International Journal of Heat and Mass Transfer 128 (2019) 980–990

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Optimized inlet geometry of a laidback fan-shaped film cooling hole – Experimental study of film cooling performance

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ARTICLE INFO

Article history:
Received 13 April 2018
Received in revised form 28 July 2018
Accepted 8 September 2018

Keywords:
Film cooling
Cooling hole geometry
Superposition approach
Internal coolant flow
Heat transfer measurements
Hole inlet optimization

ABSTRACT

The orientation of an internal coolant channel with respect to the external hot gas flow has a major impact on film cooling performance. Previous studies reported a considerable decrease of cooling performance with perpendicular coolant crossflow for a state-of-the-art laidback fan-shaped film cooling hole. The objective of this experimental study is to investigate the extent to which cooling performance in such a setup can be improved by using an optimized cooling hole inlet geometry. For this purpose, three geometries with different cooling hole inlets are investigated. Results are compared to a baseline geometry with a sharp-edged cylindrical inlet. A test rig is used which enables compliance with all relevant non-dimensional parameters. High-resolution infrared measurements are conducted and heat transfer as well as cooling effectiveness are evaluated for up to 50 cooling hole diameters downstream of the cooling hole exit.

Results show that the cooling hole inlet geometry tremendously affects cooling performance. Diffuser aerodynamics are altered for all investigated geometries with a modified inlet. This leads to a more symmetrical pattern of the film cooling jet for two of the investigated geometries. As a consequence, film cooling effectiveness is increased compared to the baseline case. The disadvantages of a perpendicular coolant flow in terms of effectiveness are entirely eliminated. Additionally, heat transfer coefficients are lowered. An overall evaluation reveals that the heat flux into the wall is significantly reduced for the proposed optimized cooling hole geometries.

1. Introduction

Thermal efficiency of gas turbines depends on the pressure ratio and the turbine inlet temperature. As a consequence, temperatures in the first turbine stages of modern gas turbines are higher than the melting temperatures of the applied materials. Vanes and blades of the first turbine stages are therefore cooled intensively by internal cooling and film cooling.

For film cooling, coolant is blown onto the surface of the turbine blades through small holes and forms an insulating coolant film. Since the coolant mixes with the hot gas, the cooling performance decreases steadily downstream of a film cooling hole.

In general, the use of coolant is associated with losses. Cooling air does not take part in the entire thermodynamic cycle, since it bypasses the combustion chamber. Moreover, mixing and discharge losses arise with film cooling. Hence, reduction of the coolant mass flow is of interest.

Film cooling affects both adiabatic wall temperature and heat transfer. It is influenced by a variety of different parameters, such as blowing and density ratio [1], hot gas Reynolds number [2], displacement thickness [2], and turbulence intensity [3]. Bogard and Thole [4] give a comprehensive overview.

The geometric shape of a film cooling hole has a major impact on film cooling performance. The simplest hole shape is a cylindrical one. Goldstein et al. [5] suggested to use holes with a cylindrical inlet and a diffuser-shaped outlet of the film cooling hole instead. Their results show that the jet momentum at the cooling hole exit and, hence, jet penetration into the hot gas is reduced for diffuser-shaped holes. The jet remains attached to the surface even for high blowing ratios. In addition, the lateral expansion of the jet is increased, which is also desirable. Diffuser-shaped holes are typically divided into three types: Laidback holes, fan-shaped holes, and laidback fan-shaped holes. Whereas laidback holes improve the centerline effectiveness only [6], fan-shaped and laidback fan-shaped holes significantly improve lateral jet expansion and film cooling effectiveness. This is especially the case for higher blowing ratios, see Gritsch et al. [7]. However, this only holds true if there is a significant diffusion of the coolant due to the film

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.09.035
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Nomenclature

A	area
D	cooling hole diameter
DR	density ratio ($= \rho_c/\rho_h$)
H	height
L	cooling hole length
M	blowing ratio ($= (\rho_c u_c)/(\rho_h u_h)$)
$NHFR$	net heat flux reduction
P	cooling hole pitch
Re	Reynolds number
T	temperature
Tu	turbulence intensity
h	heat transfer coefficient
l_ϵ	turbulent length scale
p	pressure
$\dot{q}$	convective heat flux density
r	radius
u	free stream velocity
x	streamwise coordinate
y	lateral coordinate
z	wall-normal coordinate
Greek	
α	ejection angle
δ_1	displacement thickness
η	film cooling effectiveness
Θ	non-dimensional temperature
λ	thermal conductivity
ρ	density
Subscripts/Superscripts	
aw	adiabatic wall
c	coolant
cc	cooling channel
cyl	cylindrical
f	film cooling
h	hot gas
lat	laterally averaged
max	maximum value
rec	recovery
t	total
w	wall
0	without film cooling
=	spatially averaged
Abbreviations	
BL	baseline
CFD	computational fluid dynamics
ITS	Institute of Thermal Turbomachinery
PEEK	polyether ether ketone
TiAl	titanium aluminide (TiAl6V4)

cooling hole shape. If this is not the case, performance of shaped and cylindrical holes are comparable, see Bell et al. [8]. Highest film cooling effectiveness can be achieved by the use of shaped holes with a compound angle, as shown by Bell et al. [8] and Furukawa and Ligrani [9]. A more detailed overview of shaped holes is given by Bunker [10]. Diffuser-shaped holes are state of the art and widely used in modern gas turbines.

In many studies, film cooling holes are fed by a plenum. However, in real-engine applications this is often not the case, since an internal flow is present to increase internal heat transfer. The orientation of such a flow varies. Whereas a parallel orientation of the coolant channel to the hot gas flow has only minor effects on the cooling performance [7], a perpendicular orientation has a significant impact. Such flows are present in many applications. Due to the strong deflection, the flow separates at the inlet and a helical motion is established, as shown by Kohli and Thole [11]. The strong deflection leads to high pressure losses for cylindrical as well as diffuser-shaped holes [12]. The effect of perpendicular coolant flow is different for cylindrical and diffuser-shaped holes: As a result of the helical motion, the film cooling footprint on the surface is asymmetric for cylindrical holes [13]. Results by Gritsch et al. [14] show that the helical motion of the coolant leads to a wider lateral extension and stabilizes the jet. Consequently, the coolant jet does not separate from the surface even at high blowing ratios. Compared to a case with plenum inflow, film cooling effectiveness is increased for high blowing ratios and slightly reduced for low blowing ratios. Heat transfer coefficients, on the other hand, are increased due to the intensified contact between coolant and surface [15]. For diffuser-shaped holes with perpendicular coolant flow orientation, the changed flow patterns inside the cylindrical inlet part of the cooling hole lead to an asymmetric flow separation in the diffuser part. Therefore, film cooling effectiveness is reduced in most cases, as shown by Gritsch et al. [14]. Results by McClintic et al. [16] reveal that the pattern of the asymmetric flow separation is strongly influenced by the velocity ratio between coolant flow in the internal cooling channel and inside the cooling hole, u_{cc}/u_h. In the near-hole region, heat transfer coefficients are reduced for high velocity ratios u_{cc}/u_h compared to a plenum inflow case, as is shown by results of Saumweber and Schulz [15]. This is explained by the reduced contact between coolant and hot gas. For lower velocity ratios, however, heat transfer coefficients are increased in the near-hole region, as shown by Fraas et al. [17]. In this case, the contact between coolant and surface is not reduced significantly. Flow separation at the cooling hole inlet is assumed to cause high turbulence intensities inside the coolant jet. Thus, heat transfer coefficients on the surface are increased. Farther downstream, heat transfer coefficients are increased for perpendicular coolant flow and all velocity ratios u_{cc}/u_h compared to a parallel coolant flow [17].

For perpendicular coolant flow orientation, turbulence promoters, such as ribs inside the coolant channel, can have a major impact on the coolant jet: Compared to a case with perpendicular coolant flow and a smooth channel, orthogonal ribs do not further increase the already high inflow pressure losses of cylindrical holes significantly [18]. However, the inflow pressure losses can be reduced by inclined ribs, as shown by Heneka et al. [19]. This is attributed to vortices forming at inclined ribs. Depending on the orientation, inclined ribs can lead to a reduced helical motion of the coolant inside the cylindrical film cooling hole [20], resulting in an almost symmetric footprint on the surface comparable to a plenum inflow [21,22]. For diffuser-shaped holes and low blowing ratios, a rib orientation which reduces helical motion of the coolant inside the cooling hole suppresses the asymmetric flow separation inside the diffuser, leading to a symmetric footprint on the surface. Film cooling effectiveness is increased in such cases. For diffuser-shaped holes and higher blowing ratios, however, a rib orientation which intensifies the helical motion leads to higher film cooling effectiveness. This is shown by Sakai et al. [23]. These results show that the phenomena leading to an asymmetric flow separation inside the diffuser are not yet fully understood. More studies are required.

Most studies on the cooling hole shape focus on the outlet of the cooling hole. To the knowledge of the authors, only one study by