Applied Thermal Engineering 136 (2018) 419–430

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Effect of bleed hole on internal flow and heat transfer in matrix cooling channel

Haiou Sun, Tao Sun, Lianfeng Yang, Shi Bu, Yigang Luan*

College of Power and Energy Engineering, Harbin Engineering University, Harbin, Heilongjiang Province 150001, China

HIGHLIGHTS

- Heat transfer augmentation is caused by large streamwise vortex produced by bends.
- Bleed holes improve heat transfer by extracting corner vortexes.
- Position of bleed hole affects the performance of matrix structure the most.
- Thermal performance of matrix channel can be improved with bleed holes.

ARTICLE INFO

Keywords:
Turbine blade
Matrix cooling
Bleed hole
Heat transfer
Numerical simulation

ABSTRACT

Matrix is an internal cooling scheme which has advantages of stronger heat transfer and better structural strength than conventional serpentine ribbed channels in gas turbine blades. In some compound cooling designs, coolant is extracted from the internal channel to the outer chamber to realize impingement. This paper analyzes the effect of bleed extraction on the flow field and heat transfer in matrix cooling channel by numerical simulations. RANS method is employed to present detailed flow field and heat transfer distribution. The investigated matrix channel is comprised of eight sub-channels which form two layers, the rib angle is 45° and the sub-channel aspect ratio is 1:1. The results indicate that heat transfer augmentation is caused by the large-scale streamwise vortexes which dominate the sub-channel flow. Extraction can create extremely high heat transfer enhancement level around bleed holes and alter the flow structures in the sub-channel. Cases of different diameters, positions and arrangements of holes are compared and the result shows that the bleed position has the most significant effect on the internal flow and heat transfer. Bleed holes between the sub-channel centerline and rib-side wall can provide strong heat transfer and good thermal performance. The internal matrix cooling capacity can be maintained with 25% mass extraction. Although the thermal performance of matrix channel can be improved by bleed holes, it is lower than most of the conventional cooling methods unless the baseline matrix structure was modified.

1. Introduction

Gas turbines are widely used in peak power plant, gas transmission pipeline and propulsion systems. A fundamental way to improve the output power and the overall cycle efficiency is by increasing the turbine inlet temperature. However, higher turbine inlet temperature demands more advanced methods for the protection of turbine blade, among which cooling should be of primary importance. In modern gas turbines, cooling air is extracted from the compressor and directed into the internal passage of turbine blade to remove heat, meanwhile, a proportion of the coolant is extracted through bleed holes to the outer chamber to form impingement cooling in some compound cooling designs. The influence of bleed flow on the internal cooling cannot be ignored because the reduction of coolant mass may weaken the internal cooling capacity, besides, the disturbance can alter the typical internal flow field, and therefore the heat transfer distribution can be affected.

Investigations concerning the effect of bleed extraction on the internal cooling could be found, including U-shaped channels with ribs, dimples and protrusions. Thurman et al. [1] measured heat transfer distribution in a serpentine channel with 90° transverse ribs and circular bleed holes by thermochromic liquid crystal, they discovered that heat transfer can be intensified in the vicinity of the holes and that by increasing mass flow in the holes the heat transfer enhancement level can be further improved. Yun et al. [2] studied heat transfer in rib-

* Corresponding author.
E-mail address: shandong-313@163.com (Y. Luan).

https://doi.org/10.1016/j.applthermaleng.2018.03.031
Received 18 December 2017; Received in revised form 8 March 2018; Accepted 9 March 2018
Available online 10 March 2018
1359-4311/

Nomenclature

D_s	sub-channel hydraulic diameter (mm)
d	diameter of bleed hole (mm)
f	friction factor
f_0	baseline friction factor
H_s	sub-channel height (mm)
h	convective heat transfer coefficient (W/(m^2 K))
L	sub-channel length (mm)
Nu	Nusselt number
Nu_0	baseline Nusselt number
ΔP	pressure drop (Pa)
Pr	Prandtl number
q	heat flux (W/m^2)
RANS	Reynolds Average Navier-Stokes
Re	Reynolds number
SR	suction ratio
T	temperature (K)
TPF	thermal performance factor
V	velocity (m/s)
W_s	sub-channel width (mm)
W_r	rib width (mm)

Greek Symbols

β	rib angle (°)
υ	kinematic viscosity (m^2/s)
λ	heat conductivity (W/(m K))
ρ	density (kg/m^3)

Subscripts

in	inlet
m	mainstream
w	wall

roughened channels with bleed extraction on one sidewall, they noticed that heat transfer is enhanced on the wall with bleed holes while it is weakened on the opposite wall without holes due to the reduction of coolant mass, the thermal performance is improved because of decreased pressure drop. Kyung et al. [3] investigated flow and heat transfer in a rotating smooth channel with bleed holes on the suction side, they found that the effect of bleed flow on thermal performance is much more significant than that of rotation. Liu and Feng [4] conducted an experiment on a trapezoidal U-shaped channel with ribs and bleed holes, they found that average heat transfer varies with bleed mass flow and that pressure loss decreases with the increase of mass extraction due to the reduction of mainstream mass flow. Ekkad et al. [5] carried out experiments using thermochromic liquid crystal on U-shaped channels with 90° transvers ribs, 60° inclined ribs and 60° V-ribs, they pointed out that 20–25% of mass flow can be extracted upstream of the 180° bend without adverse effect on overall internal cooing capacity, however, the heat transfer distribution will be altered. Amano et al. [6,7] conducted a numerical simulation on straight channels with bleed holes between ribs, they compared three different turbulence models including k-ε, k-ω and RSM on unstructured computational grids and the results showed that the performance of turbulence models depend on the type of rib turbulators. Felici et al. [8] used experiments and CFD to study heat transfer in a U-shaped channel with sidewall bleed holes, they noticed that heat transfer downstream of the holes can be 50% higher that in the channels without bleed holes. Kumar et al. [9] measured heat transfer in an U-shaped channel with 60° V-ribs and bleed holes between ribs, they found that the influence of extraction on average heat transfer is negligible and that heat transfer augmentation caused by the bleed holes before the bend can be weakened downstream of the bend. Rigby et al. [10] numerically investigated the flow field in a straight channel with 90° transverse ribs and bleed holes, they attributed heat transfer enhancement downstream of the holes to the thin boundary layer produced by the bleed extraction. Xie et al. [11] used RANS and LES to simulate flow and heat transfer in U-shaped channels with dimples and bleed holes, they announced that the combination of holes and dimples can create better thermal performance than smooth channels.

Until now, there is just a few of reports on flow and heat transfer in matrix cooling scheme, which is shown in Fig. 1 [12], not to mention the effect of bleed extraction on matrix channel. Bunker [13] provided experimental data of heat transfer in modeled matrix channels. Kyung et al. [14] measured heat transfer in a rotating matrix channel and looked into the difference between pressure and suction sides. Carcasci et al. [15,16] measured heat transfer in a matrix channel under stationary and rotational states. Archarya's team [17–21] has paid attention to the matrix cooling scheme, they applied transient liquid crystal in the measurement of heat transfer in converging matrix channels and investigated the effect of rotation.

Most researchers have focused on the effect of bleed extraction on the commonly used serpentine channels with ribs, published literatures concerning the effect of bleed hole on internal matrix cooling scheme can hardly be found. To the authors' knowledge, there is only one report which is from Archarya et al. [20] that provided heat transfer information in matrix channel with bleed holes. In Refs. [13–21] heat transfer data in matrix channels are without exception obtained by measurement. In this paper we carried out a numerical research on the heat transfer performance in a matrix cooling channel with bleed holes, The purpose is to reveal the mechanism of how bleed holes affect flow field and heat transfer distribution in matrix sub-channels. Specifically, much more geometries and arrangements of holes are included in comparison in order to find an optimal design of holes for the purpose of maintaining internal heat transfer rate and improving thermal performance. From the perspective of friction penalty, heat transfer

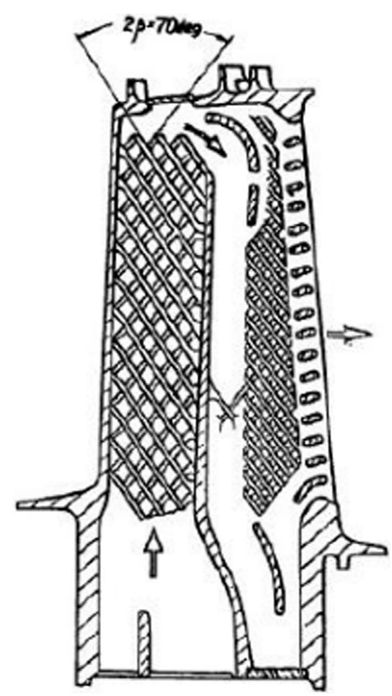

Fig. 1. A schematic diagram of typical matrix cooling structure for turbine blades [12].