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2-D ANALYTICAL STUDY OF EMPLOYMENT OF THERMAL BARRIER COATINGS TO EVALUATE THE PERFORMANCE OF ACTIVELY COOLED PANELS FOR AIRBREATHING ENGINES

Pavani Sreekireddy[1], Dr. Tadisina. Kishen Kumar Reddy[1,*], C. Chandrasekhar[2], Laxman Kamlekar[1]
*Author for correspondence
[1] Department of Mechanical Engineering,
Jawaharlal Nehru Technological University college of Engineering,
Kukatpally, Hyderabad, 500085.
[2]Defence Research and Development Laboratory, DRDL,
Kanchan Bagh, Hyderabad, 500058.
E-mail: reddykishen@jntuh.ac.in

ABSTRACT

Hypersonic vehicles operate at high flight Mach numbers exposing the airframe and engine structures to high heat loads which are quite severe in the combustor part of the high-speed air breathing engine. In order to withstand high heat loads experienced in the combustor region of the engine during hypersonic flight, actively cooled panels are employed. Herein, a fuel before being injected into the combustor serves as a coolant and is made to flow through the combustor heat exchanger panels such that the material and coolant temperatures are maintained below their critical limits. A few of the candidate materials considered for the active panels of the engine are Nb alloy Cb 752, Ni alloy Inconel X-750, and C-SiC. To enhance the heat withstanding capacity of these materials, low thermal conductivity thermal barrier coatings (TBC) are employed. Currently Yttria-Stabilized Zirconia (YSZ) material and ceramic materials are being used as popular TBC materials because of their very low thermal conductivity and high phase stability. In this analytical study, thermal properties of air-plasma-sprayed zirconia based lanthanum zirconate ($La_2Zr_2O_7$) – LZ- coatings were employed in the investigations. Lanthanum-cerium oxide ($La_2Ce_2O_7$) –LC- is considered as a new candidate material for TBCs because of its low thermal conductivity and high phase stability. With the use of $La_2Ce_2O_7$ and $La_2Zr_2O_7$ as TBC materials, the difference in the weight of the active panel material and the heat gained by the fuel are nearly identical as compared to active panel material coated with YSZ TBC. Results showed that the effect of TBC thickness on the weight of the optimised actively cooled panel is negligible, because of very small TBC layer thickness ranging from 0.5 to 3.0 mm and nearly identical thermal properties of the TBC's. Results showed that Inconel X-750 is capable of sustaining high heat transfer coefficients with fuel/coolant heat gain well below fuel coking temperature with moderate weight to area ratio.

INTRODUCTION

In this ever changing and fast growing world, transportation plays a significant role for the development of humankind. The use of state-of-the-art air breathing engine technology is indispensable for the hypersonic air breathing vehicles. Air breathing engine technology has witnessed a remarkable progress since the invention made by Wright brothers. Developmental path of the various air-breathing engines arranged chronologically viz., turbojet, ramjet, scramjet indicate that the threshold values of specific impulse and combustion efficiency have led to the advent of new technologies.

Nomenclature

H	[m]	panel thickness
T_{aw}	[K]	adiabatic wall temperature in the combustor
P_f^o	[Pa]	entry pressure of the coolant
L	[m]	height of cooling channel
w	[m]	width of cooling channel
b	[m]	combustor width
t_c	[K]	core web thickness
T_f^o	[K]	Coolant entry temperature
t_f	[m]	face sheet thickness
$T_f(z)$	[k]	Exit coolant temperature
P_{comb}	[Pa]	Pressure in the combustion chamber
h_G	[W/m^{2}K]	heat transfer coefficient on the combustor side
Z	[m]	panel length
$V^{\cdot\, eff}_{st}$	[m^2/S]	Stoichiometric volume flow rate per width of the panel
Φ	[-]	equivalence ratio
V_{eff}	[m^2/S]	Volumetric flow rate per unit width of the panel
T^*	[K]	maximum allowable temperature in the material
T_{coke}	[K]	Coking temperature of the fluid
σ_y	[MPa]	yield strength of a metallic material
E	[GPa]	Young's modulus
CTE	[K^{-1}]	Coefficient of thermal expansion
K_s	[W/mK]	thermal conductivity of the material

Investigations showed that the sub-sonic combustion ramjets assisted vehicles become inefficient beyond flight Mach 5.5. To overcome such phenomena, engine has to be configured with the concept of supersonic combustion ramjet (Scramjet).

Scramjet is the highest performing cycle in terms of specific impulse in the speed range of Mach 4-8. Figure 1 depicts the hypersonic air breathing vehicle along with the cross-section of the actively cooled scramjet combustion chamber. This hypersonic vehicle employed the concept of propulsion integrated airframe. The vehicle is propelled by the scramjet engine which is mounted underneath the vehicle.

The burning of the fuel in the supersonic combustor generates enormous heat which needs to be dissipated in a short time. This is accomplished by the same fuel flowing through the active heat sink passages put in place to extract heat from the combustor walls. The fuel heats up and cracks (thermally decomposes) while absorbing heat from the combustor active panel material. The fuel flow rate is chosen in such a way that the inner surface temperature of the panel and stresses developed in the coolant channels and panels (combustor walls) are within the permissible limits of the chosen material. In addition, fuel while extracting the heat shall not decompose to the extent where coking phenomenon starts dominating, as this will have adverse affect on the fuel flow through the coolant channels.

In order to develop high-speed combustion technology for hypersonic air breathing vehicles, the materials and coatings required to withstand the high heat loads in the engine structure during its operation in the hypersonic flight path is a major challenge to the aerospace community. The selected materials should withstand the thermal stresses as well as the stresses induced by the coolant flow. Under such extreme conditions, researchers have found the role of ceramic materials to be perplexing. Few researchers claim that ceramic materials cannot withstand such high heat fluxes [1-4] but another research group claims that its candidature is promising [5].

Researchers worldwide are pursuing active cooling techniques to circumvent the high heat load challenge being encountered in the engine. Generally, it is reported that the amount of fuel required is greater than the actual fuel being used for the combustion purpose. Efforts have been directed to restrict the fuel requirement to as desired for the combustion and also to keep the pressure losses to a minimum [6]. To achieve extra heat sink capabilities, endothermic hydrocarbon fuels are beneficial as compared to conventional hydrocarbon fuels as the fuel cracks and absorbs further heat (chemical heat sink) [7,8]. Hence the engine design for high Mach number flights should withstand extreme temperature and pressure conditions which impart adverse thermo-mechanical stresses. Also the design is restricted by the high temperature pyrolysis of the fuel which initiates coking of the fuel, generally referred to as the fuel coking temperature [9].

Indirectly the choice of fuel depends on the materials used for the active cooling panel and the thermal barrier coatings and environmental conditions and input parameters such as: pressure, temperature and velocity of fuel flow [10,11]. It was observed that cracked fuel flow is desirable as the heat transfer coefficient of the fuel is higher [12]. Thermal protection is very important in high Mach number vehicles [13,14] employing different panel materials such as Ceramics, Nb alloy Cb752, Ni alloy Inconel X-750 and GrCop-84 [6]. It is reported that the fuel initially absorbs the heat from the combustor walls in the physical heat sink mode, and, as it is not sufficient, absorbs heat in the chemical heat sink mode. This is also shown to be inadequate [15,16].

The fuel to be used should be utilised within the coking temperature to get optimal performance. Currently for temperatures below 1300^0C applications, 7-8% Yittria–zircona material has been used as a TBC material [17,18]. $La_2Zr_2O_7$ is also known to possess lower thermal conductivity as compared to 7-8% Yittria–zircona and also has high stability and comparable thermal expansion coefficient. $SrZrO_3$ is not suitable for thermal barrier coating because its transition temperature lies between $700\text{-}800^0$C [19]. Among zirconium based TBC materials: Y_2O_3-stabilized ZrO_2 (YSZ), $SrZrO_3$, $BaZrO_3$, and $La_2Zr_2O_7$, $La_2Zr_2O_7$ give better thermal stability and thermal shock behaviour [19]. The desirable properties of TBC's are: low thermal conductivity, good thermal expansion, match with metallic substrate, have no phase transformation between metallic and operating temperature of material, and high melting point [20]. Hence, the researchers are examining alternate TBC materials which possess such properties such as: high hardness, low elastic modulus and high toughness [21-24]. X. Cao et.al. [25], proposed $La_2Ce_2O_7$ also as a competitive thermal barrier coating along with $La_2Zr_2O_7$ because it has low thermal conductivity and high phase stability [26].

METHODOLOGY

Previous research has shown a methodology for deciding the type of materials to be used for active cooled panels and the choice of thermal barrier coatings, based on applied loads (external combustion pressure loads, internal fluid pressure load, thermal load due to temperature difference), structural design considerations (the induced thermo mechanical stresses must be below ultimate yield strength of the material); fuel constraints (the temperature of the fuel must be below the fuel coking temperature) and variable parameters (fuel/coolant volumetric flow rates per unit width of panel ($\dot{V}^{eff}_{Stoichometric}$ in m^2/s), and typical heat transfer coefficient from combustor side-h_G, all parameters *subject to minimum weight considerations* [6]). Valdevit et al. [6] has developed a 2D mathematical model for optimal design of the cooling panel (i) for an individual cooling panel, different heat loads (h_G) and coolant flow rates per unit width of panel ($\dot{V}^{eff}$) are applied, (ii) at each combination of h_G and $\dot{V}^{eff}$, the temperatures and stresses are calculated in the active panel, then the design is optimized according to minimum weight considerations, (iii) if a solution does not exist, then the h_G and $\dot{V}^{eff}$ combinations are varied and the above procedure is followed to obtain feasible solution, and (iv) after getting the solution then the same is applied for different materials with and without thermal barrier coatings.

Using such an approach, optimum sized panels with minimum weight and improved cooling effect were designed.

Their analysis is obtained using 2-D heat transfer relations with the assumption that the fuel/coolant temperature across any cross section of the channel (in the Z-direction) is constant at mid-point of the channel.

Valdevit et al. found that active panel materials: Nb-Cb752, and Inconel X-750 are ideally suited with the usage of YSZ as TBC material. Authors concluded that high heat transfer coefficient on the combustion side occurs at the stoichiometric fuel flow conditions. To withstand this thermal load, at high combustor side heat fluxes under stoichiometric fuel flow conditions, Niobium alloy Cb-752 satisfies the condition of least weight among the metallic structures for the active cooling panel and sustains severe heat flux conditions generated in the combustor. The other candidate materials used in the analysis by Valdevit et al. [6] are GRCop-84 and Inconel X-750. The study showed that they are found to be suitable for low flight Mach number applications albeit at about twice the weight. In the present study, Nb–Cb752 and Inconel X-750 are considered as the candidate panel metallic alloy materials in addition to ceramic panel material C-SiC.

In the present study, the 2-D heat transfer analysis done by Valdevit et al [6] has been extrapolated for prediction of material and fuel temperatures employing TBC materials viz., Lanthanum-cerium oxide ($La_2Ce_2O_7$), LC, and Lanthanum zirconium oxide ($La_2Zr_2O_7$), LZ. The weight per unit area of the panel material obtained from the present analysis is compared with the similar data obtained by Valdevit et al. [6].

Table 1
Different TBC properties:

TBC material	Thermal conductivity (W/m K)	Density (Kg/m^3)	Thermal expansion coefficient (K^{-1})
YSZ	0.8-1.2 [32]	6000 [24]	5x10^{-6} - 11x10^{-6}[44]
$La_2Zr_2O_7$ (lz)	0.7 - 0.8 [32]	6050[24]	6x10^{-6} - 10x10^{-6}[32]
$La_2Cr_2O_7$ (lc)	0.68 [43]	4644 [43]	10x10^{-6}-13x10^{-6}[45]

MATHEMATICAL MODELLING

For obtaining the optimized geometry, the author followed the procedure laid out by Valdevit [6] with Fuel/coolant Inlet pressures and temperatures and combustor temperature and pressure conditions were taken as: 4 MPa, 400 K, 0.16 MPa and 3050 K, respectively.

Heat transfer coefficients as high as 1800 W□m^2 K are considered in the analysis. For the stress analysis, linear frictionless support along Z-direction is used due to this there is a constraint in moment in Z- direction and free moment action in X-direction occurs. In this one unsupported span length b=0.5 m.

$\dot{V}^{eff}_{Stoichometric}$ = 0.003m^2/s, $\dot{V}^{eff} = \Phi.\dot{V}^{eff}_{Stoichometric}$

By following above conditions, the induced stresses and temperatures must be less than the yield strength of the particular material and maximum allowable material temperature *T**. The fuel temperature must be always below the coking temperature Tcoke=975 K of the fuel; and the design secondary constraints are: the channel width $w \geq 2$ mm, channel height $L \geq 5$ mm, face and core wall thicknesses t_c and $t_f \geq 0.4$ mm, and TBC thickness ≤ 0.3 mm [6]. Tables 1, 2 & 3 display the thermo-physical properties of thermal barrier coatings (TBC), active cooled panel materials, and fuel/coolant, respectively.

Procedure adopted for the MATLAB coding:

1. Select range of heat loads, h_G and flow rates, $\dot{V}^{eff}$
2. Select the material with and without TBC
3. Change Material properties suitably and run the program every time for required material selection

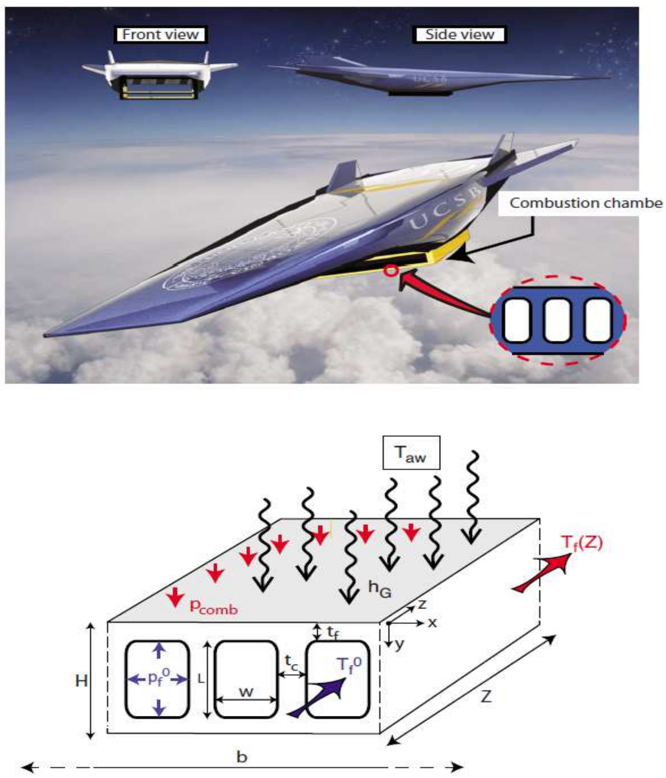

Figure 1 Hypersonic air breathing vehicle with Active cooling panel [6]

Table 2
Different material properties:

Material	T^* (K)	σ_Y	dY/dT (MPa/K)	E	CTE (10^{-6}/K)	Ks	ρ_s
Inconel X-750	1100	427	-0.31	128	16	23	8276
Nb – Cb752	1470	382	-0.17	110	7.4	50	9030
C–SiC	1810	200	-	100	2	15	2000

Table 3
Fuel Properties:

Fuel	k_f (W/m K)	μ (Pa.s)	Cp (J/kg K)	Prandtl No. Pr_{fuel}	ρ_f (kg/m^3)	T_{coke} (K)
JP-7	0.11	1.984x10^{-4}	2575	4.64	800	975

RESULTS AND DISCUSSIONS

Effect of thermal conductivity and density of the panel material on the optimised weight per area of the panel for different fuel flow rates

Figure 2 shows the variation of panel weight per unit area as a function of fuel volumetric flow rate (V^{eff}) employing different material substrates and TBC combinations. When the bare panels coupled with robust panel dimensions are required to withstand high heat fluxes and fuel temperatures below coking temperatures (975K for JP-7 fuel), the weight of the panel may increase by 3% for Nb-cb752, 7% for Inconel X-750 and no change is observed in the case of C-SiC. The below table shows the dimensions of bare cooling panel for different materials.

Table 4
Cooling panel (without TBC) dimensions:

	InconelX-750(m)	Nb-Cb-752(m)	C-SiC(m)
w	0.002	0.0018	0.0015
t_c	0.00055	0.0016	0.0015
t_f	0.0006	0.0015	0.0015
L	0.009	0.0055	0.006
H	0.0102	0.0087	0.009

High density TBC material coatings, on the other hand, cause an increase in the net weight of the panel. It is observed that panel materials coated with YSZ and LZ, the weight of the panel is almost same for all three substrate materials. Since C-SiC has low density and low thermal conductivity the weight per area of the panel is the least, ie., 13-14 kg/m^2. The thermal conductivity of Nb-Cb752 is high as compared with Inconel X-750 and C-SiC, which implies that the structure absorbs more heat from the combustor implying larger area is required to dissipate the heat resulting in heavier panels: 42- 44 kg/m^2. The density and thermal conductivity of Inconel X-750 lies midway between that of Nb-Cb752 and C-SiC hence the weight per area of panel required is 27-29 kg/m^2. Roughly, the weight per area values for the three substrate materials with TBC's are in the ratio of 1:2:3 for C-SiC: Inconel 750: Nb Cb 752, for a fixed mass flow rate of 2.5 mass flow units. With increased flow rate of the fuel/coolant in the panel, the weight of panel material per unit area decreases as it carries away more heat. However, while increasing the fuel flow rates, the fuel pressure drop restrictions should be kept in mind.

When different TBC materials for the two metallic substrates are considered, LC shows minimum weight per area in the range of fuel flow rates analysed. The weight per area is less by at least 2 - 4 % relative to the other TBC combinations. When fuel flow rate is increased, the Inconel X-750 substrate with the various TBC's shows the largest decrease in weight per area as compared to the other two materials.

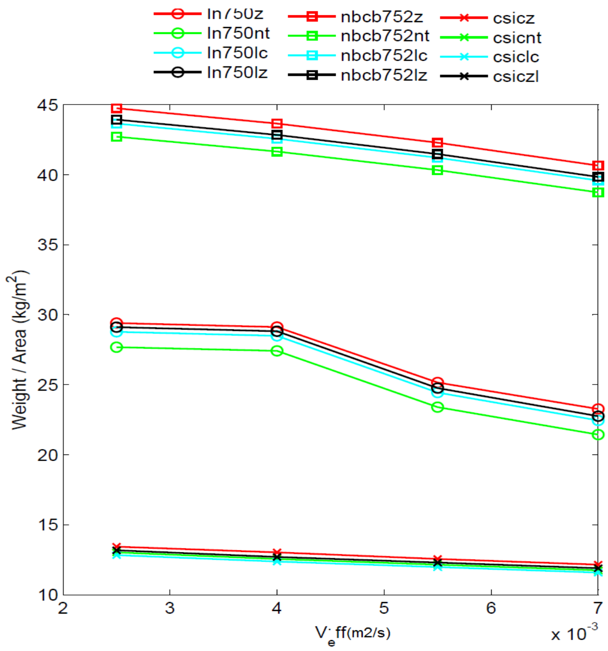

Figure 2 Variation of weight/area of the panel for different materials and TBC's with respect to fuel flow rate.
nt- No TBC; z- with YSZ; lc- with $La_2Ce_2O_7$; lz- with $La_2Zr_2O_7$

Effect of TBC thickness on heat gained by fuel/coolant

Figure 3 shows the sensitivity study of heat gained by the fuel/coolant as a function of different active panel materials coated with different TBC's and their thicknesses ranging from 0.5 to 3.5 mm. Nb-Cb 752 shows the highest fuel heat absorbing capacity due to its higher thermal conductivity which increases the amount of heat entering inside the material which is subsequently absorbed by the fuel. Inconel X-750 shows decreased fuel heat sink capacity as compared to C-SiC panel material in spite of C-SiC having lower thermal conductivity than Inconel X-750. This may be due to the lower density of C-SiC. For the three active panel materials, as the thickness of the TBC coating increases from 0.5 to 3.5mm the heat gained by the fuel decreases due to increased thermal resistance. The three TBC's show a consistent pattern with the three material substrates in that the heat gained by the fuel decreases in the order: z > lz > lc for the range of thicknesses of TBC's analysed. Higher thermal conductivity of YSZ may be the reason for this trend. When the thickness of the TBC material is varied from 0.5 to 3.5 mm, the heat absorbing capacity of the fuel decreased by 16% in the case of LC (as the TBC), 11.7% for LZ TBC, and 5.5% for YSZ. Based on the observations, it is inferred that a TBC material with low thermal conductivity absorbs less heat from the combustor side by satisfying the material and fuel temperature constraints; hence LC can be recommended as a suitable TBC for the combustor liner. The fuel heat gain ($\dot{m}\, C_p\, \Delta T$). $\dot{m}$ = ρ × Area of the panel × Velocity of the fluid

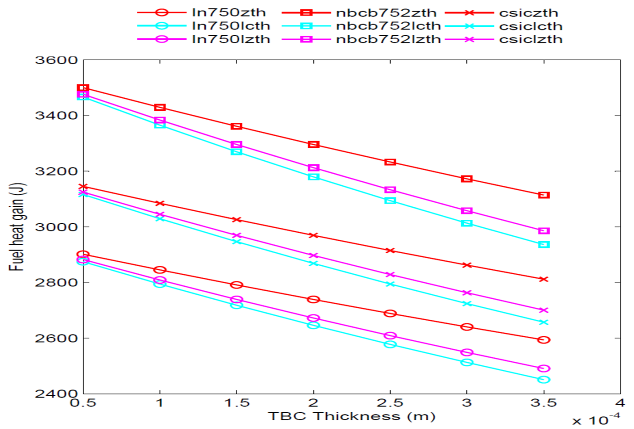

Figure 3 Variation of fuel heat gain with the thickness of the TBC. (zth- YSZ; lcth- $La_2Ce_2O_7$; lzth- $La_2Zr_2O_7$)

Effect of TBC coating thickness on the weight/area of the cooling panel

Figure 4, shows the plots of variation of thickness of the TBC's on the x-axis and weight per area of the active panel on the y-axis. The 2-D heat transfer analysis shows that the variation in weight per area of the panel is negligible for a specific material coated with the three different TBC materials for the range of TBC thicknesses considered. This indicates that the type of panel material plays a dominate role compared to the parameters such as type of TBC's and fuel flow rates are unimportant.

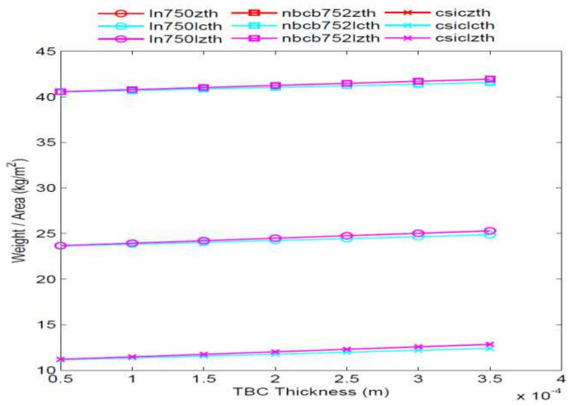

Figure 4 Change of weight of the panel to the Thickness of TBC. (zth- YSZ ; lcth- $La_2Ce_2O_7$; lzth- $La_2Zr_2O_7$)

Effect of combustor side heat transfer coefficient 'h_G' on the fuel/coolant outlet temperature

Figure 5 shows that when heat transfer coefficient from the combustor side (h_G) increases the fuel/coolant outlet temperature increases with C-SiC active panel showing the greatest increase followed by Inconel X-750 and NbCb752. The fuel/coolant outlet temperature is highest in the case of C-SiC even though the amount of heat absorbed by the fuel is less due to its lower thermal conductivity. It may be attributed to the absorbing capacity of the wall down stream of the panel is less because of lower thermal conductivity of the panel. For heat transfer coefficients above 1000 W/m^2 K, the outlet temperature of the fuel nearly reaches the coking temperature of the fuel, hence at such high heat transfer coefficient, C-SiC material is not suitable. The increase in fuel/coolant outlet temperature in case of C-SiC panel is in the range of 1020 – 1070 K, which is above the prescribed temperature limit of JP-7 fuel. In the coolant channels, the regions where the fuel temperauture has crossed above 975 K, the coke formation will take place. And this phenomenon will have detrimental affect on the structural integrity of the actively cooled panel made of C-SiC. In the contrast, Nb-Cb752 material sustains the high heat flux corresponding to heat transfer coefficient upto 1600 W/m^2 K and Inconel X-750 sustains upto 1400 W/m^2 K. The fuel/coolant outlet temperatures in these cases are well below the coking temperture of the fuel. From practical considerations in coating NbCb752 material and data presented, Inconel X-750 is capable of sustaining high heat fluxes with moderate heat gain and moderate weight.

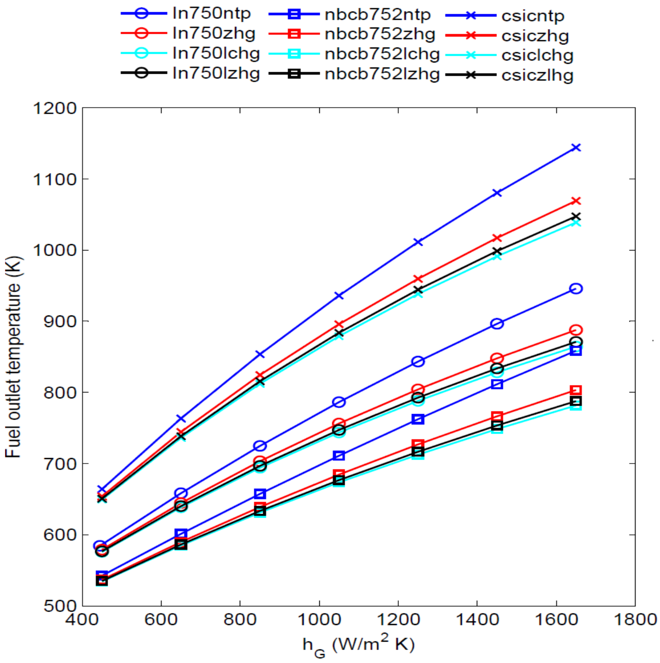

Figure 5 Variation of fuel outlet temperature as a function of Combustor side heat transfer coefficient (ntp- noTBC; z- YSZ; lc- $La_2Ce_2O_7$; lz- $La_2Zr_2O_7$)

CONCLUSIONS

1. Employing $La_2Ce_2O_7$ and $La_2Zr_2O_7$ as TBC materials, the difference in active cooled panel material weight and heat gained by the fuel are nearly identical with YSZ being used as TBC on the active cooled panel material. These resembling features of various cooled panel materials can be attributed to similar thermo-physical properties except for the thermal coefficient of expansion.
2. The variation in weight per area of a particular active cooled panel material with various thicknesses of TBC's is negligible.
3. Inconel X-750 is capable of sustaining high heat transfer coefficients with fuel/coolant heat gain well below fuel coking temperature with moderate weight to area ratio.

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