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Thermal Barrier Coatings for Temperature Management of Gas-Turbine blades

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***Abstract*—**Many types of coatings are suggested and implemented to protect various structural engineering surfaces from corrosion, erosion, and wear and to provide lubrication and thermal insulation. Of all these, thermal barrier coatings (TBCs) in the most demanding high temperature environment of industrial gas-turbines, TBCs that comprise multilayer of metals and ceramics to prevent turbine blades and combustor engine components from exposing to high heat flux due to elevated temperatures of hot combustion gases stream.

In this work a mathematical model based on conservation equations of heat diffusion in the composite structure and the associated boundary conditions at the inner and outer surfaces of the turbine blade has been developed taking into account the interface conductivities as well as the thermal contact resistances between the TBCs , bonding agent and super alloy. The heat diffusion equation and the corresponding boundary conditions are discretized using finite volume technique to arrive at a system of linear algebraic equations which are solved using tri-diagonal matrix algorithm (TDMA). The preliminary results have shown that implementing TBCs at the surface that is exposed to hot combustion gases reduces the turbine-blade temperature to the design limit. Numerical experiments have been conducted for different TBCs materials to assess the effect of thermo physical properties on the temperature distribution for different boundary conditions.

***Index Terms*—** Elevated Temperatures, Heat Transfer, TBCs, Turbine-Blades.

I. INTRODUCTION

Thermal barrier coatings (TBCs) is a technique that has been suggested and implemented to reduce the surface temperature of high temperature components such as the pistons in diesel and air craft engines as well as the exposed surface of gas turbine blades to the combustion gases. Due to the low thermal conductivity of this material, a temperature drop in the range of 200 0C to 250 0C can be achieved through thermal isolation in TBCs with an inner cooling system. The structure of thermal barrier coatings (TBCs) normally are composed of four layers of temperature resistance material: ceramic top coating, from which low thermal conductivity is required. It is, in most cases ZrO2 oxide stabilized with Y2O3, this has the lowest value of thermal conductivity in elevated temperature of a rank 2.3 W/m K in 1000 oC and thermal expansion of a rank 11x10-6 /oC that enables to reduce thermal stresses, the thickness of this layer usually within the range of 250 to 375µm. the other two are bond coating and Ni superalloy substrate layers. The fourth layer named as thermally grown oxide (TGO) is formed between the ceramic and bond coating layers as an effect of oxidation of the bond coat during oxidation and thermal shocks. Because of the considerable differences of thermal and mechanical properties of the material forming TBCs, thermal stresses developed in TBCs may result in coating failure. The high temperature and stress concentrations may result in crack development that will propagate through the TBCs that may lead directly to the failure of the turbine blades. Therefore knowledge of stress and temperature distributions is essential for the proper turbine operation.

Due to the complex shape of the turbine blades and the structure of TBCs, analytical solutions of temperature profiles within the blade are unavailable even for simple cases. Therefore it is necessary to direct our attention to the computational fluid dynamics CFD techniques to predict properly and accurately the thermal field within the blade structure. Recent development of computational fluid dynamics codes based on finite element (FEM) or finite volume (FVM) methods, much work has been done to determine temperature distributions for several working conditions. Temperature distributions with conjugate heat transfer analysis was discussed, where the thermal and flow field are solved simultaneously in the flow domain and the material structure of the blade. Gosia[2] and Buyukkaya[3] studied the influence of TBCs and quantity of cooling agent on the temperature distribution in turbine blades and the weak spots at which damage occur as well as progressive fracturing of the most affected cross sections of the blade by using the submodeling and FEM method. Cerit et al.[5] introduced a model involving transient thermal analysis and viscoplastic damage to predict the durability of turbine components. Furthermore, considerable research about stress evolution in turbine blades using TBCs has been conducted. As an example the generation and development of residual stress under cyclic loading were conducted and the effect of interface asperity on the stress formation was investigated. The influence on the thermal oxidation growth TGO at elevated temperatures on the stress distribution was studied by Baig et al[6] assumes anisotropic swelling of the elements in the TGO layer. In the literature, many other finite volume and finite elements models have been developed to simulate crack initiation and propagation process of interface by using cohesive zone elements.

In the present study a one dimensional finite volume transient model of a turbine blade with four –layers TBCs is built up to predict temperature distributions at different times during the transient process. In this model the heat conduction equation with the corresponding boundary conditions are descretized to form a system of linear algebraic equations which are solved using TDMA.

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II. MATHEMATICAL MODEL

The performance of gas turbine engines may be improved by increasing the tolerance of the turbine blades to hot gases emerging from the combustor. One approach to achieving high operating temperatures involves application of a thermal barrier coating (TBC) to the exterior surface of the blade, while passing cooling air through the blade. Typically, the blade is made from a high temperature superalloy, such as Inconel (k = 25 W/m. K), while a ceramic, such as Zirconia (k = 1.3 W/m.K) is used as TBC. In this work, the Thermal Barrier Coatings (TBC) in addition to the substrate of Ni- superalloys forms the computational domain of the one-dimensional transient model for a typical gas turbine blade, as shown in figure 1. In this figure, the left boundary is exposed to gases at high temperature from the combustor while the right boundary (the inner side of the blade) is exposed to cooling air. The interaction of both boundaries with the surrounding fluids is described by surfaces energy balance at both sides with heat transfer coefficients of 1000 W/m2 K. and 500 W/m2 K for the hot and cold fluids respectively. The conditions of hot gases at 1700 K and cooling air at 400 K are considered.

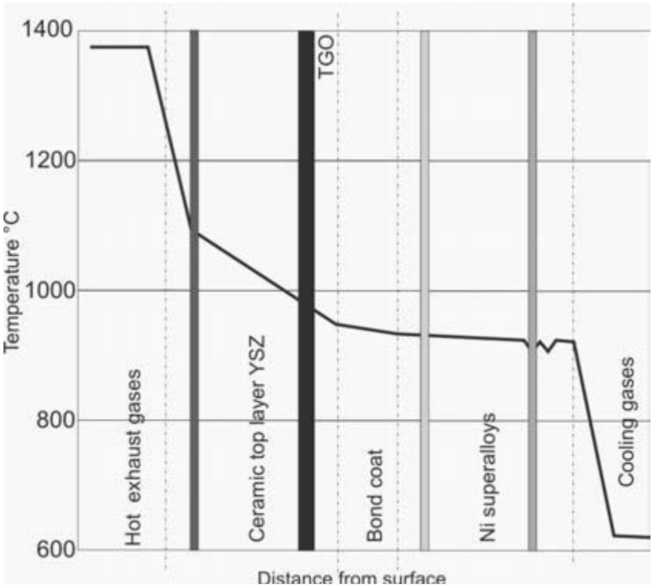

Fig. 1. Distribution of temperature on surface of an element with TBCs [1]

A. Governing heat transfer equations:

The transient heat conduction equation of the proposed model can be written as,

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) \tag{1}$$

And the associated boundary conditions are,

$$k \frac{\partial T}{\partial x} = h_g\left(T - T_g\right) \ at \ x = 0 \tag{2}$$

$$-k \frac{\partial T}{\partial x} = h_a\left(T - T_a\right) \ at \ x = L \tag{3}$$

With the interface boundary condition,

$$-k \frac{\partial T}{\partial x} = h_i\left(T_i - T_{i+1}\right) \tag{4}$$

The initial condition is,

$$T(x,0) \quad = \quad T_i \tag{5}$$

The transient heat conduction equation (equation 1) is applicable to each layer of the TBCs, while equations 2, and 3 are the results of surface energy balance at the outer and inner boundary respectively. The thermophysical properties of the material for each layer are listed in the table below. In this model it is assumed that each layer of the turbine blade is considered as an isotropic and homogeneous material.

TABLE I
TEMPERATURE DEPENDENT MATERIAL PROPERTIES FOR DIFFERENT LAYERS [1]

	Substrate	Bond Coat	TGO	Top Coat
Temperature Range (C°)	20-1100	20-1100	20-1100	20-1100
Young's Module(GPa)	220-120	200-110	400-320	48-22
Poisson's ratio	0.31-0.35	0.3-0.33	0.23-0.25	0.10-0.12
Thermal Expansion Coefficient(10^{-6}/°C)	11.0	13.6-17.	8.0-9.6	9.0-12.2
Thermal Conductivity (W/(m K))	88-69	5.8-17.0	10-4.0	2.0-1.7
Density(Kg/m^3)	8500	7380	3984	3610
Specific heat (J/kg K)	440	450	755	505

III. NUMERICAL SIMULATION

In the calculation domain, a one-dimensional turbine blade with TBCs comprising four layers (TC, TGO, BC and Ni-based alloy substrate) is shown in Fig. 1. The thicknesses of Top Coating, Bond Coating, and substrate are 0.5 mm, 0.1 mm and 5.0 mm, respectively. It was reported that the thickness of TGO is within the range of 10-20μm and it has negligible influence on stress for a thick ceramic coating higher than 50 μm. in this work the TGO thickness is set to 0.01 mm. It is worth noting that in constructing the numerical model, the following assumptions has been assumed: (1) each layer of the thermal barrier coatings was perfectly bonded without any cracks; (2) thermal and mechanical effects of porosity, creep, phase transformation, sintering of TBC and TGO were not considered; (3) radiation exchange at both boundaries was not taken into account (4) the thermophysical properties are assumed to be uniform over each control volume and independent of temperature. Based on the geometric description shown in figure 1, and the assumptions mentioned above, the conservation equations of energy; equations, 1,2 and 3 are descretized using finite volume method [7]. In this method, the calculation domain is divided into a number of non-overlapping control volumes where the conservation equations must be satisfied for each control volume and overall the computational domain. In this work a non-uniform grid is adopted where dense control volumes are constructed in regions that have abrupt change of thermal properties. The harmonic mean conductivity is adopted to account for the variation of thermal conductivity at the control volumes faces where the adjacent materials have different conductivity. When the differential equation and the associated boundary conditions are integrated over each control volume surrounding each grid point, with piecewise profiles expressing the variation of temperature between the grid points are used to evaluate the required integral, the result is an algebraic equations containing the value of the dependent variable, temperature, for a group of grid points. These algebraic equations are solved simultaneously using TDMA, TriDiagonal-Matrix Algorithm to obtain the value of temperature over each grid point.

In order to guarantee accuracy and efficiency, a mesh dependency test is performed to limit the number of control volumes to an acceptable value. In this case, several runs have been conducted and a refined grid of 120 control volumes meets the demand of mesh sensitivity. It worth noted that the code developed in this work to simulate the turbine blade uses time step of 0.2 second with fully implicit scheme.

IV. RESULTS AND DISCUSSIONS

Numerical simulations have been performed to investigate the effect of thermal barrier coating on the temperature distribution and the possible reduction of surface temperature of the gas turbine blade. In order to determine the time required to reach the steady-state solution, two simulation runs were conducted and the results are demonstrated in figures 1and 2. Fig. 1 shows that the maximum temperature of the blade surface attains the steady state condition at approximately 60 seconds. The temperature distribution at different times is shown in Fig. 2 and the steady-state distribution is reached within the range of 60 to 80 seconds.

The main objective of this work was to investigate the effect of coating on the temperature profile within the blade wall. Fig. 3 shows the results of simulations for coated and uncoated conditions, it is clear that bonding a layer of low thermal conductivity has considerable affect on reducing the temperature over the entire blade wall. It is noted that the reduction is more pronounced at the far end of the plate adjacent to cold side. This temperature drop due to the application of TBC may reduce thermal stresses, fatigue and hence increase the life time of the material (durability). In this work, 160 oC of temperature drop was achieved at the extreme locations where elevated temperatures are more pronounced. It is worth noted that the maximum allowable operation temperature of the Ni-superalloy substrate is within the limit of 1250 oC [9].

Under the same conditions, a plot of the temperature vs coating thickness is shown in Fig.4 for the ceramic coating thicknesses of 5mm, 6mm, 7mm, and 8mm for both Mg-PSZ and Y-PSZ. It is seen that the maximum temperature on top of the coating surface are 1294 K, 1323K, 1348K, and 1369K for Mg-PSZ and 1230K, 1262K, 1290K, and 1314K for Y-PSZ respectively. It is well known that the strength of the material depends on the temperature. It decreases with increasing temperature. The strength of the gas turbine blade is improved by lowering operating temperatures; this leads to increase in blade life. It is hence that very important that the temperature of the substrate is at a lower level.

V. CONCLUSION

A one-dimensional numerical model of a turbine blade with TBCs has been developed to investigate the temperature distribution. The model assumes convection-conduction boundary conditions on top of the coating surface and at the substrate side, while implementing the interface boundary condition in the interior nodes of the calculation domain. A computer code in FORTRAN has been developed to simulate the thermal conditions of the gas turbine blade (GTB). The main conclusions of this work are: (1) Application of TBC is very effective in reducing blade temperature below the maximum operating value which leads to improve blade durability. (2) Coating thickness has considerable affect on GTB temperature. (3) The type of coating material influences the temperature distribution and contributes well to the durability and life time of the GTB.

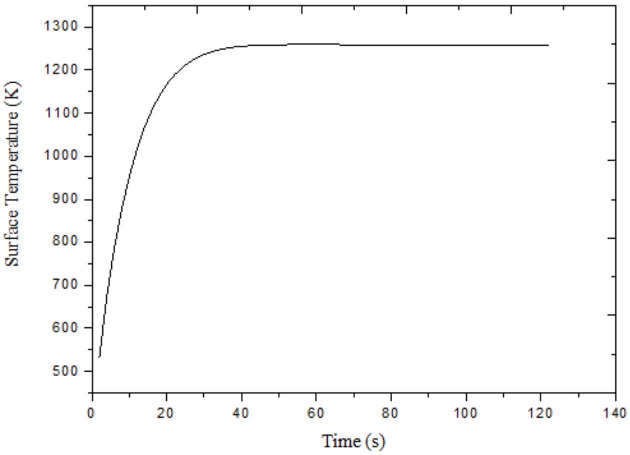

Fig.1.Temperature of top coating surface Vs Time

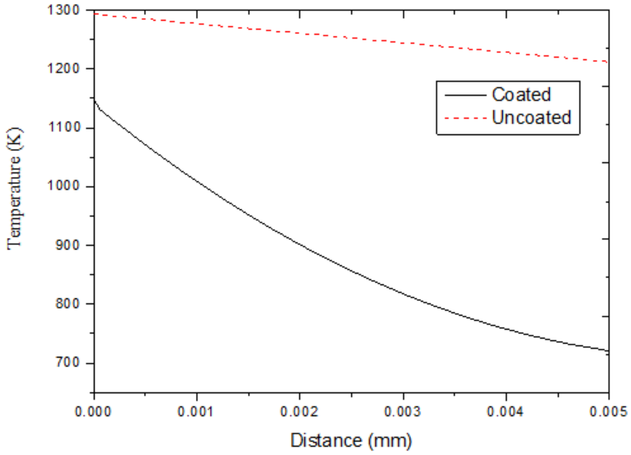

Fig.3. Temperature Distribution with coating and without coating

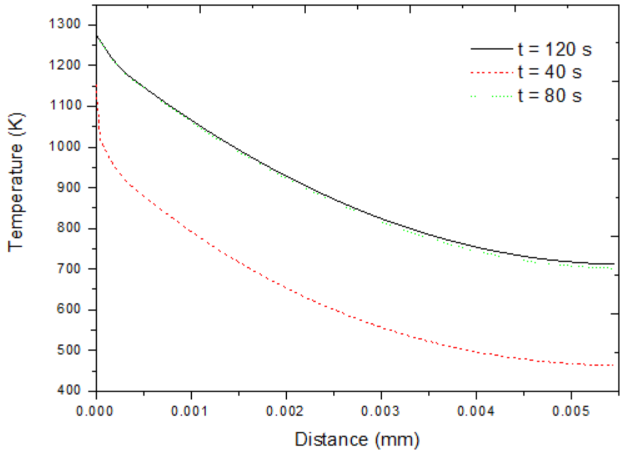

Fig.2. Distribution of temperature at different times

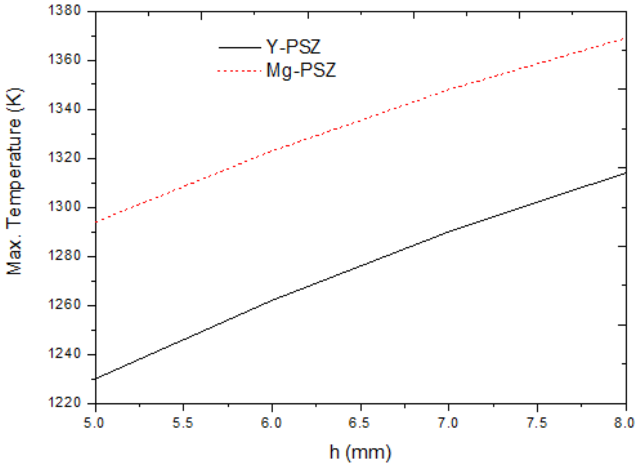

Fig.4.Maximum Temperature on the blade Vs Coating thickness

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