International Journal of Heat and Mass Transfer 105 (2017) 67–75

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Film cooling performance and flow characteristics of internal cooling channels with continuous/truncated ribs

Gongnan Xie [a,*], Xueting Liu [b], Hongbin Yan [a,*]

[a] School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an 710072, PR China
[b] School of Mechanical Engineering, Northwestern Polytechnical University, Xi'an 710072, PR China

ARTICLE INFO

Article history:
Received 14 March 2016
Received in revised form 19 September 2016
Accepted 20 September 2016

Keywords:
Film cooling
Continuous rib
Truncated rib
Fluid flow
Blowing ratio

ABSTRACT

To better evaluate the application of ribs in gas turbine blade cooling, this numerical study reports on the effects of ribs mounted on the internal cooling channel wall on external adiabatic film cooling performance. The numerical model is validated against available experimental data. For fixed mainstream and cooling flow Reynolds numbers, three ribs including the continuous rib, centrally truncated rib and laterally truncated rib at two blowing ratios (i.e., 0.5 and 1.0) are considered. At lower blowing ratio, results show that the cases with three distinct ribs provide approximately identical cooling effectiveness but significantly outperform the case without ribs. The superiority regarding laterally averaged adiabatic cooling effectiveness is 17–157%. However, at higher blowing ratio, the cases with ribs are inferior to the case without ribs, showing an inferiority of 21–68%. Further, at higher blowing ratio, the case with continuous ribs exhibits a 12–45% higher localized cooling effectiveness relative to other ribbed cases. It is found that cooling effectiveness deteriorates with the increase of spiral intensity of the coolant flow inside the film hole. Lower spiral intensity leads to a better covering of target wall by the coolant and thus results in better cooling effectiveness. The distinct relative merits among the cases at different blowing ratios are explored based on the aforementioned dominant mechanism.

1. Introduction

To further improve thermal efficiency and thrust-weight ratio of gas turbines, higher gas temperature at the inlet of their cascades is desirable [1]. Correspondingly, blade temperature may exceed the allowable metal temperature [2]. To prevent turbine blades from overheating, a plenty of cooling techniques as schematically summarized in Fig. 1 have been devised [3]. The combination of internal cooling (e.g., impingement cooling and pin-fin cooling) and external film cooling has been adopted in the majority of modern gas turbines. Numerous experimental and theoretical investigations into thermo-fluidic characteristics of such cooling structures have been performed to further improve their performance.

During past decades, most of the studies focused on either internal or external cooling with their interaction neglected. In terms of internal cooling, ribs protruding from walls of the cooling channels are commonly used. The introduction of ribs results in successive interruption and redevelopment of flow and thermal boundary layers, intensified flow mixing and enlarged heat transfer area, which can significantly enhance internal convective heat transfer and thus decrease turbine blade temperature [4]. A multitude of experimental and numerical studies have been conducted to explore the effects of various factors such as shape and configuration of ribs and shape of cooling passages on fluid flow and heat transfer [5–9]. According to the results, both of geometric parameters of channels and working conditions have significant effects on the thermal performance. Typically, these researchers in [7,9] reported that the shape of ribs has a more evident effect on pressure drop than that on heat transfer, while the inclination of ribs relative to the primary flow has evident effects on pressure drop and heat transfer concurrently. In particular, the truncation of ribs slightly deteriorates heat transfer but evidently reduces pressure drop penalty [10–13]. Consequently, truncated ribs seem to be desirable. With respect to film cooling, previous studies mainly focused on dominant factors governing the fluid flow through the film hole and mainstream such as the direction of coolant ejected from the hole, the blowing ratio, inclination angle of the hole relative to mainstream, shape of the film hole and length-to-diameter ratio of the hole [14–21]. It was reported that the inclination of hole axis relative to the mainstream leads to better covering of the target blade surface by coolant and thus results in better film cooling performance. Therefore, the inclined film hole is considered in the present study.

* Corresponding authors.
E-mail addresses: xgn@nwpu.edu.cn (G. Xie), hbyan@nwpu.edu.cn (H. Yan).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.09.065
0017-9310/© 2016 Published by Elsevier Ltd.

Nomenclature

A_h	cross-sectional area of the film hole (m^2)	T_{aw}	wall temperature (K)
C_d	discharge coefficient as defined in Eq. (5)	T_c	fluid temperature at inlet of cooling channel (K)
D	diameter of circular film hole (m)	T_g	mainstream inlet temperature (K)
D_h	hydraulic diameter of the cooling channel (m)	T_{tc}	stagnation temperature at the inlet film hole (K)
e	width or height of the square rib (m)	u	coolant inlet velocity (m/s)
H	height of film hole along z-axis (m)	U	velocity magnitude (m/s)
k	adiabatic exponent of air	u_{ch}	average velocity through the file hole (m/s)
m_h	mass flow rate through the film hole (kg/s)	u_g	mainstream inlet velocity (m/s)
$m_{in,c}$	mass flow rate entering cooling channel (kg/s)	W	width of the cooling channel (m)
$m_{out,c}$	mass flow rate exiting cooling channel (kg/s)	x, y, z	Cartesian coordinate components (m)
M	dimensionless blowing ratio		
P	pitch of ribs (m)	*Greek symbols*	
P_g	static pressure at the outlet of film hole (Pa)	α	inclination angle of the film hole (°)
P_{tc}	total pressure at the inlet of the film hole (Pa)	η	adiabatic film cooling effectiveness
R	gas constant of air (J/(mol·K))	ρ_g	mainstream inlet fluid density (kg/m^3)
Re_{Dh}	Reynolds number	ρ_c	coolant inlet density (kg/m^3)
T	local temperature (K)	μ	dynamic viscosity of air (Pa·s)

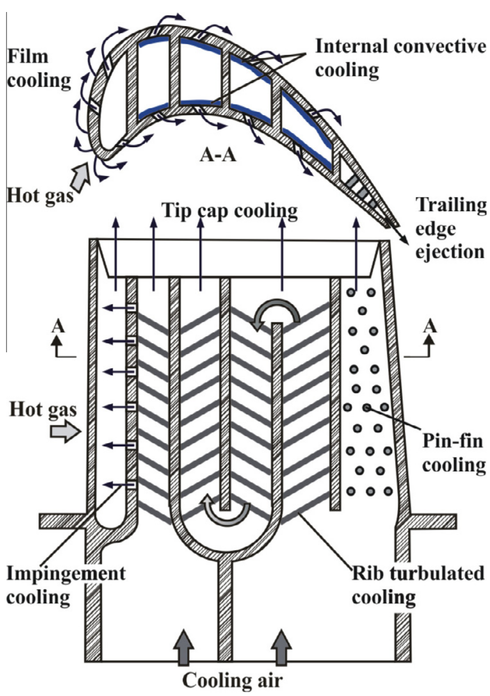

Fig. 1. A schematic summary of typical cooling techniques for modern gas turbine blades [3].

In contrast to the well-established fluid flow and heat transfer characteristics separately for the internal cooling and film cooling, investigation into the effects of internal flow on film cooling performance is limited. Experimental study by Wilfert et al. [22] revealed that film cooling performance is strongly affected by the flow conditions at the inlet of the internal cooling channel. With the aid of specially designed continuous ribs, coolant was guided into the film hole. Thus an increase of laterally averaged film cooling effectiveness up to 56% is reported. Kissel et al. [23] experimentally and numerically investigated the film cooling performance where coolant through the film hole was supplied by an internal cooling channel instead of a plenum chamber adopted in a plenty of studies. At a higher mainstream Reynolds number, adiabatic film cooling effectiveness nearby the film hole exit was enhanced. Further, internal cooling channel with continuous ribs was found to increase the laterally averaged heat transfer coefficient relative to a smooth cooling channel. Wang et al. [24] numerically analyzed the effects of different rib configurations on film cooling effectiveness. They reported that the circular rib configuration without truncation provided a higher film cooling effectiveness relative to the square rib and pin rib configurations. The effect of rib on film hole discharge coefficient was experimentally studied by Bunker and Bailey [25]. Chanteloup and Bölcs [26,27] investigated the flow and heat transfer in a stationary model consisting of a two-pass coolant passage with inclined continuous ribs and film cooling hole. The extraction of film hole was found to make the vortices asymmetrical and to enhance the heat transfer nearby the film hole.

In view of the above, numerous studies separately focus on heat transfer enhancement techniques in the internal cooling channel or film cooling flow and heat transfer in the mainstream channel. However, the exploration on the effects of internal cooling channel on external film cooling performance is limited, especially for the effect of ribs mounted on the interior passage wall on film cooling. Detailed thermo-fluidic physics regarding the interaction between the cooling flow in the ribbed channel and the mainstream channel is not yet clarified.

Actually, different internal cooling passages lead to different fluid flow behaviors in the channel, which affect film cooling effectiveness and the corresponding turbine blade temperature. In particular, it has been found by previous studies that truncated ribs exhibit well performance in improving the internal cooling and inclined film holes can enhance film cooling effectiveness. However, to the best knowledge of the present authors, the effects of internal cooling channel with truncated ribs on film cooling performance is not yet reported in the open literature. Such an insight is believed to be beneficial for comprehensively evaluating the application of truncated ribs in gas turbine blade cooling. Consequently, this paper numerically investigates the adiabatic film cooling performance and the corresponding fluid flow mechanisms with coolant provided by internal cooling channel with various specially designed truncated ribs.

2. Physical model

The physical model consisting of the internal cooling channel, film hole and the mainstream channel is schematically shown in Fig. 2(a). The film hole with a diameter (D) of 10 mm is inclined by $\alpha = 30°$ relative to the mainstream direction. The height (H) of