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Numerical Investigation of the Effect of Thermal Barrier Coating on Heat Transfer and Wall Temperature in V94.2 Gas Turbine Combustor

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Abstract

Thermal barrier coating (TBC) has been considered in current investigation in order to increase mixing chamber and inner casing lifetime in V94.2 gas turbine combustor. These parts are exposed to hot flow produced by burner. Based on the mentioned concerns, on the hot side, TBC has been considered. The temperature gradient for turbulent flow and casings are presented. The results have shown that by using TBC, heat flux rate declined notably compared to the case where TBC was not applied. In the existence of TBC, the temperature distribution has changed significantly, which is important in changing the wall temperature of the combustor. The maximum temperature in the mixing chamber decreased by 160 K whereas in the inner casing maximum temperature dropped by 24 K. Hot spots in mixing chamber and inner casing are considerably reduced. The heat flux rate in mixing chamber is higher than that of inner casing since the temperature difference and convection heat transfer coefficient in mixing chamber is higher.

Keywords: V94.2, Mixing chamber, Inner casing, TBC, Combustion

Introduction

The global demand for power grows faster than the world’s population. With a lifetime expectancy of a gas turbine, the gas turbine surpasses the design lifetime by far. Essential components of the V94.2 gas turbines especially the components of the hot gas path (mixing chamber and inner casing) are designed for an operating time of 100,000 equivalent operating hours (EOH). To assure reliable and safe operation of the gas turbine even beyond the design lifetime of the components, Turbotec company has developed the "Ultra Extended Lifetime" (UEL) program. All the suggestions for improvement are developed based on the original design of V94.2. The purpose of the UEL program is to give the operators of V94.2 gas turbines an opportunity to run the gas turbine beyond the limited design life-time of the gas turbine components. The UEL procedures are to guarantee high availability, reliability and safety. Mixing chamber and inner casing are exposed to stress caused by temperature or static and dynamic loading like creep, low-cycle fatigue (LCF) and high-cycle fatigue (HCF), erosion, oxidation and high temperature corrosion as well as mechanical stress and wear [1]. In the recent years, a lot of improvements and investigations have been performed by different organizations. Ansaldo company [2] has made some modification to upgrade V94.2 combustor. Ansaldo has employed AE94.2 Advanced Low NOx Burner for lowering the emission in V94.2 combustor. Siemens company [3] also had initiated a development in order to upgrade V94.2. Siemens has performed series of programs to improve the functionality of V94.2 gas turbine combustor which involved hiring new materials and new design for combustor elements. Bashooki et al. [4] have studied the considerable approaches to reduce NOx. In regard to their case study (FARS gas turbine power plant), the results showed that the V94.2 combustor needs to operate only in premixed mode with DLN (Dry Low NOx) burner in order to decline emissions since there is a diffusion mode for liquid fuel. Raja et al. [5] have investigated modification for combustion chamber of V94.2 gas turbine in diffusion mode. According to the results, modification on plenum has had considerable effect on uniformity of air flow distribution and maximum flame temperature of each burner. Uniformity of temperature distribution and air flow in combustor and equality of equivalence ratio in each burner would have noteworthy influence on pollution reduction. The main goal of this paper is to present a new approach in order to prolong the lifetime of the mixing chamber and inner casing in V94.2 combustor. By doing so, TBC is employed for lowering the components wall temperature.

Numerical methods

In the present study, Ansys Fluent and Ansys Meshing are employed for simulating and meshing the domain, respectively. The SIMPLE C algorithm [6] is applied for connecting the pressure and velocity terms. Discrete ordinate model (DOM) [7] is applied to model the thermal radiation. For achieving the wall temperature, the temperature profiles extracted from fluid domain have been used and after that, the wall temperatures have been imported to fluid domain in order to start the simulation from the beginning to reduce the mean deviation in solution. This procedure has been done 3 time for more accuracy.

Equations

The standard k-ε transport equations are employed in order to simulate the turbulent flow. These equations are defined as follows:

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_i k)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon \tag{1}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\frac{\partial(\rho u_i \varepsilon)}{\partial x_i}=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right]+C_{1\varepsilon}\frac{\epsilon}{k}G_k-\rho C_{2\varepsilon}\frac{\varepsilon^2}{k} \tag{2}$$

Energy equation for thermal analysis has been considered which is in the following form:

$$\frac{\partial(\rho E)}{\partial t}+\nabla\cdot\left(\vec{v}(\rho E+p)\right)=\nabla\cdot\left(k_{eff}\nabla T-\sum_j h_j\vec{J}_j+\left(\bar{\bar{\tau}}_{eff}\cdot\vec{v}\right)\right)+S_h \tag{3}$$

In a reactive flow, the radiation heat transfer must be modeled owing to the existence of a great temperature zone. DOM is expressed as follows:

$$\frac{d(Is)}{dx_i}+\left(\alpha+\alpha_p+\sigma_p\right)I(r.s)=\alpha n^2\frac{\sigma' T^4}{\pi}+E_p+\frac{\sigma_p}{4\pi}\int_0^{4\pi}I(r.\acute{s})\eta(s.\acute{s})d\acute{\Omega} \tag{4}$$

$$E_p=\lim_{V\to 0}\sum_{n=1}^{N}\varepsilon_{pn}A_{pn}\frac{\sigma T_{pn}^4}{\pi V} \tag{4-a}$$

$$\alpha_p=\lim_{V\to 0}\sum_{n=1}^{N}\varepsilon_{pn}\frac{A_{pn}}{V} \tag{4-b}$$

$$\sigma_p=\lim_{V\to 0}\sum_{n=1}^{N}(1-\sigma_{pn})(1-\varepsilon_{pn})\frac{A_{pn}}{V} \tag{4-c}$$

Geometry and Boundary Conditions

All the components exposed to hot side of V94.2 combustor have demonstrated in Figure 1. The red, yellow and brown parts refer to flame tube, mixing chamber and inner casing, respectively. For flame tube, the domain is shown by one-third (The other two-third which includes the burners, is simulated separately [8]).

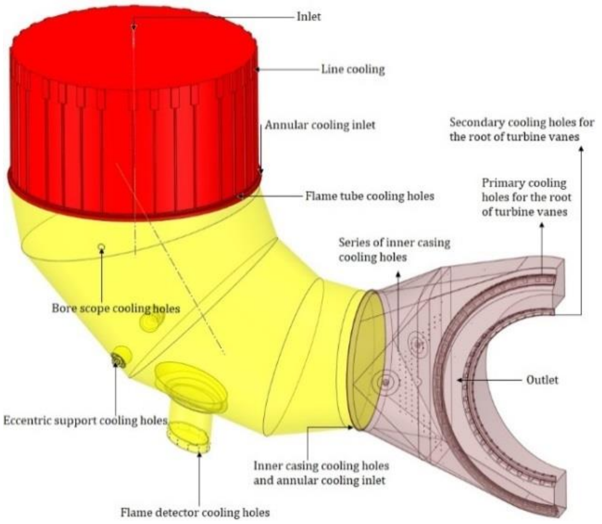

Figure 1. Fluid domain (hot zone)

Boundary conditions for fluid domain is indicated in Table 1. At all inlets, profiles extracted from previous solution [8] are used. Other boundary conditions also are extracted from aerothermal solution [8]. All the data in profile type are obtained from Ansys Fluent software (Table 1).

Table 1. Boundary conditions

Boundary condition	Value
Inlet	Profile
Annular cooling inlet	Profile
Inner casing annular cooling inlet	Profile
Wall (hot side and cold side)	Profile

The TBC coated mixing chamber and inner casing have illustrated in Figure 2. The yellow layer indicates TBC. The gray color represents the body of the mentioned components.

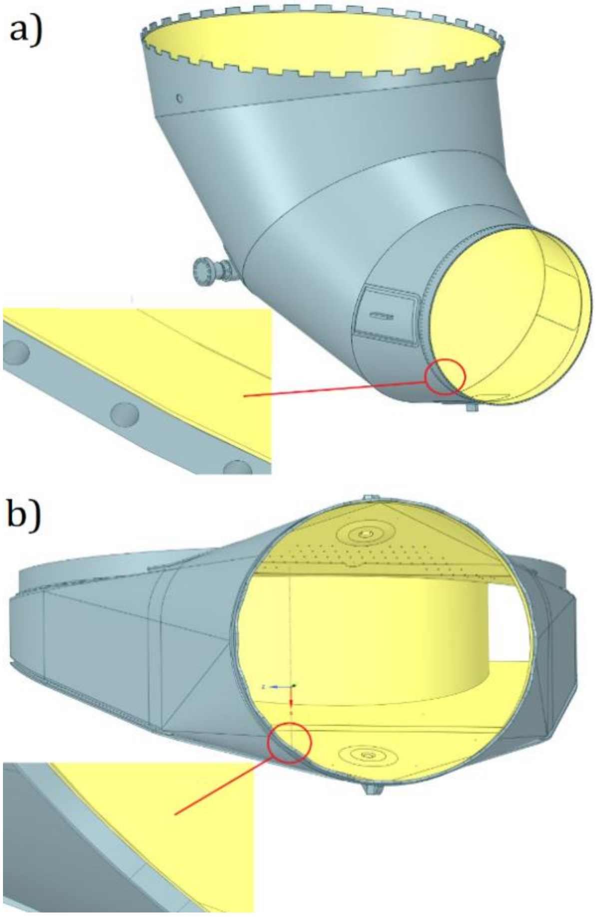

Figure 2. TBC for a) mixing chamber and b) inner casing

In order to perform the computations, the geometry is discretized by the unstructured grid. Unstructured grids for fluid domain and combustor walls are illustrated in Figure 3 and 4, respectively.

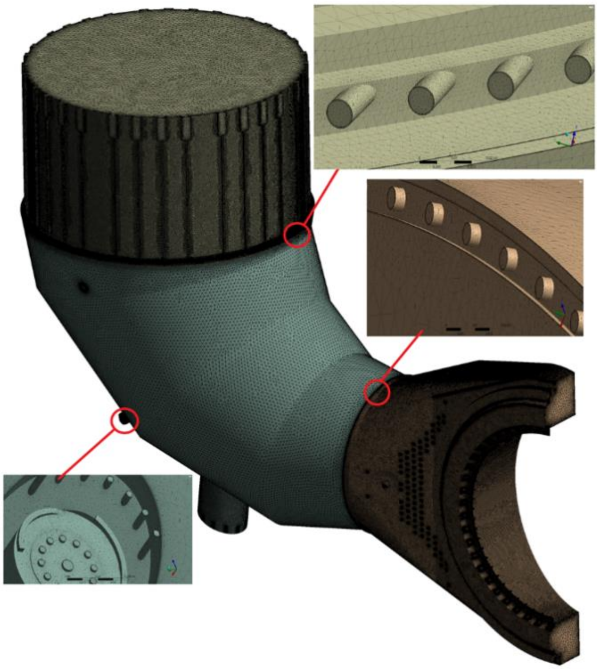

Figure 3. Unstructured grid for fluid domain

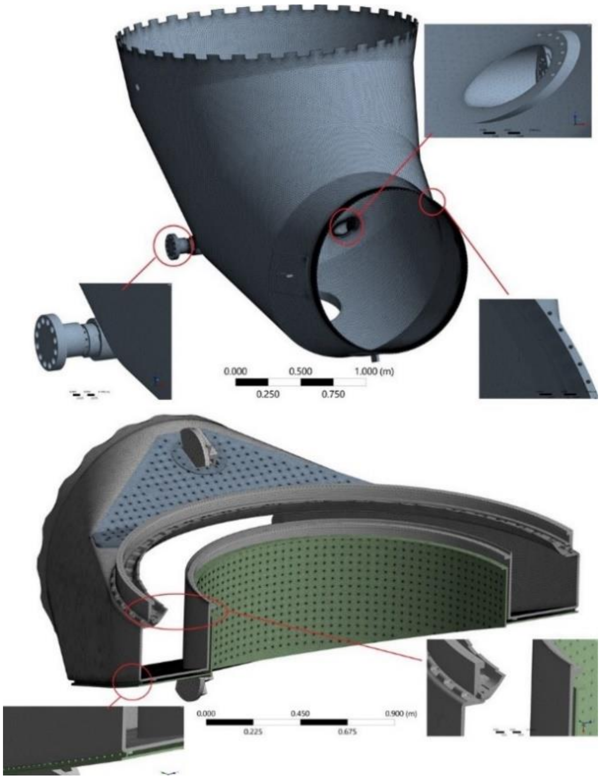

Figure 4. Unstructured grids for mixing chamber and inner casing

There has been a quite challenges for accomplishing the current grids due to complex geometries. For fluid domain, boundary layer with the first layer thickness of 0.01mm and 14 layer is included. The grid size of each domain is shown in Table 2.

Table 2. Different grid sizes

Name	Size
Fluid domain	52.7×10^6
Mixing chamber	4.7×10^6
Inner casing	5.8×10^6

Results and discussion

Simulations have performed in both the presence and the absence of TBC. All the data for temperature have been normalized. As shown in Figure 5, the temperature distribution for the mainstream is given along the combustion chamber. The TBC layer by reducing the conduction heat transfer rate, increases the average temperature in fluid domain which led to higher maximum temperature (about 2.3%). In the existence of TBC, the temperature distribution has changed significantly, which is important in changing the wall temperature of the combustor. Furthermore, the effect of cooling holes on temperature distribution near the walls can be seen.

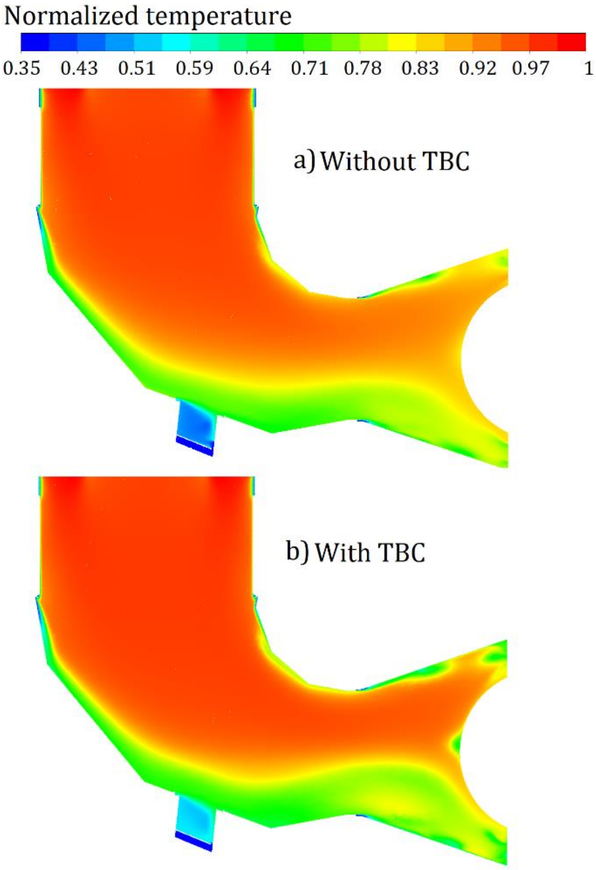

Figure 5. Normalized temperature distribution for fluid domain a) without TBC and b) with TBC

For mixing chamber, the wall temperature is shown in Figure 6. The temperature gradient is more uniform in comparison to the case without TBC. Furthermore, the temperature distribution at the inlet has not changed since no TBC layer is employed in that location. In the condition with TBC, the maximum temperature in the mixing chamber decreased by 160 K.

In addition, hot spots in the wall are highly reduced. Figure 7 indicates the wall temperature of inner casing. The temperature gradient is more desirable compared to the case without TBC. Furthermore, the region near the outlet where the temperature is high, the peak temperature happened to be lower (about 24 K) due to existence of TBC layer. In addition, Same as mixing chamber, hot spots in the wall are reduced. The noticeable difference between the two wall temperatures is the percentage of reduction in temperature due to variation of heat flux which is based on the temperature difference ($\Delta T = T_{Wall} - T_{\infty}$) and convection heat transfer coefficient (h). The temperature difference and convection heat transfer coefficient (based on Figure 5 and Figure 8) in mixing chamber is higher than that of inner casing.

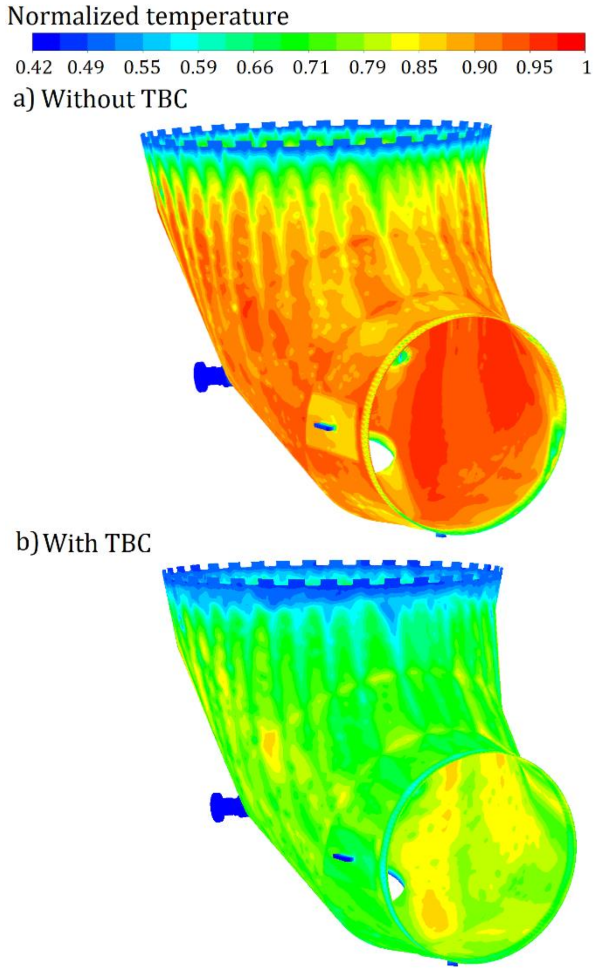

Figure 6. Normalized temperature for mixing chamber a) with TBC and b) without TBC

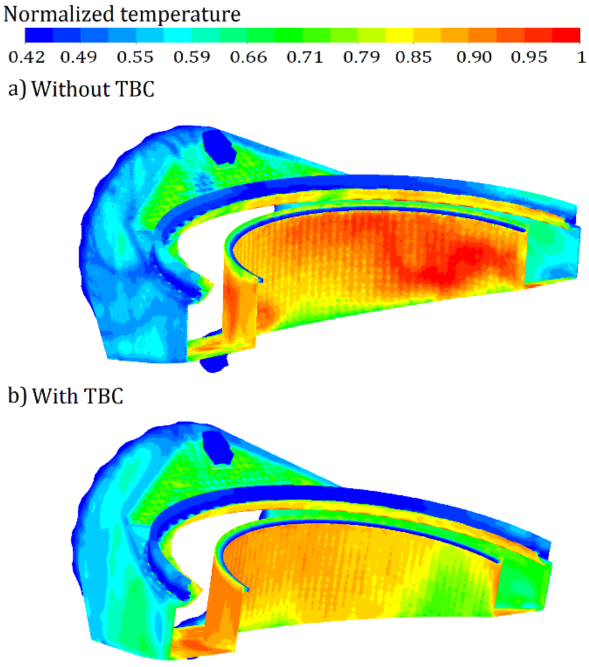

Figure 7. Temperature for inner casing a) with TBC and b) without TBC

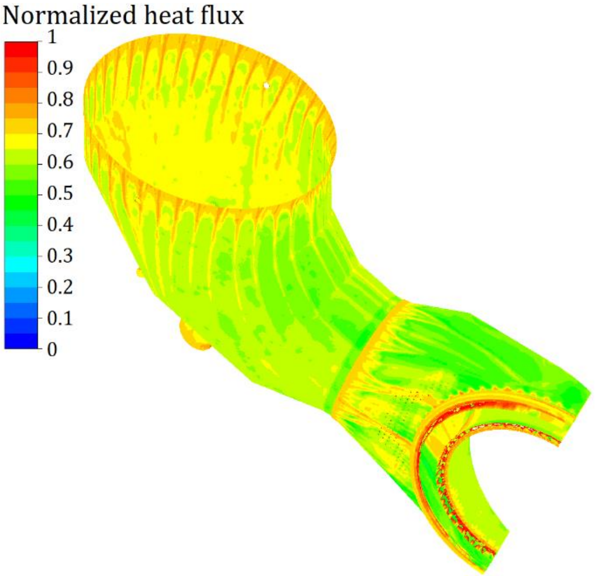

Figure 8. Normalized heat flux over the walls for mixing chamber and inner casing

Conclusions

In the present study, the effects of TBC on mixing chamber and inner casing walls in V94.2 gas turbine combustor is investigated by employing the standard k-ε transport and DOM for simulating the fluid flow and radiation, respectively. The main conclusions may be drawn, as follows:

1. In the existence of TBC, the temperature distribution has changed significantly, which is important in changing the wall temperature of the combustor.
2. For mixing chamber, the temperature gradient is more uniform in comparison to the case without TBC.
3. The noticeable difference between the two wall temperatures is the amount of reduction in

mixing chamber (about 160 K) and inner casing (about 24 K).

4. The heat flux rate in mixing chamber is higher than that of inner casing.

List of Symbols

A_{pn}	Surface area of particle
D_{pn}	Particle diameter
$C_{1\varepsilon}, C_{2\varepsilon}$	Constant number in standard k-ε equation
E	Energy
G_k	Source generation of turbulence kinetic energy
h_j	Sensible enthalpy
I	Radiation intensity
J_j	Diffusion flux of species j
k	Turbulence kinetic energy
k_{eff}	Effective conductivity
n	Refractive index
E_p	Equivalent emission
P	Pressure
S_h	Source of heat of chemical reaction
T_{Wall}	Wall temperature
T_∞	Adjacent flow temperature
T_{pn}	Particle temperature
t	Time
u_j	Velocity component (m/s)
x_j	Cartesian coordinates
ρ	Density (kg/m^3)
α	Absorption coefficient
α_p	Equivalent absorption coefficient
σ_p	Equivalent particle scattering factor
σ	Turbulent Prandtl number
τ	Viscous stress (N/m^2)
r	Position vector
s	Direction vector
ε	Dissipation rate of turbulence kinetic energy
μ	Dynamic viscosity (Ns/m^2)
υ	Velocity vector

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