International Journal of Heat and Mass Transfer 129 (2019) 47–58

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental investigation on the effects of rotation and the blowing ratio on the leading-edge film cooling of a twist turbine blade

Hai-wang Li, Feng Han, Yi-wen Ma, Hai-chao Wang, Zhi-yu Zhou, Zhi Tao *

National Key Laboratory of Science and Technology on Aero Engines Aero-thermodynamics, The Collaborative Innovation Middle for Advanced Aero-Engine of China, School of Energy and Power Engineering, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 22 December 2017
Received in revised form 18 August 2018
Accepted 2 September 2018

Keywords:
Film cooling
Leading edge
Rotating blade
Effectiveness
Blowing ratio

ABSTRACT

An experimental investigation has been performed to investigate the effects of the rotation and blowing ratio on the film cooling effectiveness distributions of the leading-edge regions of a twist gas turbine blade using a thermochromic liquid crystal (TLC) technique. The experiments were carried out at three rotating speeds, including 400 rpm (positive incidence angle), 550 rpm (zero incidence angle), and 700 rpm (negative incidence angle). The averaged blowing ratio ranged from 0.5 to 2.0. CO_2 was used as the coolant to ensure that the coolant-to-mainstream ratio was equal to 1.56. The Reynolds number, based on the mainstream velocity of the turbine outlet and the rotor blade chord length, was 6.08×10^4. The effects of the rotating speed and the blowing ratio were analyzed based on the film cooling effectiveness distribution. The results show that rotating speed plays an indispensable role in determining the film cooling effectiveness of distributions on the leading edge. The position of the stagnation line moves from the pressure side (PS) to the suction side (SS) via an increase in rotating speed. Under the same blowing ratio, the area-averaged film cooling effectiveness increases monotonously with an increase in rotating speed. Under the same rotating speed, the area-averaged film cooling effectiveness increases with the increase in blowing ratio. More details about the effects of the rotation speed and blowing ratio on the spanwise averaged film cooling effectiveness of the leading-edge region are shown in this study.

1. Introduction

In the design of the modern gas turbine engine, the inlet temperature of the turbine has been increased continuously to obtain a higher thermal efficiency. However, the higher inlet temperature exceeds the melting point of the currently used heat resistant alloys, which can greatly reduce both the reliability and the lifetime of the turbine. Therefore, a variety of cooling techniques are employed to ensure that the turbine operating temperature remains in a safe range. Film cooling, an efficient cooling technique, has been widely accepted as a method of preventing the turbine components from experiencing high-temperature thermal deterioration. In this technique, a relatively cooler coolant penetrates the film hole or gap in the end face of the turbine blade surface and forms a shielded film between the turbine components and the hot temperature gases. Over the past 5 decades, a considerable number of researchers have sought a deeper understanding of the physical process of film cooling to optimize a design configuration that can achieve more efficient protection with less cooling gas. The various aspects of the heat exchange mechanism and the cooling process of the turbine blade were described by Han et al. [1].

The leading-edge region of the turbine blade often withstands higher heat loads than any part of the blade surface due to the highest heat-transfer rate. Many investigations into the film cooling process of the leading edge of a turbine blade have been carried out with the blade in a stationary state. A detailed study of the heat transfer characteristics and film cooling effectiveness on a circular leading-edge model was performed by Mick and Mayle [2]. Those researchers reported that the maximum values of the heat exchange coefficient and film effectiveness do not occur in the same region. More recently, Cruse et al. [3] analyzed the effect of a stagnation line position on the adiabatic effectiveness of the film cooling of a leading-edge model. The results from their experiments showed that the stagnation line position is a very important factor in changing the cooling flow direction. A thermochromic liquid crystal (TLC) technique was used by Ekkad et al. [4] to study the effects of mainstream turbulence and coolant density on the effectiveness of film distribution over a leading-edge test model. The mainstream Reynolds number was $Re = 1.009 \times 10^5$ and the blowing ratio was maintained at 0.4, 0.8 and 1.2. Their results

---

* Corresponding author.
E-mail address: tao_zhi@buaa.edu.cn (Z. Tao).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.09.005
0017-9310/

Nomenclature

C	blade chord length (mm)
d	film hole diameter (mm)
DR	density ratio, ρ_c/ρ_g
M	blowing ratio, $M = \rho_c v_c/\rho_g v_g$
Ma	Mach number ($Ma = v/s$)
Re	Reynolds number, $Re = \rho_g v_{out} C/\mu$
p	hole spacing in the spanwise direction (mm)
X	distance from the stagnation line (mm)
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

Abbreviations

TLC	thermochromic liquid crystal
RGB	Pixel Red, Green and Blue values
HSV	hue, saturation, value
PS	pressure side
SS	suction side
CCS	camera control system
SCS	strobe control system
SCM	single-chip microcomputer

Greek symbols

η	adiabatic film cooling effectiveness, $\eta = (T_g - T_w)/(T_g - T_c)$
ρ	density (kg/m^3)
Ω	rotating speed (rpm)
μ	dynamic viscosity of the mainstream, kg/(m·s)

Subscripts

w	adiabatic wall
g	mainstream
c	coolant
out	turbine outlet

showed that film effectiveness decreases as mainstream turbulence increases at a low blowing ratio. The highest film cooling effectiveness was measured at M = 0.4 and M = 0.8 for air and CO_2 coolants, respectively. Ou et al. [5] 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. Those researchers noted that under high turbulence conditions, the film effectiveness increases as the blowing ratio increases from 1.0 to 2.0 for both Reynolds numbers. Film effectiveness increases as the Reynolds number rises, except for the M = 2.5 case for higher turbulence. Kim and Kim [6] used infrared thermography technology to experimentally study the influence of five different structures of the film hole on the blade's leading-edge film cooling characteristic. The blowing ratio was maintained at 0.7, 1.0, 1.3 and 1.7, respectively. Their results demonstrated that traditional cylindrical holes show the lowest level of film cooling performance. Those researchers also found that the shape of the holes can effectively improve the film cooling characteristic. Rozati and Tafti [7] studied the effect of the blowing ratio on leading-edge area film cooling via contributions from a large eddy simulation (LES) method. They reported that film cooling effectiveness decreases with an increase in the blowing ratio. Johnson et al. [8] studied the influence of a fluctuating flow on the film cooling characteristics of a turbine blade leading-edge model. They found the film cooling effectiveness with an oscillating stagnation line was degraded by as much as 25% compared to the effectiveness of a steady flow with the stagnation line aligned with the roe of holes at the leading edge. Li et al. [9] presented the film cooling characteristics of the leading edge using the Pressure Sensitive Paint (PSP) technique. Their results showed that shaped holes can provide better protection than cylindrical holes at a higher blowing ratio. Radial angle-shaped holes can provide the highest cooling effectiveness at a higher density ratio. In Chowdhury et al. [10], an experimental study was conducted in a wind-tunnel facility to consider the effect of turbine blade leading-edge shape on film cooling. Three leading-edge models were considered including a semi-cylinder of radius R = 38.1 mm, elliptical leading edges of major radius 1.5R and 2.0R with an after body. That study's results suggest that a 1.5R leading-edge model can provide better cooling performance than the other two models.

Although there have been numerous studies of film cooling characteristics, most of those studies were conducted in the stationary state. Only a few useful results use experimental investigation to study film cooling under rotating conditions because of the great difficulty in conducting such experiments. The film cooling performance of a blade under rotating conditions was first studied by Dring et al. [11]. Film coolant was injected from cooling holes on both the pressure side (PS) and the suction side (SS). According to the obtained results, the radial component of the jet trajectory has an indispensable influence on the distribution of cooling effectiveness. On the SS, the radial deviation of the jet is small, which is consistent with a previous research result taken on a flat plate. An obvious radial deviation caused by the radial component of the main flow on the PS results in lower cooling effectiveness. A heat-mass transfer analogy was used by Takeishi et al. [12] to measure the film cooling effectiveness of a low-speed cascade under the stationary state and under the rotating conditions of the blade, in turn. Those researchers reported that film cooling effectiveness on the SS of the rotating blade is consistent with the result of the stationary cascade and is only 30% lower downstream. The cooling effectiveness of the PS is lower because of the radial flow of the concave surface and the strong mix between the coolant jets and mainstream fuel. Ahn et al. [13] presented an experimental investigation in which film cooling effectiveness was measured on the blade's leading edge in a 3-stage turbine under rotating conditions via a PSP method. All their experiments were carried out at rotational speeds of 2400 (positive incidence angle), 2550 (zero incidence angle) and 3000 (negative incidence angle) r/min. Their results demonstrate that rotation is the most important factor in determining the distribution of film cooling effectiveness. Under the same blowing ratio, the average film effectiveness shows a decreasing trend with an increase in rotating speed. The average film effectiveness shows a decreasing trend with an increase in the blow ratio at Ω = 3000 r/min, whereas it is not sensitive to a blowing ratio at 2400 and 2550 r/min cases. Subsequent research by Ahn et al. [14] involved a further study on the blade's leading edge under rotating conditions. They reported that the rotating speed changes the direction of the coolant traces. For the three rotational speed conditions, the average film effectiveness increases slightly as the blowing ratio rises. An experiment on the film cooling performance of the blade under rotating