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Experimental investigations of the effects of the injection angle and blowing ratio on the leading-edge film cooling of a rotating twisted turbine blade

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ABSTRACT

Experimental investigations were performed to study the effects of the injection angle of cylindrical holes and the blowing ratio on the leading-edge-region film cooling of a twisted turbine blade under rotating conditions. The experiments were carried out at a test facility with a 1-stage turbine using the thermochromic liquid crystal (TLC) technique. All experiments were performed at a rotating speed of 574 rpm with an average blowing ratio ranging from 0.5 to 2.0. The Reynolds number was fixed at 6.3378 $\times 10^4$ based on the mainstream velocity of the turbine outlet and the rotor blade chord length. CO_2 was used as the coolant to achieve a coolant-to-mainstream density ratio of 1.56. The film-hole injection angles tested were 30°, 45° and 60°. The results show that both the injection angle and the blowing ratio have significant impacts on film cooling effectiveness. For $\alpha = 30°$ and $\alpha = 45°$, the radial average film cooling effectiveness increases as the blowing ratio increases in all regions. For $\alpha = 60°$, this effectiveness first increases and then decreases as the blowing ratio increases, with the case of M = 1.5 yielding the best average cooling performance. At each blowing ratio, the $\alpha = 30°$ case always yields the highest streamwise average film cooling effectiveness in the region of $-4.3 < X/D < 2$. For $2.75 < X/D < 3.75$, the effectiveness first increases and then decreases as the injection angle increases. For $\alpha = 30°$ and $\alpha = 45°$, the area average film cooling effectiveness monotonously increases as the blowing ratio increases. For $\alpha = 60°$, this effectiveness first increases and then decreases as the blowing ratio increases from 0.5 to 2.0, with the best blowing ratio M = 1.5. Under the same blowing ratio, the $\alpha = 30°$ case always yields the highest area average film cooling effectiveness in the leading edge region.

1. Introduction

To achieve higher thermal efficiency and higher specific power output, modern gas turbine engines operate at increasing entry temperatures. Turbine components struggle to work at temperatures greatly exceeding the temperature limit of the metal from which they were constructed. Film cooling is one of the most classical and effective methods for protecting blade surfaces from hot gas. In this method, relatively cooler air extracted from a compressor is injected into the mainstream gas through discrete film holes and forms a protective film separating a blade from the surrounding hot mainstream gas. Goldstein [1] offered a fundamental understanding of film cooling in 1971. A comprehensive compilation of the state-of-the-art cooling technology was documented by Han et al. in 2012. [2]. Because of stagnation flow, the leading edge of a blade is the weakest region and can be ablated more easily because it can withstand the highest heat load.

Several investigations on leading edge film cooling have been conducted. Luckey et al. [3] performed an experimental investigation to consider the influence of the blowing ratio (M = 0–2.0), film injection angle (25°, 35° and 45°) and injection location on the film cooling of a cylindrical leading edge model. Their results indicate that when the film injection angle increases from 25° to 45°, the corresponding blowing ratio for the highest level of film cooling performance decreases from 1.07 to 0.6 at injection location $\theta_i = 40°$. Ekkad et al. [4] performed an experimental study on the leading edge of a rotor blade model using the thermochromic liquid crystal (TLC) technique. The mainstream Reynolds number $Re = 1.009 \times 10^5$, and the blowing ratio was maintained at 0.4, 0.8 and 1.2. They found that the highest film cooling effectiveness for air and CO_2 coolants can be measured at M = 0.4 and M = 0.8, respectively. Ou et al. [5] conducted a film cooling investigation, in which the film effectiveness on a circular leading edge model

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Nomenclature

C	chord length of the rotor blade (mm)
d	film-hole diameter (mm)
DR	density ratio (ρ_c/ρ_m)
M	average blowing ratio ($M = \rho_c v_c/\rho_\infty v_\infty$)
Ma	Mach number ($Ma = v/s$)
Re	Reynolds number ($Re = \rho_m v_{out} C/\mu$)
Ro	rotating number ($Ro = \Omega d/v_{in}$)
T	temperature (K)
v	velocity (m/s)
s	sound velocity (m/s) ($s = \sqrt{kRT}$)
R	gas constant [J/(kg·K)]
k	specific heat ratio
p	hole spacing in the spanwise direction (mm)
X	the streamwise distance from the middle-row film holes (mm)

Abbreviations

TLC	thermochromic liquid crystal
RGB	red, green, blue
HSI	hue, saturation, intensity
PS	pressure side
SS	suction side
CCS	camera control system
SCS	strobe control system
SCM	single-chip microcomputer

Greek symbols

α	spanwise inclination angle of a film hole (°)
η	adiabatic film cooling effectiveness [$\eta = (T_m - T_{aw})/(T_m - T_c)$]
ρ	density (kg/m^3)
Ω	rotating speed (rpm)
μ	dynamic viscosity of the mainstream [kg/(m·s)]

Subscripts

aw	adiabatic wall
m	mainstream
c	coolant
in	turbine inlet
out	turbine outlet
∞	turbine stage inlet

was measured. The mainstream Reynolds number varied from 3.0×10^4 to 6.0×10^4, and the blowing ratio was set to 1.0, 1.5, 2.0 and 2.5. They noted that for the same Reynolds number, the film effectiveness follows an increasing trend until the blowing ratio reaches 2.0 for high turbulence. The film effectiveness increases as the Reynolds number increases, except when M = 2.5 for higher turbulence. Kim and Kim [6] used infrared thermography technology to experimentally study the influences of the films holes of five different structures on the blade leading edge film cooling characteristic. The blowing ratio was maintained at 0.7, 1.0, 1.3 and 1.7. Their results demonstrate that the traditional cylindrical holes yield the poorest film cooling performance, while shaped holes can effectively improve the film cooling characteristic. Azzi et al. [7] conducted a numerical simulation to study the effect of lateral injection angles on the film effectiveness at the leading edge of a symmetrical turbine blade. The lateral injection angle was maintained at 25°, 30°, 35° and 45°. The results indicate that the optimal film coverage and the highest film cooling effectiveness are provided by the 25° injection case. Rozati and Tafti [8] studied the effect of the blowing ratio on leading-edge-area film cooling via a large eddy simulation (LES). The researchers reported that the film cooling effectiveness decreases as the blowing ratio increases. Johnson et al. [9] studied the influence of a fluctuating flow on the film cooling characteristic of a turbine-blade leading edge model. They found that the film cooling effectiveness of a stabilized flow with a stagnation line is higher than that of an oscillating stagnation line at the leading edge. Li et al. [10] presented the film cooling characteristic on a leading edge by using the pressure sensitive paint (PSP) mass transfer analogy. Their results reveal that shaped holes can provide better protection than cylindrical holes at higher blowing ratios and that radial-angle-shaped holes can provide the highest cooling effectiveness at a higher density ratio. Liu et al. [11,12] conducted an experimental investigation to study the film cooling characteristics of cylindrical and laid-back holes on a leading edge as well as the effects of the radial angle (30°, 45°) and hole pitch (5d, 8d) on the film cooling characteristics. They noted that for a fixed blowing ratio and compared to models with a large radial angle, models with a small radial angle can provide higher average film cooling effectiveness. In addition, models with p = 5d can offer larger film cooling coverage than models with p = 8d. Recently, in Chowdhury et al. [13], an experimental study was conducted in a wind-tunnel facility to consider the effect of the turbine-blade leading edge shape on film cooling. The influence of the density ratios (1.0–2.0) with blowing ratios ranging from 0.5 to 1.5 were also studied. The results suggest that the 1.5R leading edge model can provide better cooling performance than the other two models tested. For all models and density ratios, the film cooling effectiveness shows a tendency to increase as the blowing ratio increases, with the DR = 2.0 case yielding relatively higher levels of film effectiveness at high blowing ratios. Gao et al. [14] carried out a numerical simulation to study the leading-edge film cooling performance of cylindrical film holes with five different compound angles. They found that the film cooling effectiveness increases as the blowing ratio increases, while it slightly decreases when M = 2.0, and that the best blowing ratio is approximately 1.4.

A number of works have been conducted in the stationary state to study the film cooling characteristics. Due to the great difficulty in conducting experiments, only few useful results regarding the experimental investigation of film cooling under rotating conditions exist, although it has great significance in the design of turbines. The film cooling performance on a turbine blade under rotating conditions has been studied since 1980. Dring et al. [15] presented an experimental investigation in which the film cooling performance on the leading edge of a blade under rotating conditions was studied for the first time. Coolant was injected via film cooling holes on both the pressure side (PS) and suction side (SS). Their results show that the radial component of the coolant trajectory has an indispensable influence on the distribution of the cooling effectiveness. On the SS, the radial deviation of the jet is small, which is in good agreement with the previous research results on a flat plate. A very obvious radial deviation due to the radial component of the main flow on the PS occurs, resulting in a smaller cooling effectiveness. A heat-mass transfer analogy was used by Takeishi et al. [16] to measure the film cooling effectiveness on a low-speed cascade in the stationary state and on a blade under rotating conditions. The researchers reported that the film cooling effectiveness on the SS of the rotating blade was in agreement with the result of the stationary cascade and was only 30% lower downstream. The cooling effectiveness on the PS was lower