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To cite this article: P Prapamonthon *et al* 2019 *J. Phys.: Conf. Ser.* **1369** 012001

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5th International Workshop on Heat/Mass Transfer Advances
for Energy Conservation and Pollution Control
August 13-16, 2019, Novosibirsk, Russia

Numerically thermal analysis of a turbine vane at high temperature

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Abstract. Using conjugate heat transfer, thermal analysis of a turbine vane coated with thermal barrier coating (TBC) at a high temperature is presented. Numerical results are carried out at two turbine inlet temperatures (T_∞) i.e. 783 K (low) and 1566 K (high) under two turbulence intensities (Tus) i.e. 8.3% and 16.6%. The main findings of this research are that for both Tus , the metal surface temperature reduction at the high temperature is higher than that at the low temperature because of the lower heat-flux ratio at the higher temperature. Based on the metal temperature reduction, the increasing inlet temperature has a greater influence than the increasing turbulence intensity. The results also indicate that at $T_\infty = 783$ K, on the pressure side (PS) the metal surface temperature reduction at $Tu = 8.3\%$ is lower than that at $Tu = 16.6\%$, while on the suction side (SS) no significant difference happens when Tu increases. Interestingly, an inverse phenomenon happens for both PS and SS, that is the metal surface temperature reduction at $Tu = 8.3\%$ increases above that at $Tu = 16.6\%$ when T_∞ increases. This discrepancy may suggest the instability of the surface heat-flux ratio due to complex heat convection at the different inlet temperatures.

1. Introduction

It is a well-known fact that to obtain high power output and thermal efficiency, a gas-turbine engine needs to run under high-temperature operating conditions with high thermal load and high turbulence. Therefore, a highly sophisticated cooling system, as well as an effective thermal barrier coating (TBC), is basically essential for state-of-the-art gas turbines. So far, numerical and experimental studies of thermal analysis and aerodynamic feature at high temperatures of turbine airfoils have been provided for more than four decades. For example, Halila et al. [1] tested high-pressure turbine of energy efficient engine (E3) at 2012 K. Aero-thermal results of a film-cooled vane with a TBC thickness of 355.6 microns were carried out and their results were used as a reference for gas-turbine designers and investigators. Boyle et al. [2] Numerical investigated the role of ceramic matrix composites for a high-pressure turbine vane coated with a low conductivity layer thickness of 0.25 mm at 2141 K and 50 atm. Their conclusion was drawn by comparing the stress distribution of the vane with trailing edge ejection to that without trailing edge ejection. Feist et al. [3] experimentally studied to provide temperature data of a turbine engine with modified TBCs in the hot section at high temperature. Presently, computational fluid dynamics (CFD) is an effective computational approach that is commonly used in the gas-turbine field. Sadowski and Golewski [4] used this technique and computational structure mechanics (CSM) to analyze heat transfer and thermal stresses of a coated turbine vane with TBC at high temperatures up to 1600 K. Alizadeh et al. [5] used this approach with conjugate heat transfer (CHT) to indicate thermal sensitivity of a turbine blade at various temperature from 1450 to 1510 K and TBC thickness from 10 to 300 micron. Although the high-temperature investigation within turbine parts has been investigated in several aspects by many researchers as mentioned above, complicated phenomena of fluid flow and heat transfer under real circumstances are



still challenging because there are many thorny questions that have not been addressed. The object of this research is to conduct a numerical study and predict thermal analysis of a convectively internal cooling turbine vane coated with a TBC layer at a high temperature. Effects of TBC and turbulence intensity (Tu) on thermally physical characteristics of the vane at high temperature are presented, as well known that Tu is an important physical factor that significantly affects heat transfer. This paper fulfills a real operating condition of using gas turbines in practice.

2. Model and Methods

2.1. Vane model

The model in this research is the model of the C3X turbine vane, as the previous study by Hylton et al. [6]. This vane has 10 cylindrical holes for internal coolant air supply as shown in figure 1(a).

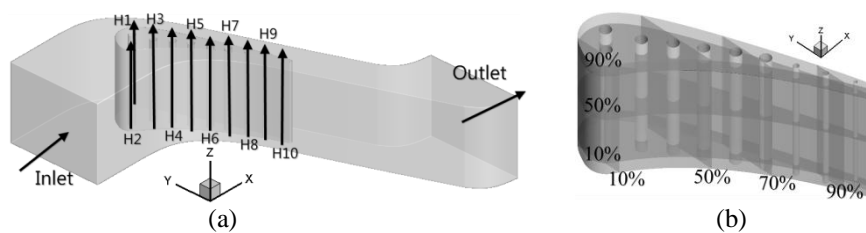


Figure 1. (a) Vane model and its cascade (b) cross-section planes along the span and streamwise directions.

2.2. Problem Description

This research is conducted at two turbine inlet temperatures (T_∞) i.e. a low temperature of 783 K (a condition done by [6]) and a high temperature of 1566 K (an assumed condition by the present work) under two Tus i.e. 8.3% (a condition of done by [6]) and 16.6% (an assumed condition by the present work). The turbine vane is protected by a TBC thickness of 355.6 microns as used by [1]. To achieve in Numerical thermal analysis of the coated turbine vane at the high temperature, thermal characteristics are discussed in terms of metal temperature reduction (R) on the surface and three cross-section planes in span ($z = 10, 50$ and 90%) and four cross-section planes in streamwise ($x = 10, 50, 70$ and 90%) directions, as seen in figure 1(b). The metal temperature reduction (R) is defined by equation (1).

$$R = \left(\frac{T - T_{TBC}}{T_{TBC}} \right) \times 100\% \quad (1)$$

where T and T_{TBC} are the metal temperature without and with TBC, respectively. In equation (1), T_{TBC} is chosen as the denominator in preference to T because coated vanes are presently more common to be used in real situations. Surface heat-flux ratio (Q/Q_{TBC}) on the pressure side (PS) and the suction side (SS) are also presented, where Q and Q_{TBC} are the surface heat transfer by convection in case of without and with TBC, respectively. It should be noted that Q is calculated from mainstream-metal surfaces and Q_{TBC} is calculated from mainstream-TBC surfaces.

2.3. Computational Technique

All computational mesh is generated using ICEM and the number of the computational mesh used in this work is 5,574,920. The value of y^+ for the first cell of the computational mesh is less than 5. Details of three numbers of mesh independent study and computational mesh domains used in this work were presented in the previous study [7]. FLUENT code is used to solve continuity, momentum and energy equations in the fluid domain, while heat conduction is solved in the solid domain. With a very thin TBC thickness, its thermally protective ability is considered as 1D conduction within the TBC layer through the interface technique as described in [7]. The vane is made of steel, the air is used as fluid and TBC is made of ZrO_2 . All properties of the materials can be seen in [7]. Numerical results are checked by the criteria of convergence of continuity and energy equations. The

convergence of the results is rechecked by mass balance of all inlets and outlets and monitoring temperature at six points on the leading edge (LE), trailing edge (TE), PS, and SS. Boundary conditions are listed in tables 1 and 2, and the pressure at all outlets of the coolant is 100 kPa.

Table 1. Boundary conditions of the mainstream.

Boundary	Condition
Mainstream inlet	$T_\infty = 783$ and 1566 K, $P_{t,in} = 321.7$ kPa, $Tu = 8.3$ and 16.6%
Mainstream outlet	$P_{s,out} = 192.5$ kPa
Upper and lower cascades	Adiabatic wall with a nonslip condition
Lateral cascade	Periodic

Table 2. Boundary conditions of internal coolant passages.

Coolant passage number	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10
$T_{c,in}$ (K)	387	388	371	376	355	412	367	356	406	420
[8]										
\dot{m} (kg/s)	0.0078	0.0066	0.0063	0.0067	0.0065	0.0067	0.0063	0.0023	0.0014	0.00068

3. Numerical Validation

Figure 2 shows the validation of pressure and temperature distributions along the vane surface at midspan. CFD with CHT and SST $k-\omega$ model in the FLUENT solver is used for the simulation. It is found that the SST $k-\omega$ model gives acceptable numerical results of aerothermal characteristics when comparing to the experimental data of the run number 4112 obtained by [6]. Only slight differences of pressure are observed on the SS and the maximum error about 3% of surface temperature is detected.

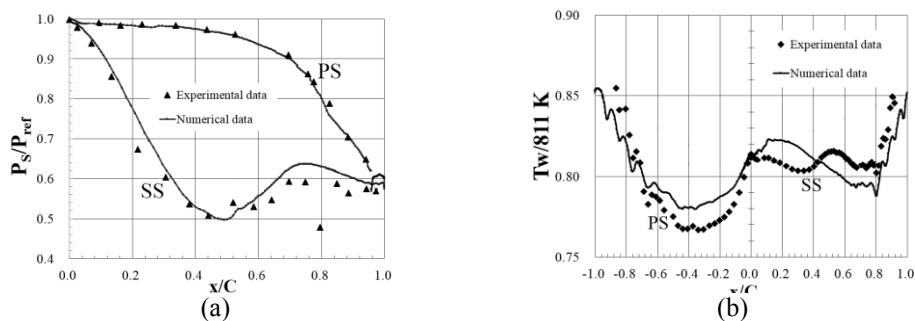


Figure 2. Validations of aero-thermal characteristics along the vane surface at midspan [7].

4. Results and Discussion

4.1. Effects on Metal Surface Temperature

Figure 3 presents the effects of Tu and T_∞ on R of the TBC turbine vane at midspan, which is usually used as the representative of the vane. One can clearly observe that at the same Tu , the higher R always happens at $T_\infty = 1566$ K. In addition, for both inlet temperatures, the influence of the increasing Tu on R is not large, especially in the TE and on the further downstream PS and SS near the TE. Namely, at $T_\infty = 783$ K, R on the PS at $Tu = 16.6\%$ is higher than that at $Tu = 8.3\%$, but no significant difference between R at the two Tus happens on the SS. Interestingly, at $T_\infty = 1566$ K, it is opposite to the results obtained at $T_\infty = 783$ K. Namely, R for both the PS and SS at $Tu = 16.6\%$ is lower than that at $Tu = 8.3\%$.

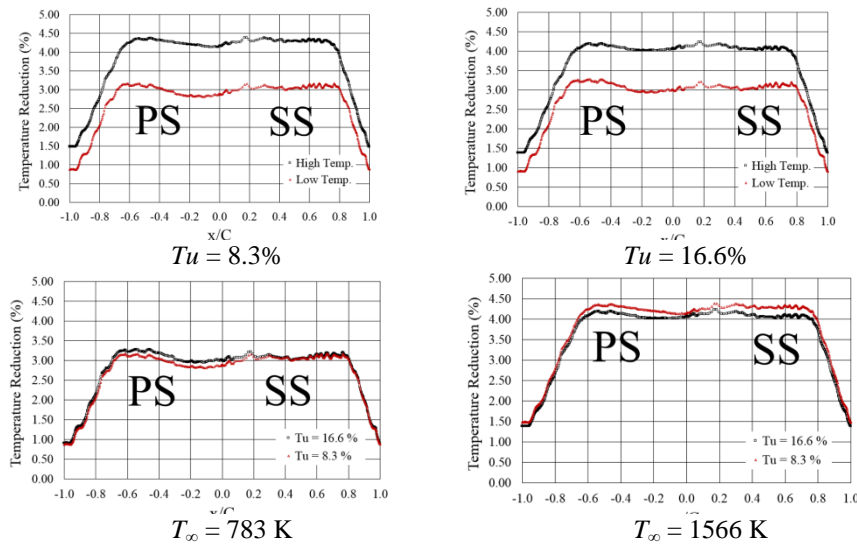


Figure 3. Metal temperature reduction at midspan at $T_\infty = 783$ K and 1566 K, and at $Tu = 8.3\%$ and 16.6%.

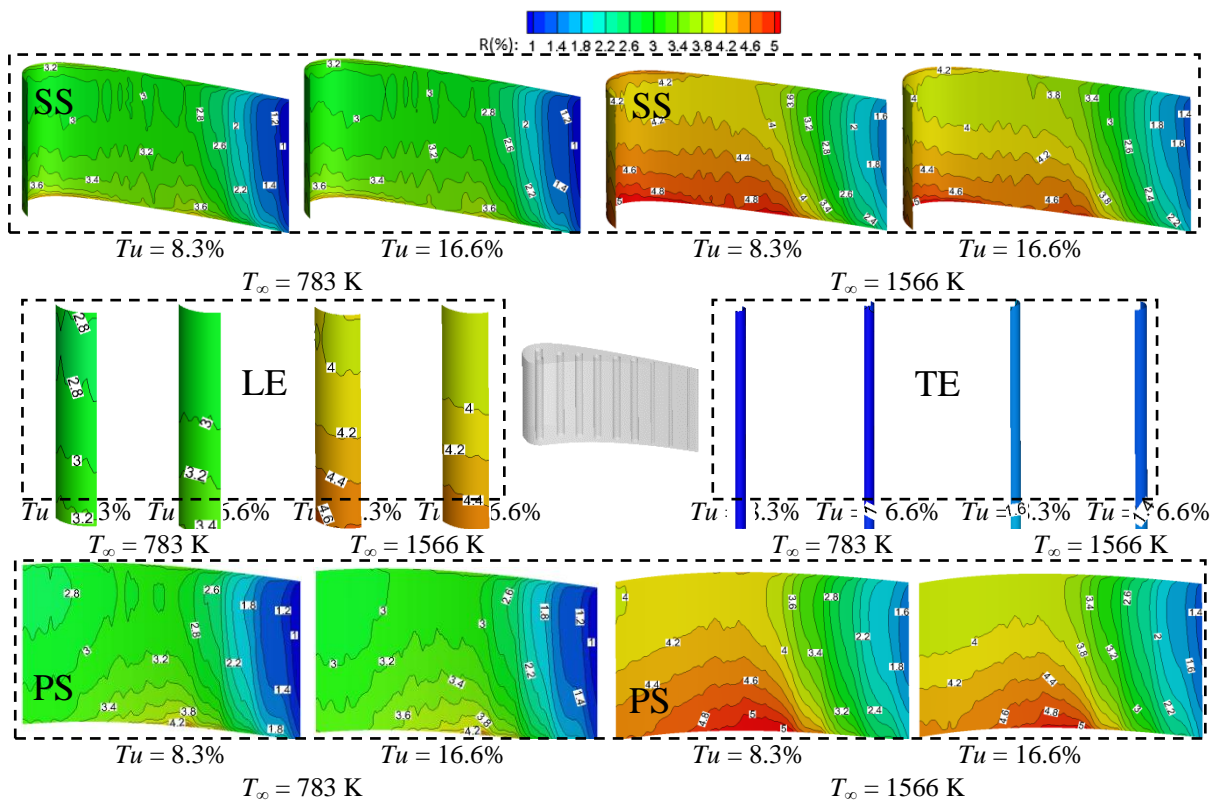


Figure 4. Metal temperature reduction on surfaces at $T_\infty = 783$ K and 1566 K, and at $Tu = 8.3\%$ and 16.6%.

These phenomena are also found on the metal surfaces of the vane as presented in contours of the metal surface temperature in figure 4. These phenomena may be explained by the contours of the Q/Q_{TBC} ratio illustrated in figure 5. Namely, at the same Tu and for both PS and SS, Q/Q_{TBC} at the high temperature is lower than Q/Q_{TBC} at the low temperature, that is why the higher R happens at the higher inlet temperature. Unexpectedly, at $T_\infty = 783$ K, R on the PS increases with the level of Tu , and it is opposite at $T_\infty = 1566$ K. The difference phenomena mentioned happens even though the level of Q/Q_{TBC} at $Tu = 8.3\%$ is lower than that at $Tu = 16.6\%$. This may suggest the instability of the surface

heat flux due to the complex heat convection at the different inlet temperatures on the TBC turbine vane.

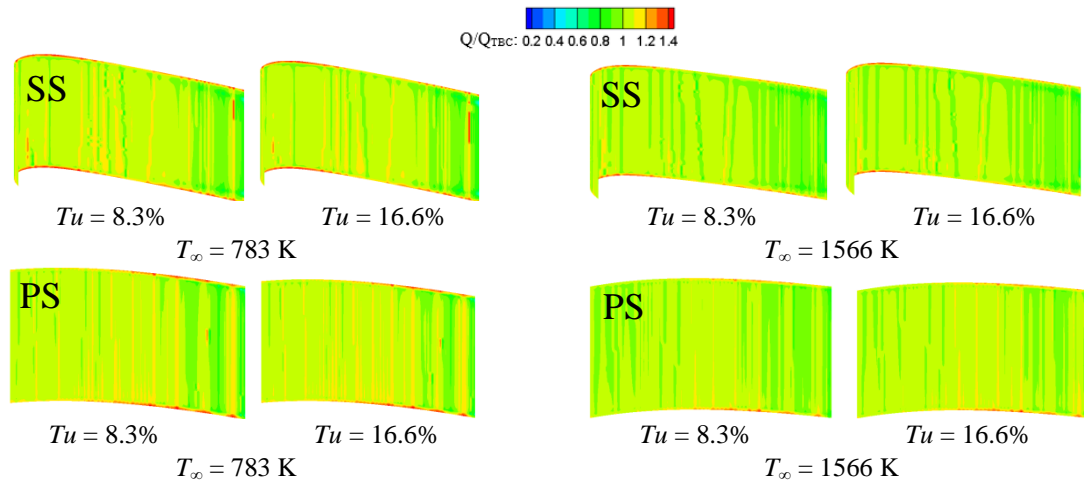


Figure 5. Heat-flux ratio on SS and PS at $T_{\infty} = 783$ K and 1566 K, and at $Tu = 8.3\%$ and 16.6%.

4.2. Effects on Structural Temperature

Effects of Tu and T_{∞} on R within the vane body are illustrated by contours of the reduction in figures 6 and 7 for the three section planes and the four section planes in span and streamwise directions, respectively. The figures indicate that the phenomena of the structural temperature affected by increasing in Tu and T_{∞} are similar to the metal surface temperature, that is R within the vane body corresponds to R at the metal surface. However, for both Tus , R distributions at $T_{\infty} = 1566$ K are more uniform than those at $T_{\infty} = 783$ K. This is because of the lower Q/Q_{TBC} at the higher temperature, so the lower heat conduction within the structure plays a part in the uniform distributions of R .

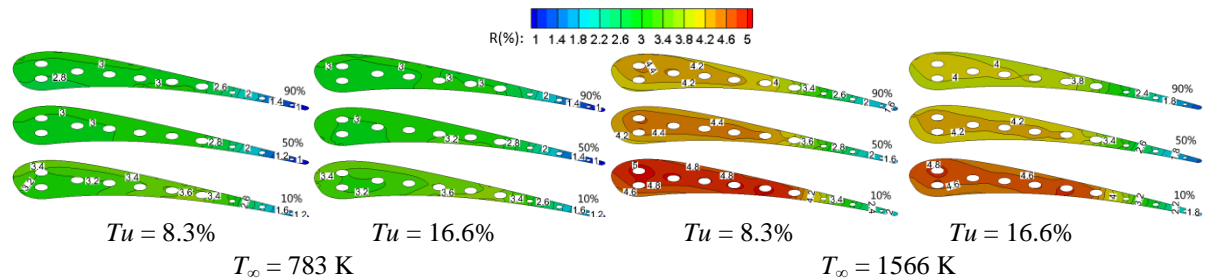


Figure 6. R on three planes along z -direction under low and high temperatures at $Tu = 8.3\%$ and 16.6%.

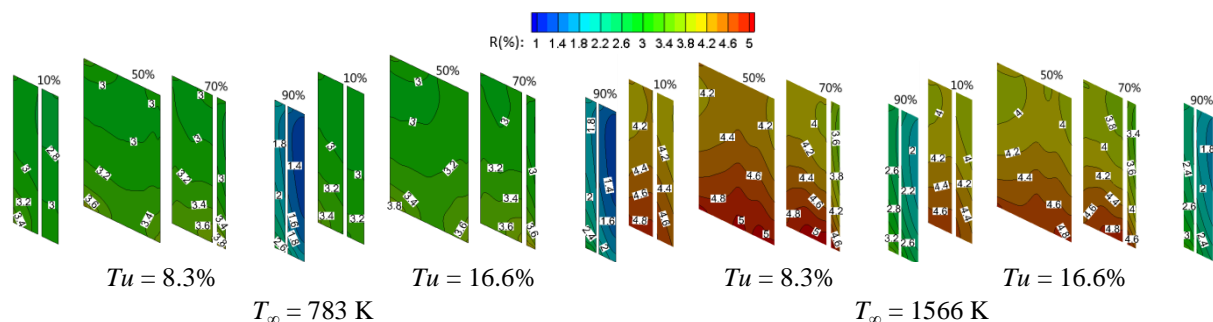


Figure 7. R on four planes along x -direction under low and high temperatures at $Tu = 8.3\%$ and 16.6%.

5. Conclusion

In this research, conjugate heat transfer is used to numerical thermal analysis of a *TBC* turbine vane at the two inlet turbine temperatures i.e. 783 K (low) and 1566 K (high) under two *Tus* i.e. 8.3% and 16.6%. Through the discussion, the conclusions can be drawn as follows:

- (1) For both *Tus*, the metal surface temperature reduction at $T_\infty = 1566$ K is higher than that at $T_\infty = 783$ K. This is because the heat-flux ratio at $T_\infty = 1566$ K is lower than that at $T_\infty = 783$ K.
- (2) Based on the metal temperature reduction, the increasing inlet temperature has a greater influence than the increasing turbulence intensity.
- (3) At 783 K, on the *PS* the metal surface temperature reduction at $Tu = 8.3\%$ is lower than that at $Tu = 16.6\%$, while on the *SS* it seems that no significant difference happens when Tu increases.
- (4) For both *PS* and *SS*, the metal surface temperature reduction at $Tu = 8.3\%$ increases above that at $Tu = 16.6\%$ when T_∞ increases. The noticeable difference of the two phenomena in (3) and (4) may suggest the instability of surface heat flux ratio from complex heat convection at the different inlet temperatures on the turbine vane coated with *TBC*.
- (5) As results from (1)-(4), it may lead to a similar effect on the structural temperature reductions within the vane body. However, the distributions of the temperature reduction are more uniform at the high temperature for both *Tus*.

Acknowledgments

This research is supported by the International Academy of Aviation Industry, King Mongkut's Institute of Technology Ladkrabang (Contract No: 2561-15-06). The first author would like to express appreciation to the Chinese Academy of Sciences (CAS) for providing the PIFI program. In addition, the first author would like to express gratitude to Associate Professor Bo Yin and Professor Guowei Yang, Institute of Mechanics, CAS, and Professor Jianhua Wang and Dr. Huazhao Xu, University of Science and Technology of China for their support and guidance.

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