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The effect of a hub turning vane on turbulent flow and heat transfer in a four-pass channel at high rotation numbers

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ABSTRACT

This paper investigates effects of rotation and a turning vane on flow field and heat transfer of a 4-pass smooth channel through CFD (Computational Fluid Dynamics) simulations. An 180° hub U-bend connecting the middle two passages (*AR* = 2:1) is the focus of the study. Reynolds number varies from 10,000 to 40,000 and rotation number changes from 0 to 0.4. In stationary conditions, effect of the turning vane is to reduce recirculation and non-uniformity of mainstream. In addition, pressure drop and secondary flow kinetic energy (SKE) are largely reduced by the turning vane. Heat transfer deterioration due to flow separation and recirculation is suppressed by the turning vane in Hub Turn. In rotating conditions, size of recirculation is reduced and uniformity of mainstream is increased comparing to stationary case. Velocity distribution and heat transfer exhibit different profiles on LE and TE considering the flow direction due to Coriolis. Effects of turning vane to suppress recirculation and to reduce pressure drop are not obvious. In Hub Turn and downstream 3rd pass, heat transfer enhancement due to turning vane is very weak.

1. Introduction

Various cooling techniques summarized and discussed in Han et al. [1] have been applied to gas turbines to prevent the detrimental problems. The cross section of the internal cooling passages varies with the thickness of the blade from the leading edge to the trailing edge. Typically, in laboratory experiments, rectangular channels are used to model the internal cooling passages. In current study, a four-pass channel with rectangular cross-sections (*AR* = 1:1 and 2:1) is used to model the passages in the mid or rear portion of the blade as shown in Fig. 1.

1.1. Rotation number effect

In real turbines, the blade rotates at a very high speed and the effect of rotation is referred as rotation number (*Ro*). It describes the ratio of the Coriolis force to flow inertia force. The investigations of the rotation effects on heat transfer in smooth channel with various aspect ratios were done as follows. Wagner et al. [2,3] provided sets of data in a serpentine multi-passage rotating smooth square channel with both radial outward and inward flow. Han et al. [4] studied the influence of uneven wall temperature in a two-pass smooth square channel. Dutta et al. [5] carried out simulations using a two-equation turbulence model with new term for Coriolis and rotation-induced buoyancy to predict the heat transfer on the leading and trailing surfaces of a rotating square channel with radial outward flow. Flow separation on the leading wall was observed and explained. Huh et al. [6] studied the rotation effect on heat transfer in a two-pass smooth rectangular channel (*AR* = 2:1) with developing flow in radial outward direction in the first passage. The rotation number varied from 0.0 to 0.45. Liu et al. [7] experimentally investigated the rotational effect on heat transfer in a smooth two-pass rectangular channel (*AR* = 1:4) with developing entrance. Rotation number ranged from 0.0 to 0.67 and inlet density ratio varied from 0.11 to 0.16. Zhou et al. [8] studied the effect of rotation on heat transfer in a smooth two-pass channel (*AR* = 4:1) with Reynolds number ranging from 10,000 to 150,000. Rotation number is from 0.0 to 0.6 and inlet density ratio is from 0.1 to 0.2. The generalized conclusions from above papers showed that heat transfer increased on trailing surface but decreased on leading surface for radial outward flow. The reverse was true for radial inward flow.

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Nomenclature

AR	aspect ratio
Bo_x	local buoyancy parameter
C_p	pressure coefficient
D_h	hydraulic diameter
H	channel height
h	heat transfer coefficient
k	thermal conductivity of the air
LE	leading edge
Nu	Nusselt number
P	static pressure
Pr	Prandtl number of the air
q''	heat flux
R	radius of rotation
Re	Reynolds number
Ro	rotation number
SKE	secondary kinetic energy
T	temperature
TE	trailing edge
U	velocity in streamwise direction
W	channel width

Greek symbols

α	position angle of secondary plane in Hub Turn
μ	viscosity of air
ρ	density of air
k	thermal conductivity of air
Ω	rotational speed

Subscripts

x	local
o	fully-developed turbulent flow in non-rotating smooth pipe
s	stationary
se	secondary flow
w	wall
b	bulk
f	film
in	inlet
e	exit
r	relative
ref	reference

1.2. Rotational buoyancy effect

Effects of density ratio and rotational buoyancy are investigated by Wagner et al. [2,3] in a serpentine multi-passage rotating smooth channel. Density ratios were in the range of 0.07–0.22 while Reynolds number, rotation number and rotating radius were kept constant. Corresponding rotational buoyancy parameters were varying between 0.20 and 0.62. On both leading and trailing surfaces, heat transfer ratio got increased with larger density ratio. And, correlations between heat transfer data and buoyancy parameters were developed. The increase of heat transfer coefficient on leading surface of the first pass was attributed to the unstabilization of the near-wall flow. However, in the CFD (Computational Fluid Dynamics) predictions by both Prakash and Zerkle [9] and Dutta et al. [5], this phenomenon was explained as the mainstream flow separation due to high rotational buoyancy force.

1.3. Turn effect

Heat transfer is largely affected in the turn region by the turn induced complicated flow behaviors of separation, recirculation, and secondary vortices. Han et al. [10] obtained a detailed mass transfer distribution around 180° sharp turn in a two-pass square channel for both smooth and ribbed surfaces using naphthalene sublimation technique. Results showed that the Sherwood number after the turn was higher than that before the turn. Schabacker et al. [11] studied the flow characteristics of a two-pass square channel with roughed top walls using PIV (Particle Image Velocimetry) techniques. It was observed that in the 180° sharp turn region the flow field was more complicated by the interaction of the rib-induced and turn-induced secondary flows. Son et al. [12] carried out experiments using PIV to study the correlations between high Reynolds number turbulent flow and wall heat transfer in a two-pass square channel roughed by orthogonal ribs. Results suggest that the characteristics of secondary flow were closely correlated with the wall heat transfer enhancements for both smooth and ribbed walls.

In the rotating condition, the combined effects of rotation and turn increases the complexity of the flow and heat transfer in the turn region and afterward passages. Cheah et al. [13] measured the velocity field using LDA (Laser Doppler Anemometry) in a rotating two-pass smooth channel connected by an 180° U-bend.

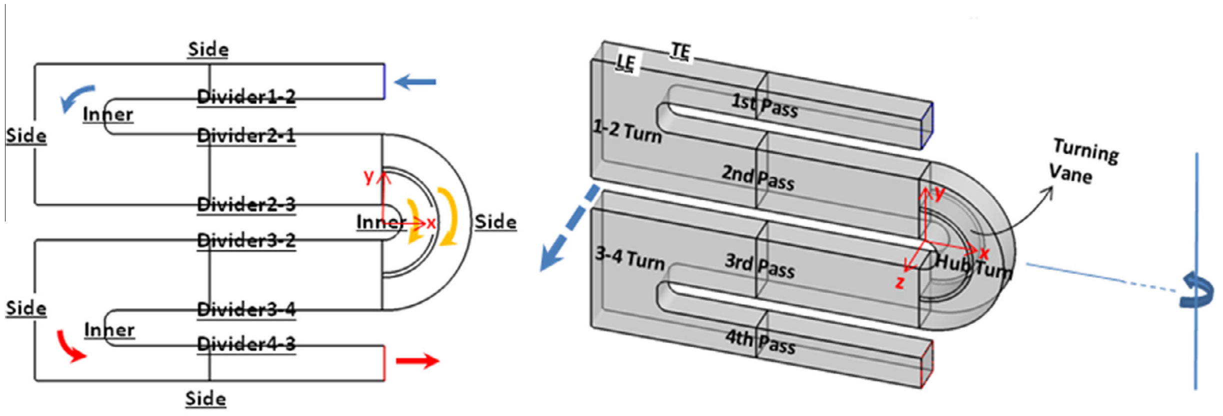

Fig. 1. Schematic of a four-pass cooling channel with a turning guide vane located in the Hub Turn region between 2nd and 3rd passes.