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Film cooling characteristics on the leading edge of a rotating turbine blade with various mainstream Reynolds numbers and coolant densities

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ABSTRACT

This paper reports on an experimental investigation of the influences of mainstream Reynolds number and coolant density on film cooling characteristics on the leading edge of a twisted turbine blade under rotational conditions. The experiments were carried out at a test facility with a 1-stage turbine using the thermochromic liquid crystal (TLC) technique. The mainstream Reynolds number varied from 4.4201×10^4 to 7.1797×10^4. All tests were carried out at three rotational speeds of 400 r/min, 500 r/min and 650 r/min to fix the rotation number at 0.0018. The coolant-to-mainstream density ratios were fixed at 1.04 and 1.56 with N_2 and CO_2 as coolants, respectively. The blowing ratio effect was also considered. The results showed that under the same blowing ratio, the averaged film cooling effectiveness on the measurement area increased with increasing mainstream Reynolds number for both coolant gases. Under the same Reynolds number, the span-wise averaged film cooling effectiveness increased as the blowing ratio increased for both coolant gases. Under the same Reynolds number and blowing ratio, higher-density coolant jets (CO_2) provided higher averaged film cooling effectiveness than lower-density coolant jets (N_2) on the measurement area. Overall, mainstream Reynolds number, blowing ratio and coolant density played significant roles in the film cooling characteristics of the leading edge under rotational conditions.

1. Introduction

Increasing the gas temperature at the inlet of a turbine has become the primary means of obtaining greater thrust and improved performance in advanced engines. However, higher inlet temperatures now exceed the melting points of currently employed heat-resistant alloys, which greatly reduces the reliability and lifetime of the turbine. Therefore, a variety of cooling methods are employed to ensure that turbine operating temperatures remain within safe ranges. A fundamental understanding of film cooling was provided by Goldstein [1] in 1971. A comprehensive compilation of state-of-the-art cooling technology was documented by Han et al. in 2012. [2]. Film cooling is an extensively accepted cooling method to protect turbine components from high-temperature thermal deterioration. In this technique, relatively cooler coolant is penetrated through the film hole or gap in the end face or the turbine blade surface. The extrusive coolant establishes a shielding film between the turbine component and high-temperature gas. The film cooling characteristics are determined using numerous crucial parameters such as mainstream Reynolds number (*Re*), mainstream turbulence intensity, rotation number (*Ro*), Mach number, density ratio (DR), blowing ratio (M), secondary flow, blade surface curvature, and hole geometry [3–7].

The leading edge is the weakest region and can be ablated more easily than the remainder of the turbine blade. This is because the total temperature of gas is highest there and because existing cooling techniques are ineffective due to limitations of shape and structure. Over the past five decades, numerous studies on techniques for cooling the leading edge region have been carried out in the stationary state. Mick and Mayle [8] conducted a cooling performance study in which film efficiency was measured on a leading edge model joined by a flat afterbody. Their results demonstrated that film efficiency decreases with an increasing averaged secondary-to-incident mass flux rate. Mehendale et al. [9] presented a study in which the film efficiency was measured on a leading edge model. The mainstream Reynolds number was $Re = 1.0 \times 10^5$, and the mainstream turbulence intensity was maintained at 0.75%, 9.67% and 12.9%. The effects of three blowing ratios (0.4, 0.8 and 1.2) were also considered. It was concluded that film efficiency shows a decreasing trend with an increasing blowing

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Nomenclature

C_R	chord length of the rotor blade, mm
C_S	chord length of the stator blade, mm
D	film hole diameter, mm
DR	density ratio, ρ_c/ρ_m
M	average blowing ratio, $M = \frac{\rho_c v_c}{\rho_\infty v_\infty}$
Re	Reynolds number, $Re = \rho_m v_{out} C/\mu$
Ro	rotation number, $Ro = \Omega d/v_{in}$
T	temperature, K
v	velocity, m/s
P	hole spacing in the spanwise direction, mm
X	stream-wise distance from the middle film row holes, mm

Abbreviations

TLC	thermochromic liquid crystal
RGB	red, green, blue
HSV	hue, saturation, value
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 the film hole, °
η	film cooling effectiveness
ρ	density, kg/m^3
Ω	rotational speed, r/min
μ	dynamic viscosity of the mainstream, kg/(m·s)

Subscripts

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

ratio. For M = 0.4, the film efficiency decreases sharply with increasing mainstream turbulence. Subsequently, Mehendale et al. [10] conducted a cooling performance study in which the film efficiency and heat flux were measured on the leading edge in a wind tunnel. The mainstream Reynolds number was maintained at 1.0×10^5, 2.5×10^5 and 4.0×10^5. The results indicated that film efficiency increases as Reynolds number increases. The lowest level of heat flux ratio over most of the test surface was measured for *Re* = 1.0×10^5. Ekkad et al. [11] conducted a film cooling investigation in which the influences of mainstream turbulence and coolant density on film cooling characteristics were analyzed for a cylindrical leading edge. The density ratios were fixed at 1.0 and 1.5. The mainstream Reynolds number was *Re* = 1.009×10^5, and the blowing ratio was maintained at 0.4, 0.8 and 1.2. The authors found that the highest film cooling effectiveness occurred at M = 0.4 and M = 0.8 for air and CO_2 coolants, respectively. Large mainstream turbulence makes very little difference to the Nusselt number at the same blowing ratio for both coolant gases. Ou et al. [12] conducted a film cooling investigation in which film effectiveness was measured on a circular leading edge model. 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 at the same Reynolds number, the film effectiveness showed an increasing trend before the blowing ratio rose to 2.0 for high turbulence. The film effectiveness increased with increasing Reynolds number, except for the case of M = 2.5 for higher turbulence. Kim and Kim [13] used infrared thermography technology to experimentally study the influences of five different film hole structures on blade leading edge film cooling characteristics. The mainstream Reynolds number was *Re* = 7.1×10^4, and the blowing ratio was maintained at 0.7, 1.0, 1.3 and 1.7. Their results demonstrated that traditional cylindrical holes were the least effective in film cooling. It was also found the shaped holes can effectively improve film cooling characteristics. A detailed study of film cooling characteristics on a blade leading edge was provided by Liu et al. [14]. The mainstream Reynolds number was maintained at 3.8×10^4, and the density ratio was maintained at 1.0. Their results suggested that as the blowing ratio increases, the coolant traces on the leading edge surface deviate gradually from the mainstream direction to the spanwise direction. Li et al. [15] employed the pressure-sensitive paint (PSP) method to study the effect of density ratio on leading edge film cooling characteristics. The Reynolds number was *Re* = 1.009×10^5, and the density ratio was controlled at 1.0, 1.5 and 2.0. All the experiments were completed with varying blowing ratios in the range of 0.5 to 2.1. Their results indicated that the higher-density coolant provided increased film attachment to the surface, which offered a better protective effect. Liu et al. [16] performed a film cooling investigation in which the film cooling efficiency was obtained on an enlarged blade leading edge in a transonic cascade. The effects of inlet Reynolds number and exit Mach number were considered. The Reynolds number was maintained at 2.57×10^5, 5.07×10^5 and 5.6×10^5. The film cooling efficiency increased on the PS with an increasing blowing ratio. The Reynolds number and Mach number had very small effects on film efficiency on the PS; however, these two parameters played opposite roles in the distribution of film efficiency on the SS.

A multitude of previous studies have been carried out under static conditions to investigate film cooling characteristics. Due to limitations in test rigs and measurement techniques, only a few available experimental results can be found in the open literature on rotating turbines, although rotation is a key factor that influences film cooling characteristics. Dring et al. [17] presented a cooling performance study in which film cooling adiabatic effectiveness was measured in a rotating facility. The density ratio changed in the range of 1.0 to 4.0. The Reynolds number was *Re* = 5.6×10^5, and the rotational speed was fixed at 405 r/min. The authors found that the film cooling efficiency was in reasonably good agreement with existing results obtained on the SS of a flat plate, and the cooling efficiency was lower than results from the PS of the flat plate. A film cooling experiment in a 1-stage turbine test rig was provided by Takeishi et al. [18]. The experiment was conducted at room temperature, and the density ratio was approximately 1.0. Their results showed that the film cooling effectiveness obtained under rotational conditions was in close agreement with the data measured under static conditions until x/d = 45 on the SS. However, the effectiveness was approximately 30% lower than the data for the stationary blade over x/d = 45. Abhari et al. [19] presented a film cooling experiment in which both average and time-resolved heat transfer were measured on a 1-stage transonic turbine under rotational conditions. The rotational speed was maintained at 6190 r/min, and the density ratio was maintained at 0.63. The findings indicated that on the SS, the time-averaged heat transfer was reduced by approximately 60% with the cooled rotor blade. The uncooled blade results are