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Study on TBCs insulation characteristics of a turbine blade under serving conditions

J.H. Liu [a], Y.B. Liu [a,*], X. He [a], L. Liu [b]

[a] College of Power Engineering, Naval University of Engineering, Wuhan 430033, China
[b] College of Physics Science and Engineering Technology, Yichun University, Yichun 336000, China

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ABSTRACT

It is a key problem to study thermal barrier coatings (TBCs) insulation and followed stresses for the coated blade. This article focused on the insulation characteristics of TBCs by coupling heat transfer and flow with a multilayer blade. We found that the coated blade can benefit more in the decline of average temperature than the decline of maximum temperature, compared to the uncoated case. Temperature fluctuation on TBCs surface is evident. The inlet temperature of main flow (T_{in}) more than the heat transfer coefficient of cooling passages (h_{cool}) impacted the fluctuation. And there is a non-homogeneous distribution of the temperature decline (ΔT) across the coatings around the blade. At the suction side and the head, ΔT was generally higher than that of the pressure side and the tail. The TBCs thickness and T_{in} can affect ΔT more than h_{cool}. We suggest that in the sequential TBCs stresses simulation the actual temperature distribution should be prescribed.

1. Introduction

Thermal barrier coatings (TBCs) have been widely used to protect the hot components of the gas turbine, such as combustion, guide vane, and turbine blade, for the low thermal conductivity and well corrosion resistance [1,2]. TBCs normally consists of four layers including top coating (TC), thermally grown oxide (TGO), bond coating (BC), and substrate (SUB). Due to the differences of material properties and harsh environment in service, residual stresses always develops in the layers and result in coatings failure [3]. In the elevated temperature, the oxide diffusion and reaction with the aluminum gradually conduces the TGO growth, which accelerates the coatings failure [4,5]. Thermal mismatch and TGO growth are regarded as the major factors responsible for general failure of TBCs. Many investigations concentrated to explain the failure mechanism after thermal cycles [6–15].

However, the computational models of previous literatures based on the two dimensional periodic unit cannot cover the entire turbine blade geometry and the corresponding working conditions. Ranjbar-far et al. [14,15] built a model of TBCs considering the non-uniform temperature distribution, but the limit of the scale restricted the application to the whole blade.

Finite element method (FEM) has been used for blade heat transfer analysis. Tietz and Koshel [16] simulated three dimensional steady state temperatures distribution of a blade without TBCs using a FEM code. Kumar and Kale [17]

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* Corresponding author.
E-mail addresses: ljh363418@sina.cn (J.H. Liu), yongbaoliu@aliyun.com (Y.B. Liu), hexing_mail@163.com (X. He), ll4246@126.com (L. Liu).

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computed blade temperature field with a single layer TBCs considering radiation. But for these FEM model, the surface conditions such as wall temperature and heat transfer coefficient are required to be assigned, which was difficult to measure. Currently the couple of gas flow and heat transfer has been used to calculate the blade temperature with the conjugate heat transfer method (CHT) at the fluid-solid interface (FSI). Bohn et al. [18–20], York et al. [21,22], and Dong et al. [23] studied the couple of gas flow and heat transfer using CHT. The major advantage of CHT is that it is required no boundary conditions on FSI.

But numerical simulation on actual turbine component with multilayered TBCs encounters troubles in two aspects. One is the geometry dimension difference between the thickness of TBCs and the component space scale. The other is the complex actual service condition. The big dimension difference tends to induce difficulties in constructing the multilayered blade and bring cumbersomeness in meshing and simulation. Yang et al. [24], Zhu et al. [25], and Tang et al. [26] have made good efforts to build the actual blade with multiple layers. Yang et al. [24] and Zhu et al. [25] ignored the gas flow environment. In the latest work [26], the computational fluid dynamics (CFD) and conjugate heat transfer method (CHT) were used to calculate the temperature of TBCs considering the cascade flow and heat transfer conditions.

However, under the couple of gas flow and heat transfer, insulation characteristics of TBCs and surface temperature fluctuation of the blade were paid little attention, but it is important to assess insulation of TBCs and stresses distribution in aerodynamic environment. Temperature dependences of the material properties and the thermal load history can result in unique residual stresses.

In this paper a cascade computational model with multilayered blade was built, coupling the gas flow, heat transfer, and inner cooling by CHT technology. The effects of inlet temperature, inner passage heat transfer coefficient, and coating thickness on TBCs insulation performances were studied. Meanwhile the surface temperature fluctuation was also discussed.

2. Numerical methods

2.1. Computational model and couple method

Aerodynamic cascade flow model and the stator blade (Mark II guide vane) originated from Hylton et al. [27]. The blade has a constant cross section and ten coolant passages (marked with Arabic numeral 1–10 in Fig. 1). In the paper, three layers (TC, TGO, BC) were added upon the outer surface. The thickness of BC and TGO are 150 μm and 10 μm, and TC is variable from 100 μm to 300 μm. The boundary conditions were kept consistent with the experiment (run number 42) [27]; the inner boundaries of coolant passages were listed in Table 1 [28]. But for exploring the influences of the variable aerodynamic conditions on insulation of TBCs, the inlet temperature of main flow and the heat transfer coefficients of ten passages were modified. Ideal gas assumption and mesh the fluid and solid domain in a uniform frame were adopted, keeping the grids node to node align at interface, as shown in Fig. 1. To resolve the viscous boundary layer, Y plus value (y^+) of the grids adjacent to the solid wall was less than 1. Mesh independence was done and a steady analysis was carried out using shear stress transport turbulence model considering boundary transition. For realizing the couple of gas flow and heat transfer,

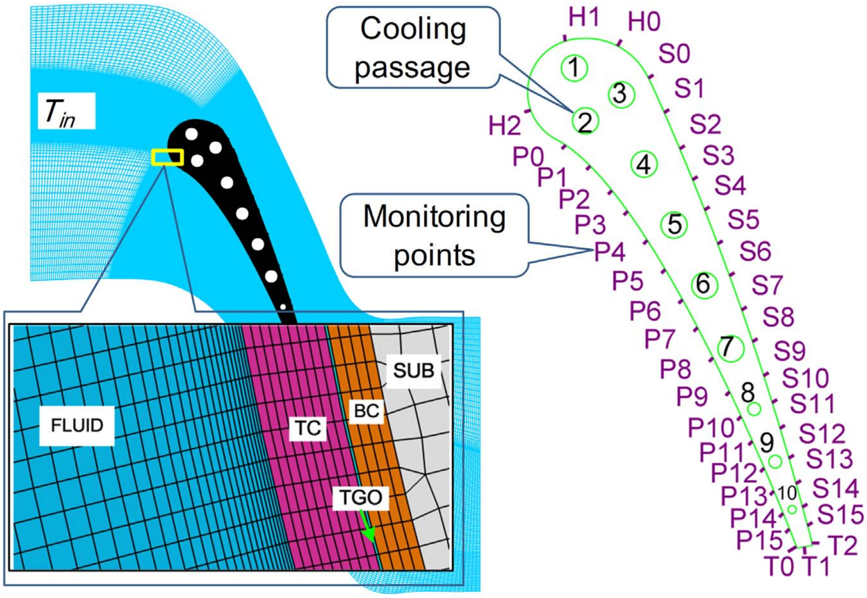

Fig. 1. Aerodynamic computational model and the local mesh (H0–H2, P0–P15, S0–S15, T0–T2 are the monitoring points at the head, the pressure side, the suction side, and the tail, respectively).