0525x10^{4}N-s/m^2 respectively.

4. Heat transfer analysis coupled with fluid flow

Three-dimensional steady state heat transfer analysis coupled with fluid flow based on Finite element method (FEM) has been carried out for regenerative fuel-cooled combustor wall. The analysis is carried out for the domain of combustor bottom wall having periodic-symmetry using ANSYS software [4]. The finite element grid of coolant and combustor wall along with channel in the heat transfer analysis domain is modeled using FLUID116 elements and SOLID90 element respectively. Surface effect element, SURF152, with film coefficients are used in between the coolant and channel wall to couple the convection loads. The finite element mesh of the combustor wall is shown in Fig. 4. Grid independence study has been carried out to arrive at a correct mesh size for the analysis domain. As a result, the combustor wall mesh consists of 143986 nodes and 130480 elements. Heat flux distribution of the scramjet combustor inner surface is obtained from N-S CFD simulation. The heat flux distribution along the length at bottom wall (at y = 0.25Y) of the scramjet combustor corresponds to an isothermal condition of 300K (Fig. 2) is in the range of 1MW/m^2 – 1.75 MW/m^2. The convective heat transfer boundary conditions are applied on the inner surface of the combustor wall and inner surface of the channel. Remainder of the cell perimeter is thermally insulated. Fuel temperature at inlet is 300K. Advantage of this methodology is faster as compare to conjugate heat transfer analysis using CFD software. Temperature dependent thermo-physical properties of the JP-7 fuel and combustor wall materials are used in the present analysis. Thermal conductivity of Cb-752, C-SiC, YS Zirconia and Y_2O_3 at room temperature condition is 37.5W/m-K, 15W/m-K, 37.4W/m-K, 1.04W/m-K and 0.3W/m-K respectively.

4. Thermal design of regenerative fuel-cooled wall

In order to select the suitable materials of construction for regenerative fuel-cooled scramjet combustor wall, heat transfer analysis coupled with fluid flow has been carried out considering the various combinations of materials of construction, wall thickness, location of the cooling channel, TBC and bond coat material. Ten cases have been analyzed. The counter flow between coolant inside the channel and hot gases of the combustor has been considered for effective heat transfer. The hydrocarbon fuel undergoes cracking [5] when the temperature reaches to 773K at supercritical pressure. The cracking reaction alters the fuel properties which results in drastic change in overall heat transfer coefficient and put in more complexity for the thermal management. Hence, the major constraint of the thermal design is to maintain the fuel temperature within a limit of thermal stability of the fuel without undergoing any change in chemical composition during the channel flow.

The coolant channel is located away from the combustor wall inner surface for all the configuration of the combustor wall except case-1 and case-2. The TBC alongwith bond coat is considered on the inner surface of the combustor wall for the cases 5 to 10. In case-4, TBC along with bond coat is introduced between the combustor wall made of C-SiC material and coolant duct made up of Cb-752 material. The layer of Y_2O_3 TBC is considered in addition to YSZ in case-6 while Y_2O_3 is the TBC for the combustor wall from case-7 to case-10. In case-8, $NbSi_2$ is considered as bond coat material in place of NiCoCrAlY because of its good compatibility between Niobium alloy (Cb-752 and C-103) and Y_2O_3 TBC. The C-103 alloy is material of construction for combustor wall in the case-9 and case-10.

5. Results and discussion

Result summary of heat transfer analysis of the regenerative fuel-cooled scramjet combustor wall for all the cases is given in Table. 1. Due to change in the location of the coolant channel away from the inner surface of the combustor wall as shown in case-3, the coolant attains the temperature lesser than the configuration of case-1. A drastic reduction in the fuel temperature is observed due to presence of YSZ TBC between combustor wall and coolant channel (case-4). In all the cases of TBC considered at the inner surface of the combustor, temperature attained by the fuel as well as the combustor wall is lesser than case-4. The effectiveness of the YSZ TBC is improved by addition of Y_2O_3 layer on its external surface and the fuel attains the temperature of the order of 817K.

Table. 1: Result summary of heat transfer analysis of the regenerative fuel-cooled Scramjet engine wall

Case	Combustor wall		TBC		Bond coat		Max. T_{fmax}, K
	Material (thickness)	T_{wmax}, K	Material (thickness)	T_{wmax}, K	Material	T_{wmax}, K	
1	Cb-752 (3b)	1387	---	---	---	---	**1291**
2	C-SiC (3b)	1402	---	---	---	---	**1249**
3	Cb-752 (3b)	1398	---	---	---	---	**1258**
4	C-SiC (2b), Cb-752(b)	1690, 1142	YSZ (0.5mm)	1454	NiCoCrAlY	1151	**1059**
5	Cb-752(2b)	1027	YSZ (1.5mm)	2072	NiCoCrAlY	1034	**933**
6	Cb-752(2b)	895	Y_2O_3 (0.5mm) + YSZ (1.0mm)	1454	NiCoCrAlY	902	**817**
7	Cb-752 (2b)	849	Y_2O_3 (1.0mm)	2481	NiCoCrAlY	855	**775**
8	Cb-752(2b)	850	Y_2O_3 (1.0mm)	2478	$NbSi_2$	853	**776**
9	C-103(1.5b)	851	Y_2O_3 (1.0mm)	2478	$NbSi_2$	854	**776**
10	C-103(1.5b)	1029	Y_2O_3 (0.5mm)	2089	$NbSi_2$	1025	**929**

The wall temperature distribution of the combustor wall for case-8 is shown in Fig. 5. The low thermal conductivity of the Y_2O_3 results in significant reduction of wall temperature in the case-7, case-8 and case-9. And the temperature attained by the coolant at the exit of the channel for these cases is of the order of 776K which is close to the thermal stability limit of hydrocarbon fuel (~773K). The temperature distribution of the fuel and at various locations across the channel along with combustor wall for case-8 is shown in Fig. 6. Since thermal conductivity of Cb-752 and C-103 alloy is almost same, not much change in results of the analysis for case-8 and case-9. As layer thickness of Y_2O_3 TBC decreased by half of the value compare to that of case-9, significant rise in the combustor wall temperature as well as fuel temperature observed in case-10. It is observed from the analysis that TBC along with regenerative cooling is playing the major role in reducing the engine wall temperature thereby the fuel temperature inside the channel. The configuration of case-8 and case-9 having Cb752/C-103 material with 1.0mm Y_2O_3 TBC having compatible bond coat of $NbSi_2$ is feasible solution for the scramjet engine walls for long duration mission.

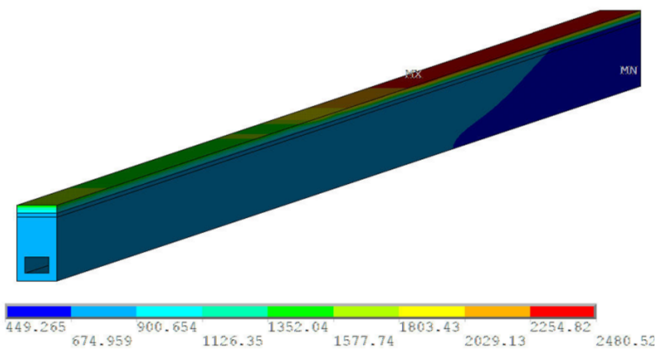

Fig. 5: Wall temperature distribution of the combustor wall (case-8)

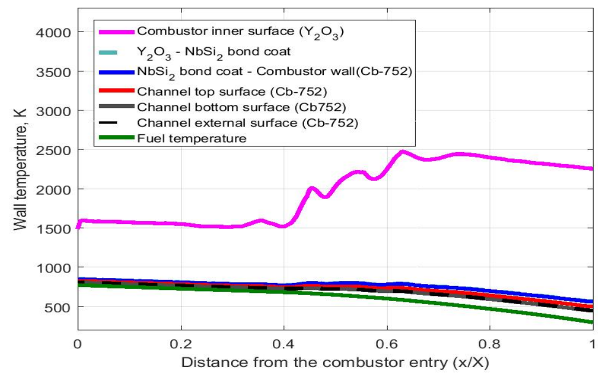

Fig. 6: Temperature distribution at various locations across the combustor wall

6. Conclusion

Thermal design methodology for regenerative cooled engine walls considering physical heat sink of the hydrocarbon fuel has been presented. The procedure encompasses a three dimensional transfer analysis coupled with fluid flow based on FEM for thermal response study of regeneration cooled combustor wall configuration and selection of materials of construction. The methodology has been applied to the scramjet engine combustor walls with constraint to maintain coolant temperature within the thermal stability limit. The thermal load corresponds to the realistic operating conditions of the engine for a steady-state flight conditions is considered in the analysis. All the materials considered in the study present feasible thermal design of combustor wall. Due to high thermal resistance, TBC along with regenerative cooling is playing the major role in reducing the wall temperature thereby the fuel temperature inside the channel. In the present application, Cb752/C-103 material with 1mm thick Y_2O_3 TBC having compatible bond coat of $NbSi_2$ remains viable solution for the regenerative fuel-cooled scramjet engine walls. The finalized configuration of combustor wall is being pursued for fabrication and testing.

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