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Effects of film cooling hole locations on flow and heat transfer characteristics of impingement/effusion cooling at turbine blade leading edge

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ABSTRACT

In order to investigate the effects of the film cooling hole locations on the flow and heat transfer characteristics of the impingment/effusion cooling, the film cooling holes are established on a concave target channel with three inclined angle (0°, 30°, 60° between film cooling hole axis and jet hole axis). The film cooling holes are both in-line and staggered arranged with jet holes when the inclined angle is 30° and 60° and only staggered arranged when the inclined angle is 0°. The film extraction flow distributions, static pressure development, total pressure drop, overall averaged Nusselt number and combined thermal performance are compared among different cases. The development of vortex and cross flow inside the target channel in different cases are studied and compared. The span averaged Nusselt number, Nusselt number contour on the target surface and Nusselt number distribution at several cross sections are studied and compared. Results show that the location of the film cooling holes affects the flow distributions of the film extraction air and the flow development inside the target channel. The heat transfer performance inside the target channel is affected by the impinging effect and the development of the cross flow and vortices.

1. Introduction

In order to gain high thermal efficiency and power, extremely high gas temperature is applied at the turbine inlet. However, excessively high temperature will melt the blade, generate big internal thermal stress and reduce the service life of gas turbine. As a result, appropriate and effective cooling methods are needed to protect the blade.

One of the effective methods to cool down the blade is internal cooling. A large number of studies have been conducted to enhance the heat transfer coefficient between cooling air and internal walls. Many internal cooling schemes have been raised, such as pin-fin cooling, rib turbulated cooling, dimpled wall cooling, impingement cooling and swirl cooling. Han et al. [1] provided a review of the internal cooling method and showed that all the cooling schemes mentioned above can enhance the mixing of the flow and hence enhance the heat transfer performance.

Impingement cooling allows the coolant impinges on the internal wall directly, so the impingement cooling has the most significant potential to increase the local heat transfer coefficient. Investigations on impingement heat transfer characteristics on a plat surface are well documented in several reviews [2–4]. In general, for the flat plate impingement cooling, the Nusselt numbers are mainly affected by several parameters: the impinging jet Reynolds number, the jet hole shape, the jet-to-target surface spacing, and the hole-to-hole spacing. Researchers also investigate the flow and heat transfer characteristics of impingement cooling with multiple jet arrays. Martin et al. [5] applied both circular and slotted single jets as well as multiple jet arrays. Hollworth et al. [6] found that the effects of cross flow become more dominant as the flow propagates downstream and the heat transfer of the downstream region is gradually dominated by the convection effect between the cross flow and the wall surface instead of jet impingement. Florschuetz et al. [7] and Rao et al. [8] studied the Nusselt number distribution of the target surface with one jet array. It is found that the pressure drop induced by the cross flow between the jet plane and target plane resulting in a nonuniform heat transfer intensity. Terzis et al. [9] experimentally studied the flow distributions and heat transfer characteristics of narrow impingement channels with varying jet diameters and varying jet-to-target surface spacings. Results show that the increasing jet diameter shows the best heat transfer capability for the target plate. Weigand et al. [10] summarized investigations about the effects of jet pattern, jet diameter or

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Nomenclature

D	diameter of jet hole (m)
D_H	hydraulic diameter of the target chamber (m)
f	friction factor
L	length of jet hole (m)
L_1	width of coolant supply chamber (m)
L_2	height of coolant supply chamber (m)
l	axial length of the target chamber (m)
$\dot{m}$	mass flow rate ($kg\cdot s^{-1}$)
Nu	Nusselt number
Nu_D	Nusselt number based on the jet hole diameter
P	pressure (Pa)
P_s	static pressure (Pa)
P_t	total pressure (Pa)
q	heat flux ($W\cdot m^{-2}$)
R	radius of the target chamber (m)
Re_D	Reynolds number based on the diameter of the jet hole
S	jet hole spacing (m)
T	temperature (K)
Tu	turbulent intensity
u	velocity along x direction ($m\cdot s^{-1}$)
u_{av}	mass averaged velocity at coolant supply channel inlet ($m\cdot s^{-1}$)
v	velocity along y direction ($m\cdot s^{-1}$)
w	velocity along z direction ($m\cdot s^{-1}$)
x	coordinate along the chamber axial direction (m)
y	coordinate along the jet hole axial direction (m)
y^+	non-dimensional wall distance
Z	height of the target chamber (m)
z	coordinate along the direction normal to both the x and y directions (m)

Greek letter

β	mass flow rate ratio of film cooling air to total cooling air
η	thermal performance parameter
η_{cb}	combined thermal performance
λ	thermal conductivity of cooling air under the reference temperature ($W\cdot m^{-1}\cdot K^{-1}$)
μ	dynamic viscosity ($Pa\cdot s^{-1}$)
ρ	density ($kg\cdot m^{-3}$)

Subscript

av	span averaged
c	coolant
f	reference parameter of the cooling air
baseline	baseline impingement case without film extraction
hole	film cooling hole
i	one of the film cooling hole
in	coolant supply chamber inlet
out	target chamber outlet
overall	overall averaged parameter at the target chamber surface
t	total parameter
tar	target channel
total	total coolant air
w	target channel internal surface

open area, cross flow, jet-to-jet spacing and jet-to-target plate separation distance.

Impingement cooling is also widely applied inside the leading edge of the blade as this region suffers the highest thermal load and most complex flow field. So it is necessary to know how the heat transfer characteristics will be for the impingement on a curved surface (leading edge). Chupp et al. [11] studied heat transfer characteristics of the impingement cooling on a curved surface with a single row of circular impinging holes. Authors found that the target surface Nusselt numbers were affected by the target surface curvature. Harrington et al. [12] experimentally studied the effect of target wall curvature on heat transfer and pressure loss with 6 impingement jet arrays applied. Results found that the target wall curvature didn't cause any significant change in either the flow distribution or the heat transfer level. Fenot et al. [13] experimentally studied the heat transfer characteristics of hot round jets impinging on a concave surface under different jet-to-jet spacings. Results show that decreasing the jet-to-jet spacing will lead to a higher overall heat transfer and an increased jet-to-jet interaction, but the stagnation region heat transfer coefficients are not enhanced. Furlani et al. [14] reported the detailed experimental data about the flow field inside a blade leading edge cooling channel by means of 2D and stereo PIV in both static and rotating conditions. Multiple internal impinging jets and coolant extractions are also applied in their experimental geometry. Results show that the flow inside the feeding channel is significantly affected by rotation, however, little effects are found on the jets structures inside the target channel. Jordan et al. [15] experimentally investigate the effects of hole shapes and differing hole inlet conditions on Nusselt number distributions for a concave, cylindrical surface which is similar as the leading edge internal channel of a turbine airfoil. Results show that the filleted hole can lead to a larger stagnation region but decrease the peak Nusselt number.

In practice, both impingement cooling and film cooling are applied on the blade which is called the impingement/effusion cooling. The film extraction flow will also affect the heat transfer performance of the internal impingement cooling. The impingement/effusion cooling has been investigated by lots of researchers. Hollworth et al. [16,17] studied the averaged and local heat transfer coefficients of arrays of cooling jets impinging on target surfaces with and without film cooling holes. Results show that better heat transfer performance is obtained with staggered arranged film cooling holes than that without film cooling holes. Huang and Ekkad [18,19] experimentally studied the heat transfer distributions for an array of cooling jets impinging on a target plate with film cooling holes. With film cooling holes applied, the effect of the cross flow is weakened and the heat transfer coefficient distribution becomes more uniform. Dabagh et al. [20,21] investigated the effects of jet holes and film cooling holes number on the heat transfer performance for the impingement/effusion cooling. They found that the number of film cooling holes could significantly affect the heat transfer coefficient on the target surface. Metzger [22] studied the local heat transfer performance of impingement cooling at a turbine blade leading edge with film cooling air extraction. Results show that the jet Reynolds number has the largest effect on the local heat transfer performance. Rhee et al. [23] investigated the effects of the cross flow on heat and mass transfer on a target plate for array impinging jets with and without film cooling holes. They found that the heat and mass transfer coefficients without film cooling holes are non-uniform due to the strong effect of cross flow. However, with film cooling holes applied, uniform distribution and enhancement of heat and