International Journal of Heat and Mass Transfer 105 (2017) 638–647

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Numerical study on vortex cooling flow and heat transfer behavior under rotating conditions

Changhe Du, Liang Li [*], Xiaojun Fan

Institute of Turbomachinery, Xi'an Jiaotong University, Xi'an 710049, China

ARTICLE INFO

Article history:
Received 6 May 2016
Received in revised form 31 August 2016
Accepted 8 October 2016
Available online 15 October 2016

Keywords:
Vortex cooling
Rotating conditions
Rotation number
Rotating direction
Density ratio

ABSTRACT

The vortex cooling mechanism under rotating conditions is researched by solving 3D steady Reynolds-averaged Navier–Stokes equations coupled with the standard k–ω turbulence model. Grid independence analysis is performed to confirm the suitable mesh number for numerical simulation. Effects of rotation number, rotating direction and density ratio on vortex cooling flow and heat transfer behavior under rotating conditions are discussed in detail. Results show that rotation has a pronounced effect on vortex cooling characteristics. When the rotation number increases, the cooling air velocity decreases and pressure drop increases, leading to the decreasing heat transfer intensity. As the cooling air velocity and streamline are not very sensitive to rotating direction, slightly higher heat transfer intensity and more uniform Nusselt number distribution at $Ro = 0.384$ can be observed. The cooling air streamline almost stays unchanged and air velocity increases slightly with increasing density ratio. An increase in density ratio results in the increasing vortex heat transfer intensity.

1. Introduction

Aircraft engine blade leading edge suffers extremely high thermal load as it is directly impacted by upwind hot gas. Generally, blade leading edge temperature has been far more beyond material melting point [1]. In addition, large centrifugal force makes rotor blade working conditions much more serious. Therefore, necessary measures must be taken to protect blade from high temperature damage. One effective method is to design complex cooling system to decrease blade temperature. For blade leading edge, the vortex cooling technique shows excellent performance since it can provide good cooling effect, uniform thermal distribution and low aerodynamic loss.

A volume of work has been carried out on the mechanism of vortex cooling. Kreith and Margolis [2] measured the heat transfer and friction coefficients in vortex flow. They claimed that swirling flow can generate large radial pressure gradient and thinner thermal boundary layer, resulting in obvious heat transfer augmentation. Hay and West [3] experimentally investigated the flow field and heat transfer characteristics of vortex cooling at various nozzle aspect ratios and injecting angles. Experimental results illustrated that vortex cooling heat transfer improvement was highly dependent on the flow swirling number. By conducting an experiment, Chang and Dhir [4] proposed that the high axial velocity near the wall and turbulence level have significant influences on vortex cooling thermal behavior. Ligrani et al. [5] captured the Görtler swirling pairs in the vortex cooling passages and determined their significant effects on heat transfer enhancement. Qian et al. [6] performed a comparison between impingement cooling and vortex cooling, and they noted that Görtler vortex pairs and favorable flow pattern both contribute to high vortex heat transfer intensity. Du et al. [7] numerically researched the steam vortex cooling performance in a typical vortex chamber. They summarized that vortex cooling heat transfer improvement was not only related to thin boundary layer, violent flow mixing and Görtler vortex pairs, but also it was dependent on the radial convection, which was induced by rotational flow and uneven density distribution.

In term of vortex cooling behavior affecting factors, quite a few studies have been reported. Glezer et al. [8] first introduced the vortex cooling technology to gas turbine blade cooling system design. They concluded from the experimental data that the heat transfer intensity would increase with an increase in Reynolds number. Zhang et al. [9] experimentally explored the thermal and pressure drop characteristics in circular tubes with twisted-tape insets and axial interrupted ribs. It was presented that when Reynolds number increased, the Nusselt number ratio would decrease and the friction factor ratio would increase. Meanwhile, the number of twisted-tape insert turns behaved pronounced impact on heat transfer and pressure property. Helund

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[*] Corresponding author.
E-mail address: liliang@mail.xjtu.edu.cn (L. Li).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.10.028
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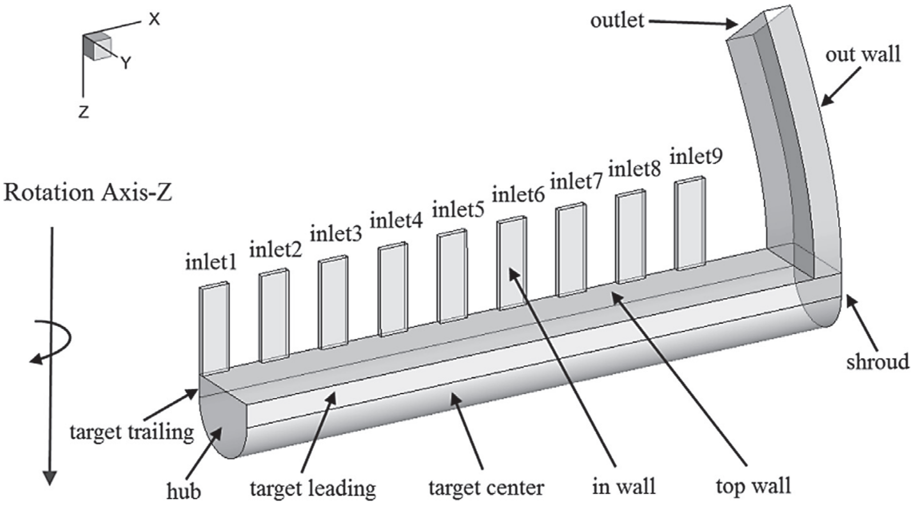
Nomenclature

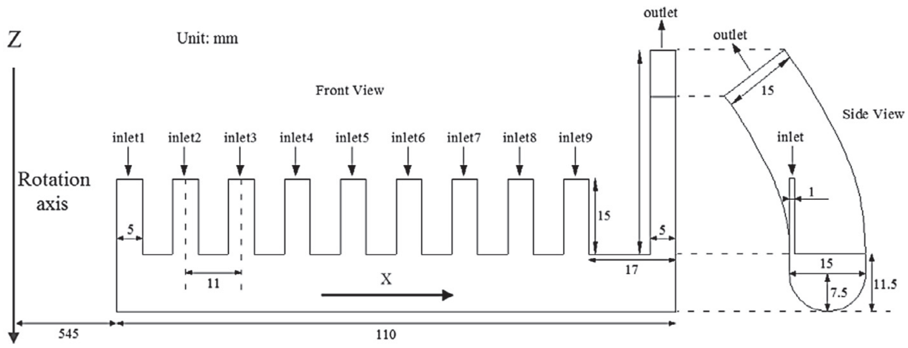
D_h	hydraulic diameter of chamber cross section, m
Nu	Nusselt number, $q_wD_h/\lambda(T_w - T_j)$
Nu_{span}	spanwise averaged Nusselt number
Nu_a	globally averaged Nusselt number
P	pressure, kPa
P_{span}	spanwise averaged pressure, kPa
q_w	wall heat flux, W/m^2
Ro	rotation number, $\omega D_h/U$
T_j	inlet temperature, K
T_w	wall temperature, K
U	mean axial velocity, m/s
X	X dimension, m
X_1	X-0.545 m, m
Greek	
ρ	fluid density, kg/m^3
$\Delta\rho/\rho$	inlet to wall density ratio
μ	fluid dynamic viscosity, kg/(m·s)
λ	fluid thermal conductivity, W/(m·K)
ω	rotational angular velocity, r/min

et al. [10–12] examined the flow structure and heat transfer coefficient at various temperature ratios and Reynolds numbers. On the basis of experimental results, they also obtained the heat transfer correlation in terms of temperature ratio, Reynolds number and Nusselt number. Hwang et al. [13,14] tested the heat transfer performance in a triangular duct using multiple side-entry jets at different Reynolds number and jet inlet angles. Ling et al. [15] carefully compared the heat transfer details between normal impingement cooling and vortex cooling. Du et al. [16] established a vortex chamber model with nine jet nozzles and proper geometrical sizes, and numerically investigated effects of jet nozzle area and aspect ratio on vortex cooling aerodynamic and thermal behavior. Based on the experimental model by Ling et al. [15], Liu et al. [17–19] systematically researched various aerodynamic and geometrical parameters on vortex cooling property.

Recently, Kusterer et al. [20] proposed the double swirling chamber cooling technique (DSC), which has drawn much attention of researchers. Unlike normal vortex cooling, DSC cooling can enhance the heat transfer intensity by its unique flowing characteristics. Lin et al. [21] numerically studied the DSC cooling prin-



(a) Three dimensional view of vortex chamber model



(b) Detailed geometrical parameters

Fig. 1. Computational model and geometries.