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Experimental investigation on the leading edge film cooling of cylindrical and laid-back holes with different radial angles

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ABSTRACT

Film cooling performances of the cylindrical film holes and the laid-back film holes on the turbine blade leading edge model are investigated in this paper. Experimental measurements have been carried out to investigate the influence of the inclined angle in the spanwise direction (i.e. radial angle for a blade in the engine) on the film cooling performances of these two kinds of holes. Three rows of holes are arranged in a semi-cylinder model which is used to model the blade leading edge. Two inclined angles and three blowing ratios are tested. Transient heat transfer measurement technique with double thermochromic liquid crystals is employed in the present experiment. The results show that the trajectory of the film jets in the leading edge region deviates from the mainstream direction to the spanwise direction gradually as the blowing ratio increases. Under large blowing ratio, more area can benefit from the film protection and the film cooling effectiveness distribution is more uniform than those under small blowing ratio, while the heat transfer coefficient is also higher. The basic distribution features of heat transfer coefficient are similar for all the tested models. The heat transfer coefficient in the region where the jet core flows through is relatively lower, while the heat transfer coefficient in the jet edge region is relatively higher. Compared with the cylindrical holes, the jets from the laid-back holes have better film coverage and meanwhile make more area have relatively higher heat transfer coefficient, especially under large blowing ratio. Under the same blowing ratio, the jets from film holes with small radial angle can attach on the wall surface better and give higher film cooling effectiveness in the region close to the hole exit than the film holes with large radial angle, while they also produce relatively higher heat transfer coefficient.

1. Introduction

The desire for higher overall efficiency and higher specific power output in gas turbines renders the need for increase in turbine entry temperatures resulting in a need for effective cooling technologies. Film cooling is one of the major cooling technologies for protection of turbine airfoils from the hot gas stream. In a gas turbine, the leading edge of a turbine vane or blade withstands higher heat loads than any part of the airfoil surface due to the higher temperatures and the increased heat transfer coefficients that occur around the stagnation line. Film cooling is typically applied on the leading edge through an array of hole rows. Increases in film effectiveness in the leading edge will lead to significant benefits in life and efficiency of the turbine blade.

Cylindrical film hole is a basic configuration for the film cooling application. In the early stage, cylindrical leading edge models with a single row of cylindrical holes were studied by Luckey et al. [1] and Karni and Goldstein [2]. Luckey et al. [1] conducted the experiments with the spanwise-angled film holes for a range of the blowing ratio and three film injection angles and three positions of the hole row. Karni and Goldstein [2] studied the effects of blowing ratio and injection location on the mass transfer coefficient of the leading edge region. Mehendale and Han [3,4] and Ou and Rivir [5] further investigated the influences of the mainstream turbulence and mainstream Reynolds number on the leading edge film cooling of cylindrical holes. Results showed that large turbulence intensity had an attenuation on the film cooling effectiveness as well as on the heat transfer coefficient. In Ou and Rivir [5], the transient liquid crystal measurement technique was employed. More recent studies on the leading edge film cooling of cylindrical holes can be found in Kim et al. [6], Johnson et al. [7], Carroll et al. [8] and Dyson et al. [9]. In Kim et al. [6], the leading edge film cooling characteristics of three different arrangements of injection holes were studied under a range of Reynolds number. Johnson et al. [7] developed an experimental facility to consider and investigate the effect of the oscillation of the stagnation line position, which was caused by the blade passing through wakes from upstream vanes, on the leading edge film cooling. Carroll et al. [8] conducted a water channel study on a cylindrical leading edge

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Nomenclature

c	specific heat of wall [J/kg K]
d	diameter of the film hole [m]
D	diameter of semi-cylinder model [m]
$Froe$	Frössling number $\left(= Nu_D/\mathrm{Re}_D^{0.5} = (hD/\lambda)/(\rho_g U_g D/\mu_g)^{0.5}\right)$
h	convective heat transfer coefficient [W/m^2 K]
M	momentum flux ratio ($=\rho_c U_c/\rho_g U_g$)
p	hole pitch [m]
Re_D	Reynolds number based on diameter of semi-cylinder model ($=\rho_g U_g D/\mu_g$)
t	time [s]
T	temperature [K]
U	velocity, [m/s]
X	streamwise coordinate originating at the stagnation line [m]
Y	coordinate normal to the model surface [m]
Z	spanwise coordinate [m]

Greek symbols

α	radially inclined angle of the film hole [°]
η	film cooling effectiveness
ρ	density [kg/m^3]
λ	thermal conductivity of wall [W/m K]

Subscripts

aw	adiabatic wall
c	jet
g	mainstream
i	initial $t = 0$
s	surface

model to assess the effects of surface modifications on the film spreading. Dyson et al. [9] measured the overall cooling effectiveness of a simulated film-cooled turbine blade leading edge model with matched Biot number to the engine conditions.

Many studies show that using shaped holes is an effective way to improve the film cooling performance [10]. The study of Goldstein et al. [11] reported a significant increase in film cooling effectiveness in the near hole region as well as greater lateral coolant coverage for fan-shaped holes compared with standard cylindrical holes. Sen et al. [12], Gritsch et al. [13] and Yu et al. [14] further investigated the improvement in film cooling performance brought by the laid-back hole, fan-shaped hole and laid-back fan-shaped hole. However, the above studies were performed in flat plate model without considering the case with curvature effects like a real turbine blade leading edge. Recently, the shaped holes have come into consideration for the leading edge film cooling. Reiss and Bölcs [15] studied the effects of the shaped holes with compound angle orientation using the transient liquid crystal measurement technique. They compared the performances of the cylindrical holes, laid-back holes and fan-shaped holes. Five rows of film holes, which are radially inclined 45° to the surface, were arranged in the cylindrical leading edge model. They found that the laidback holes gave the best overall film cooling performance. The fan-shaped holes performed better than the cylindrical holes, but not as well as the laid-back holes. Kim et al. [16] studied the film cooling performances of the cylindrical holes, laid-back holes and teardrop shaped (spanwise- and streamwise-diffused) holes with an infrared thermography method. A cylindrical leading edge model with three rows of radial angle holes were investigated. They showed that the holes with a laid-back type exit gave higher film cooling effectiveness than the tear-drop shaped holes. Both the laid-back holes and the tear-drop shaped holes were found to perform better than the cylindrical holes. Mouzon et al. [17] compared the film performances of the laid-back holes and cylindrical holes on a three-hole-row leading edge model using the infrared thermography method. They found that the laid-back holes resulted in much higher net heat flux reduction than the cylindrical holes. Lu et al. [18] also studied the effects of the hole orientation and the hole shape on leading edge film cooling. They examined the compound angle cylindrical holes and the compound angle laid-back fan-shaped holes on a blunt model with a semi-cylinder leading edge with three rows of film cooling holes. They found that the shaped holes gave much higher effectiveness than the cylindrical holes. For the compound angle holes, the effectiveness was improved at lower blowing ratios, but reduced at higher blowing ratios due to the jet lift-off. Gao et al. [19] studied the effect of the film-hole geometry and angle on the turbine blade leading edge film cooling experimentally using the pressure sensitive paint technique. The leading edge is modeled by a blunt body with a semi-cylinder and an after-body. Four different film cooling hole configurations are compared: radial angle cylindrical holes, compound angle cylindrical holes, radial angle laid-back fan-shaped holes, and compound angle laid-back fan-shaped holes. The results show that the shaped holes provide higher film cooling effectiveness than the cylindrical holes, particularly at higher average blowing ratios.

As it can be seen from the literature survey given above, the laid-back hole has obvious advantage in the film cooling of leading edge region. The objective of the present study is to further explore the potential improvement of the film cooling with shaped holes for the leading edge region. Film cooling performances of the laid-back hole and cylindrical hole on a leading edge model were investigated. The leading edge was modeled with a semi-cylinder and an after body which had been proved to be an effective method and employed by many researchers. Special attention was focused on the influence of the radially inclined angle of the film holes. Transient liquid crystal measurement technique has been used in the present work to obtain detailed distributions of the film cooling effectiveness and the heat transfer coefficient.

2. Experimental apparatus and approach

2.1. Experimental apparatus

As shown in Fig. 1, the experiment system includes two parts: mainstream path and secondary flow path. The mainstream supplied by a blower passes through air surge tank, valves, settling chamber with three flow-conditioning screens in it, contraction section with a contraction ratio of 5.4-to-1 before entering the mesh heater. Moreover, another contraction with a contraction ratio of 2-to-1 is placed after the mesh heater to ensure a uniform mainstream entering the test tunnel which is a Perspex rectangular duct with 220 mm in width and 110 mm in height. The light source and the DV for the liquid crystal measurement are placed outside of the test tunnel, as indicated in Fig. 1. The secondary flow supplied by another blower passes through air surge tank, flow meter, valve, air heater and a bypass system which consists of two solenoid valves and enters the test model from the bottom.