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Influence of coolant mass flow rate on the endwall conjugate heat transfer

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ABSTRACT

The switch from diffusive combustion to premixed combustion in a modern gas turbine will change the combustor exit temperature profile to a more uniform one. As a result, the temperature near the inner and outer shroud of the turbine vane will increase which is a big challenge for the endwall cooling. Two typical vane endwall configurations with different cooling arrangements are investigated both experimentally and numerically in this study. One endwall has film cooling method only while the other has both film cooling and impingement cooling. The coolant to mainstream mass flow ratio (MFR) changes from 0.8% to 2.5% in the numerical investigation. The numerical method is validated by the experimental data. Detailed analysis of the coolant mass flow rate effect on the endwall conjugate heat transfer is conducted based on the numerical results. The results indicate that the speed of the overall effectiveness increment slows down when the MFR increases. As the MFR increases, the advantage of the combination of film and impingement enlarges. The warming effect of the coolant increases as the MFR increases which leads to a lower coolant discharge temperature.

1. Introduction

Increasing the turbine inlet temperature is an effective way to further increase the efficiency of a modern gas turbine. However this brings big challenge to the cooling technologies for the protection of hot components. In order to reduce NOx and other pollutants generated during combustion, premixed combustion is switched to. The exit temperature profile for a premixed combusotr is more uniform in the radial direction because of less air for the dilution. This means a much higher mainstream temperature for the endwalls.

Cooling method including film cooling and impingement cooling is widely used for endwall cooling. The cooling performance of endwall depends on many parameters, such as the complex flow field near the endwall, cooling arrangement, coolant mass flowrate, the interaction between mainstream and coolant injections, etc. The conjugate heat transfer characteristics of endwalls are of vital importance for proper evaluation of component life.

The conjugate heat transfer of endwall involves external convective heat transfer, film cooling, internal passage convective heat transfer, impingement heat transfer and solid conduction. Some of the aspects have been investigated separately. The work of Graziani et al. [1] and Goldstein and Spores [2] gave a detailed description of heat transfer patterns in the endwall passage under the influence of the secondary flows. Laveau et al. [3] provided a high resolution experimental data of endwall heat transfer coefficient and adiabatic wall temperature for real turbine geometry under realistic conditions but without film cooling. Werschnik et al. [4] studied the influence of varied inflow conditions due to the combustor-turbine interaction on the endwall heat transfer and film cooling effectiveness using IR technique. Takeishi et al. [5] studied the influence of secondary flows in the passage on endwall film cooling and found that the endwall film cooling jets were deflected from the pressure side to the suction side. Friedrichs et al. [6–8] optimized the endwall film cooling depending on the flow pattern near the endwall. Chowdhury et al. [9] and Chen et al. [10] used PSP technique to investigate the effect of slashface leakage and coolant mass flow rate on the vane/blade endwall film. Ornano et al. [11] investigated the effect of momentum flux ratio on the endwall film cooling system using IR and numerical simulations. They found that the SST k-w model overpredicts the levels of film cooling effectiveness. However, conjugate heat transfer research considering all the effects including external convective heat transfer, film cooling, internal convective cooling and conduction of the endwall is rare. Mensch et al. conducted a series of investigation on the endwall heat transfer and cooling [12,13]. They used infrared thermography method for the measurement of the overall effectiveness on endwall with film cooling and impingement [12]. The research showed that the impingement had a greater influence on the scaled wall temperature, and the film cooling mainly affected the local region near film cooling hole.

Although there have been some conjugate heat transfer results on endwall cooling published recently, they mainly focused on the overall effectiveness of endwall with a simplified model. Moreover, the coolant mass flow rate is a critical aspect concerned both in endwall conjugate

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Nomenclature

C_{ax}	Axial chord length [m]
D	Film hole diameter [m]
d	Impingement hole diameter [m]
k	Conductivity [W/m-K]
L	Hole Length [m]
M	Blowing ratio [-]
$\dot{m}$	Mass flow rate [kg/s]
Ma	Mach number [-]
P	Pressure [Pa]
p	Pitch length [m]
Re	Reynolds number [-]
S	Vane span [m]
T	Temperature [K]
t	Wall thickness [m]
U	Velocity [m/s]
X, Y, Z	Coordinates [m]

Greeks

α	Inclined angle[°]
β	Compound angle[°]
χ	Warming factor[-]
ϕ	Overall effectiveness[-]
δ	Boundary layer thickness[m]

Subscripts

c	Coolant
c,exit	Coolant at film hole exit
i	Internal
∞	External
t	Total/stagnation
w	wall

Acronyms

CFD	Computational fluid dynamics
MFR	Mass flow ratio
TSP	Temperature sensitive paint

heat transfer characteristics and cooling design. It is important to investigate the effect of coolant mass flow rate on endwall conjugate heat transfer.

Two typical vane endwall configurations with different cooling arrangements are investigated both experimentally and numerically in this study. The numerical method is firstly validated by the experimental data. Then detailed analysis of the coolant mass flow rate effect on the endwall conjugate heat transfer is conducted based on the numerical results.

2. Experimental facilities

Conjugate heat transfer measurements of the endwall are conducted in the endwall cooling test rig built in Tsinghua University, as in Fig. 1. The test rig was described in detail in the previous works [14]. The mainstream is an open loop wind tunnel driven by a radial compressor. The main flow field was rectified to a homogeneous flow field before entering the cascade. The temperature, pressure and turbulence intensity were measured upstream of the vane leading edge. The secondary flow for the endwall coolant was fed and controlled by an independent system. A displacement air compressor provided the coolant gas to the endwall. The coolant mass flow rate was set and controlled by

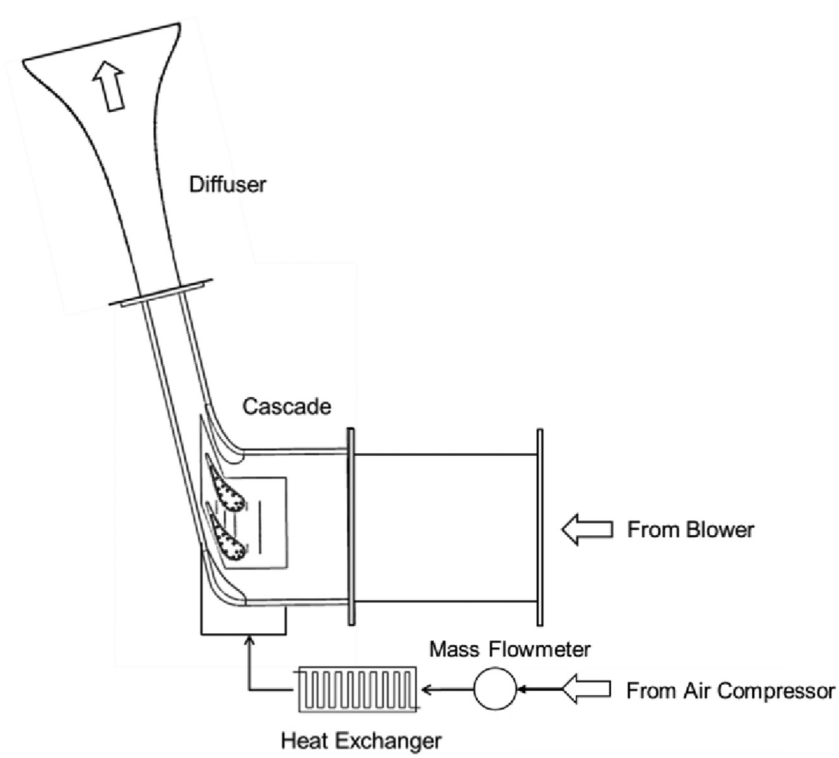

Fig. 1. Wind tunnel of the experiment.