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Research Paper

Conjugate heat transfer simulations of pulsed film cooling on an entire turbine vane

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HIGHLIGHTS

- Pulsed film cooling effects on leading edge, pressure side and suction side are compared.
- Pulsed film cooling with high blowing ratios on suction side deteriorates heat transfer.
- Pulsed film cooling with high blowing ratios on pressure side improves heat transfer.
- The effects of pulsing frequency on pressure side and suction side are opposite.

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ABSTRACT

This paper presents a numerical investigation on pulsed film cooling using conjugate heat transfer with an entire NASA C3X vane model, which has nine rows of film hole: five in leading edge region, two at suction side and two at pressure side. Square and sinusoidal waves are considered to pulse the cooling air. The normalized Nusselt number distributions over the vane surface are calculated and discussed at three blowing ratios (BR = 0.78, 1.17 and 1.56) and four Strouhal numbers (*St* = 0.0029, 0.0058, 0.0116 and 0.0232). Based on the entire turbine vane and conjugate heat transfer algorithm, the present simulations exhibit three interesting phenomena: (1) At suction side, normalized Nusselt number increases with BR for pulsed flow, indicating pulsing film cooling with high BRs should not be used. (2) At pressure side, when BR increases, normalized Nusselt number of the pulsed flow becomes smaller than that of the steady flow, indicating pulsed film cooling with high BRs is more suitable. (3) In leading edge region, normalized Nusselt number decreases with an increasing of Strouhal number from 0.0029 to 0.0116, but then increases at *St* = 0.0232 for both pulsed flow types. This phenomenon indicates the importance of choosing an appropriate pulsing frequency.

1. Introduction

To increase power output of gas turbines, turbine inlet temperature is continuously increasing nowadays. Consequently, turbine vanes are experiencing severe thermal conditions, which far exceed the allowable temperatures of turbine vane materials. Therefore, developing more effective cooling schemes, such as film cooling, has become one of the main concerns to turbine designers for a long time.

Film cooling has been extensively used to reduce turbine airfoil temperatures. Gao et al. [1] measured the film cooling effectiveness on pressure side (PS) and suction side (SS) of a high pressure turbine blade with axial laid-back, fan-shaped cooling holes, and they found the film cooling effectiveness on SS is usually higher than that on PS. Yao et al. [2] numerically studied the film cooling performance of a single row of converging slot-holes on a blade SS, and their results showed that the converging slot-holes suppress the coolant jet penetration, result in a film cooling enhancement. Yu et al. [3] focused on the effects of diffusion-hole geometry on film cooling performance, and the results indicated that the diffusion shaped hole produces a significant increase in film cooling effectiveness and decreases the heat transfer coefficient compared to straight circular hole. Zhu et al. [4] investigated the effects of radial angle of leading edge cooling holes on film cooling performance, and found that for SS close to the stagnation region and PS, small radial angle improves film cooling performance, whereas large radial angle facilitates the effectiveness downstream of SS. Liu et al. [5] numerically simulated the impingement and film composite cooling on blade leading edge region, and found the external film cooling effectiveness varies rapidly with the blowing ratio.

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Nomenclature

D	hole diameter, mm
P_h	hole pitch, mm
P	pressure, Pa
C_{ax}	axial chord, mm
t	time, s
T	temperature, K
T_p	pulsation period, s
f	pulsation frequency
λ	metal conductivity, W/(m·K)
x, y, z	Cartesian coordinates, mm
k_f	mainstream thermal conductivity, W/(m·K)
Q	wall heat flux, W/m^2
h	heat transfer coefficient, $Q/(T_\infty - T_w)$, $W/(m^2 \cdot K)$
Nu	Nusselt number, hC_{ax}/k_f
Nu_o	reference Nusselt number based on reference heat transfer coefficient (h_0) for normalization from Hylton et al. [19], 1100
Nu_{ave}	average Nusselt number in the spanwise direction of the model
St	Strouhal number, fD/U_∞
BR	blowing ratio, $\rho_c U_c / \rho_\infty U_\infty$
LE	leading edge
PS	pressure side
SS	suction side
DC	duty cycle

Subscript

ave	average
c	relative to coolant flow
∞	relative to mainstream flow
ref	reference
w	wall

On one hand, pulsed film cooling is deliberately introduced in film cooling scheme to reduce cooling air consumption and increase engine power thereby. On the other hand, in real running conditions of turbine vane, pulsing phenomenon naturally occurs due to the periodic interaction between rotor and stator.

In the aspect of pulsed film cooling study, Coulthard et al. [6,7] experimentally investigated pulsing effects on film cooling effectiveness and heat transfer on a flat plate, their results showed that pulsing at high frequencies can increase Stanton numbers and improve film cooling performances due to the reducing of jet lift-off. Muldoon and Acharya [8] and Babaee et al. [9] numerically studied a pulsed film cooling jet on a flat plate using direct numerical simulation. They found that when cooling air injection is closed, mainstream flow ingests into delivery tube, and squeezes residual cooling air out from holes, which provides an improved film coverage. The best film cooling effectiveness is at duty cycle DC = 0.14 and Strouhal number *St* = 1.03 when blowing ratio BR = 1.5. Rutledge et al. [10,11] conducted pulsed film cooling investigations on a cylindrical leading edge (LE) surface using both numerical simulations [10] and experimental methods [11]. Their results showed that the net heat flux is generally increased by pulsing film cooling. In our previous work, Ke and Wang [12], an entire NASA C3X vane was used, and adiabatic film effectiveness of pulsed flow at LE, PS and SS was numerically compared with steady cooling air injection. The comparisons indicated that both BR and pulsing frequency may induce opposite effects on the film effectiveness at PS and SS, and sinusoidal wave can improve adiabatic film effectiveness at LE with high BRs.

Conjugate heat transfer algorithm has been widely recognized due to the fact that it is the real running condition of gas turbine. Silieti et al. [13] numerically compared the film cooling results of adiabatic flat plate with those of conjugate heat transfer case. They concluded that the conjugate heat transfer models predict a significant difference of temperature distribution from the adiabatic plate, so they emphasized the importance of considering the heat conduction of flat plate. Mensch and Thole [14,15] conducted both experimental and numerical investigations on conjugate heat transfer of a turbine endwall with impingement cooling holes and film holes, and discussed film cooling schemes thereby. Dyson et al. [16] evaluated the performances of fully conjugated steady RANS simulations in predicting turbine vane temperature. They found that the SST k- ω model under-predicts jet diffusion, while over-predicted adiabatic film effectiveness for an attached jet. Alizadeh et al. [17] developed a numerical methodology for conjugate heat transfer simulation, and assessed multiple heat transfer parameters that affect turbine blade life. Albert and Bogard [18] measured adiabatic and overall film cooling effectiveness on a turbine vane using matched-Boit number modeling technique, the results showed that adiabatic and overall film cooling effectiveness increase with blowing ratio for the showerhead and pressure side trenched holes.

Conjugate heat transfer is a real running condition of film cooled turbine vane, and pulsed cooling air phenomenon cannot be eliminated due to the periodic interaction of rotor and stator. However, up to now there is no study concerned the pulsed film cooling of entire turbine vanes using conjugate heat transfer algorithm. In the present work, conjugate heat transfer simulations of pulsed film cooling over an entire NASA C3X vane are conducted, and square wave and sinusoidal wave are used as pulsing cooling air injection. The aim of this investigation is to provide the designers and manufacturers of turbine vanes with a relatively real and comprehensive reference.

2. Geometry and mesh

The geometrical model investigated in this work is C3X vane presented by Hylton et al. [19]. The vane is cut into a nose part and a tail part by a thermal barrier as shown in Fig. 1. The nose part has three plenums, feeding cooling air to the film hole arrays at SS, LE, and PS, which have 2, 5 and 2 rows of film holes, respectively, as shown in Fig. 1b. Details of hole arrays are listed in Table 1. The tail part is internally cooled by 10 radial channels.

The computational domain of the current work is a linear cascade with one vane, as shown in Fig. 2. It extends $1.5C_{ax}$ upstream of the blade (along the streamwise direction) and $2C_{ax}$ downstream of the blade. The domain includes internal cooling air, metal vane structure and one vane pitch of external mainstream. The main characteristics of the cascade are listed in Table 2.

Fig. 3 shows the computational grids for the current numerical simulations. The grids are generated in commercial software ANSYS ICEM CFD 14.5 using hybrid grid approach. The 10 radical channels are meshed with hexahedral grids, while the other regions are meshed with tetrahedral grids. To allow the resolution of boundary layers, 20 layers of prism grids are stretched from the wall surface at fluid side, and the value of y^+ for the computational point of the first cell is less than 2.

Grid independence of the numerical results is validated with three mesh strategies defined as coarse, medium and fine meshes,