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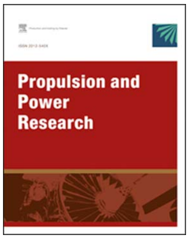

ORIGINAL ARTICLE

Numerical investigation of flow unsteadiness and heat transfer on suction surface of rotating airfoils within a gas turbine cascade

Liang Guo[a,b], **Yuying Yan**[b,*], **Wanchen Sun**[a,*], **Jie Zhu**[b]

[a]*State Key Laboratory of Automotive Simulation and Control, Jilin University, Changchun 130022, China*
[b]*Fluids & Thermal Engineering Research Group, Faulty of Engineering, University of Nottingham, Nottingham NG7 2RD, United Kingdom*

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Abstract The effects of the periodical turbulence and pressure fluctuation on suction surface heat transfer over airfoils of a row of rotor blades with a certain type have been investigated numerically in this paper. The calculation is performed using $\overline{v^2}-f$ model with the numerical results of pressure fluctuation and heat transfer performance over 4 sample points being analyzed and compared with existing experimental data. It shows that the static pressure change has significant impact on heat transfer performance of the fore suction surface, especially in the active region of the shock waves formed from the trailing edge of upstream nuzzles. While, for the rear suction surface, the flow turbulence contributes more to the heat transfer change over the surface, due to the reduced pressure oscillation through this region. Phase shifted phenomenon across the surface can be observed for both pressure and heat transfer parameters, which should be a result of turbulence migration and wake passing across the airfoil.

1. Introduction

The fluid flow across the turbomachinery has extremely high unsteadiness which is influential to the whole turbine system. It has been proved that the performance of heat transfer upon the engine components can be affected significantly by the

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[*]Corresponding authors. Tel.: (44) 115 95 13168.

E-mail addresses: yuying.yan@nottingham.ac.uk (Yuying Yan), sunwc@jlu.edu.cn (Wanchen Sun).

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Nomenclature

C_r	chord length of rotor blade
C_μ	coefficient for $k-\varepsilon$ model
f	elliptic relaxation function of $\overline{\nu^2}-f$
Nu	Nusselt number
P	pressure
$\dot{q}$	heat flux
Re	Reynolds number
T	temperature
Tu	turbulence intensity
x, y	x and y coordinate
k	turbulence kinetic energy

Greek letters

ε	dissipation rate of turbulence kinetic energy
κ	thermal conductivity
ρ	density
μ_t	eddy viscosity
μ'	fluctuating velocity
$\overline{\nu^2}$	scalar velocity scale

Subscripts

1	inlet of nozzle guide vane
2	exit of nozzle guide vane
3	exit of rotor blade
s	static
t	total
gas	parameter relates to freestream condition
$wall$	parameter relates to wall condition
x	in x direction
y	in y direction

turbulent flow and also the turbulence induced boundary layer transition. In order to further increase the thermal efficiency with an extended lifetime of the modern turbine engine, an in-depth understanding on the behaviors of the unsteady flow through the turbine cascade is therefore very important.

Over the past decades, many studies have been carried out to investigate the essence of flow turbulence and its effect on the boundary layer transition. The theoretical system about the turbulent flow and laminar-to-turbulent transition were built up gradually [1–4] with the mechanism of the transition becoming more clear. For the gas turbine, the effect of the free stream turbulence on turbine component heat transfer is a key factor that determines the thermal efficiency of turbomachinery [5–8]. A large amount of experimental studies have been carried out to investigate the effect of flow unsteadiness on boundary layer separation and surface heat transfer of turbine blades. Rhee et al. [9] reported that the blade relative position changes the incoming flow significantly which leads to variations in velocity and turbulence intensity of the cascade flow. With the changing relative position, the maximum difference in heat/mass transfer coefficients in certain region could be 30%-50% of the average value. According to experimental results of Schobeiri et al. [10,11], velocity behaviour was completely decoupled from thermal boundary layer but the thermal behaviour is tightly coupled with the boundary layer aerodynamics. In addition, increasing the turbulence level of the cascade flow mitigates the boundary layer transition, and the effects of the unsteady wake on time-averaged heat transfer coefficient can retain noticeable until the wakes are completely merged into the freestream turbulence. The effects of turbulence and unsteady wake entrained by a coming flow on convective heat transfer of a heated cylindrical surface were experimentally studied by Huang et al. [12]. They concluded that the upstream wake does not only produce stronger turbulence downstream, but also causes enhanced heat transfer upon the corresponding surface. Although, it is hard to deny that the experimental methods can bring most truthful results, but it is still difficult to carry out any transition related experiments under real engine operating circumstances, due to large difference between the environments of laboratory and engine cascade, conflicting conclusions may be obtained from similar objective reality. Thus, for experimental studies, a thorough understanding into the mechanism of the influence of turbulent flow on surface heat transfer can only be expected when more sophisticated technology is available.

As an alternative of confined experimental methods, the numerical approaches are wildly applied to provide addition solutions for the turbulence-heat transfer problems. Benefited from the rapid development of modern computing technology, the computational researches with higher accuracy and more reliability become accessible. Direct numerical simulations of flow and heat transfer in a turbine cascade with incoming wakes were carried out by Wissink and Rodi [13–15], the impinging induced flow structure changes are depicted in their studies and it shows that along the pre-transitional region of the suction surface the calculated heat transfer can be significantly increased by the free stream fluctuations, and this is regarded as a resulted of the introduced streamwise vortices into the boundary layer. Choi et al. [16] explained the mechanism of the turbulence enhanced heat transfer. The increasing turbulence intensity triggers earlier boundary layer transition and promotes a broader transition region. And then it disturbs the separated laminar boundaries and will finally result in spread of the enhanced heat transfer in relevant region. Guo et al. [17,18] studied the effects of turbulence on performance of cooling flow applied to gas turbine blade, it shows that the less the turbulence, the higher the film cooling effectiveness and lower heat transfer between mainstream and blade walls. Hwang et al. [19] conducted an analysis for steady-state and unsteady-state conjugate heat transfer for an aeronautic high pressure gas turbine, the calculation results shows that due to nozzle exit flow, the

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