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Research Paper

Experimental investigation of heat transfer characteristics on turbine endwall with full coverage film cooling

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HIGHLIGHTS

- Thermal measurement on turbine endwall with full coverage film cooling is conducted.
- The effect of full coverage film cooling on heat transfer of endwall is analyzed.
- Different heat transfer characteristics appear in different regions of the endwall.

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ABSTRACT

Transient heat transfer measurement by Thermochromic Liquid Crystal (TLC) is applied in this paper to investigate heat transfer characteristics of the nozzle endwall with full coverage film cooling. The endwall heat transfer coefficient (h) with different blowing ratios (M) ranging from 0.7 to 4.0 at a constant mainstream Reynolds Number 1.63×10^5 is measured and analysed. The experiment results show that the heat transfer characteristics of the endwall are significantly affected by the film cooling. However, this effect changes with blowing ratio and varies in different regions of the endwall. At low M ($M = 0.7$), coolant jets get into the boundary layer of the secondary flow, and enhance heat transfer, but lead to highly uneven h on the endwall. With the increase of M, coolant jets start to detach from the endwall while the turbulent mixing begins to enhance the heat transfer of the endwall downstream. Therefore h on the endwall first decreases and then increases with M. However, different turning points (the cases of $M = 1$ or $M = 1.5$) and increasing trends with M (staying constant or increasing monotonically) appear in different regions of the endwall.

1. Introduction

Due to the high-pressure and high-temperature circumstance of the first stage turbine vane, the efficient cooling system provides vital thermal protection for turbine performance. In order to improve the coolant design of the endwall, reliable and low-cost thermal measurement is of great importance. Traditional thermal measurement by using the thin-foil heater and thermocouple provided valuable data on the heat transfer characteristics on the endwall [1–3].

From the result, it was found that the heat transfer on the endwall was significantly affected by the secondary flow [1], which was investigated in detail by Langston et al. [4,5] using a variety of techniques. However the inevitable time-consuming and high uncertainty caused by heat losses and axial conduction effects makes this traditional method only available for measurement in some discrete points [6].

With the adding of the leakage flow from upstream and film cooling into the research objective, the heat transfer character and flow field on the endwall become much more complicated [7,8]. For the flow field measurement, Pu et al. [9] utilized a planar Time-Resolved Particle Image Velocimetry (TR-PIV) system to reveal the time-dependent flow field of secondary flow within a linear turbine cascade. The experiment result showed that the coolant could suppress the formation of the horseshoe vortex, and it disappeared at a blowing ratio of 1.5. The interaction between the endwall film cooling and the mainstream in transonic annular cascade was investigated experimentally by El-Gabry et al. [10]. It was found that the coolant significantly impacted the secondary flow and flow field in the downstream.

For heat transfer measurement on the endwall, several techniques were applied nowadays for fast and reliable two-dimensional measurement. The Infrared thermography was widely applied for research in many areas due to its fast response and wide measurement range. This measurement technique was applied to measure the heat transfer

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Nomenclature

a	thermal diffusivity
C_p	specific heat at constant pressure
C_{ax}	axial chord length of the vane
H	hue
h	heat transfer coefficient
h_{ave}	pitch-wise averaged h on endwall
h_a	area averaged h on endwall
L	thickness of the endwall plate
M	blowing ratio
$P^*_{coolant}$	total pressure of coolant
P^*_{inlet}	total pressure of mainstream flow
P_{inlet}	static pressure of mainstream flow
Re	Reynolds number
T	temperature
T_c	temperature of coolant
T_f	room temperature
T_m	temperature of mainstream gas
T_0	initial wall temperature on the endwall
T_{aw}	adiabatic wall temperature
x	distance from endwall surface
y	distance from leading edge of vane in axial direction

Greek

λ	heat conduction coefficient
μ	dynamic viscosity
ρ	density
τ	time

character on the endwall by Lynch et al. [11] and Thrift et al. [12]. However, the optical requirement for the infrared measurement limited its wide usage in the heat transfer measurement of the turbine vane endwall.

The pressure sensitive paint (PSP) technique which is based on the heat and mass transfer analogy [6,13] is another technique of thermal measurement. It measures the static pressure on the endwall and then it is translated into the adiabatic wall temperature and then the cooling effectiveness. Li et al. [14] applied this technique to explore the cooling effects of six individual rows of cylindrical holes at different locations on a typical flat vane endwall once at a time. Different results were presented in different places of the endwall. However, after the comparison of single row film cooling experiment and multiple rows film cooling experiment, it was revealed by Li et al. [15] that the superposition method could not provide quantitatively reliable film cooling effectiveness of the endwall multi-rows case, especially for the full coverage film cooling. Therefore a full coverage film cooling would be needed for the investigation of heat transfer characteristics on the endwall. Then the configuration of the full coverage film cooling holes shows its importance on the cooling effect of the endwall [16,17]. It was reported that the film cooling hole configuration that designed from heat transfer coefficient map on the endwall without film cooling provided a better overall film-cooling effectiveness [16,17]. However Satta and Tanda [16] used a different technique, the Liquid Crystal Thermography (TLC), to measure the cooling effectiveness, which could be used to measure the heat transfer coefficient on the wall as well.

The application of Thermochromic Liquid Crystal for transient or steady thermal measurement was widely used due to its high reliability and convenience [18–21]. Yan et al. [18] discussed the application of TLC for heat transfer measurement in detail, while Liu et al. [19] expanded this method to situation of nonuniform initial temperature. The variation of wall temperature with time is indicated by a thin coating layer of TLC on the surface. Heat transfer coefficient and cooling effectiveness can be both obtained by this technique. For most of the researches of the heat transfer characteristics on the endwall with full coverage film cooling, only its cooling effectiveness was reported [16,17]. However, both film cooling effectiveness and heat transfer coefficient would be needed for the thermal analysis [22]. In addition, the heat transfer coefficient was already found to be affected by the coolant [23]. Therefore full coverage film cooling on the endwall may highly affect the heat transfer character on the endwall, which have not been explored in detail.

In this paper, the heat transfer characteristics on the turbine vane endwall with full coverage film cooling holes are investigated experimentally by transient TLC. Film cooling holes are all arranged in different regions of endwall between two vanes of a three-vane cascade in a wind tunnel. The coolant is supplied through all the film cooling holes from a pressure stabilization cavity. The heat transfer coefficient on the endwall with or without film cooling holes is measured by TLC. The mainstream Reynolds number (Re) varies from 1.63×10^5 to 2.09×10^5 to reveal the heat transfer character on the endwall without film cooling, while the heat transfer characteristics on the full coverage film cooling endwall are explored and presented with the pressure based blowing ratio ranging from 0.7 to 4.0 at $Re = 1.63 \times 10^5$.

2. Theoretical model

In this paper, unsteady heat transfer on one dimensional semi-infinite plate with third boundary condition is applied to obtain the heat transfer coefficient on the turbine vane endwall, as shown in Fig. 1. The variation of wall temperature with time in a semi-infinite plate under the effect of incoming flow with the sudden imposing of temperature difference could be determined by solving the equation below with third boundary condition and certain initial condition.

$$\frac{\partial T}{\partial \tau} = a\frac{\partial^2 T}{\partial x^2} \tag{1}$$

where x is the vertical distance from surface in the plate, T is the wall temperature and τ is the time from the moment that wall temperature starts to change, as shown in Fig. 1. When $\tau \leqslant 0$, the temperature of the plate is considered as uniform, *i.e.* $T_w(x) = T_{aw} = T_0$, $\tau \leqslant 0$. Based on the boundary condition and initial condition above, the equation could be solved to obtain the variation of wall temperature ($T_w(\tau)$) at $x = 0$ with time (for $\tau > 0$) as below.

$$\frac{T_w(\tau)-T_0}{T_{aw}-T_0} = 1-\exp\left(\frac{h^2 a\tau}{\lambda^2}\right)erfc\left(\frac{h\sqrt{a\tau}}{\lambda}\right) \tag{2}$$

where T_{aw} and T_0 is the adiabatic wall temperature and surface temperature at $\tau = 0$, h is the heat transfer coefficient ($h = q/(T_{aw}-T_w)$) and a is the thermal conductivity of the wall.

If the temperature of mainstream gas (T_m) and coolant (T_c) are the same, *i.e.* $T_m = T_c$,T_{aw} is the same as T_m and T_c. Otherwise, T_{aw} is contributed by both T_m and T_c and can only be obtained from the film cooling effectiveness $\eta = (T_m-T_{aw})/(T_m-T_c)$ on the adiabatic wall which makes the measurement of h impossible. Therefore in order to measure the h, the approach of setting the temperature of mainstream gas and

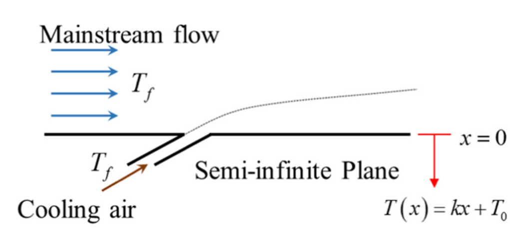

Fig. 1. Schematic figure of film cooling on semi-infinite plate.