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Heat transfer in a smooth rotating multi-passage channel with hub turning vane and trailing-edge slot ejection

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ABSTRACT

This paper experimentally investigates the effects of rotation, turning vane, trailing edge ejection, and channel orientation on heat transfer (HT) in a typical turbine blade three-passage internal cooling test model. The cross section of the first and second passage are rectangular with aspect ratio 1:1 (AR = 1) and 2:1 (AR = 2) respectively, while the third passage is wedged shaped with slot discharge configuration to simulate the trailing edge ejection design. The flow direction in the first passage is radial outward, after the 180° tip turn, the flow turns radial inward at the second passage. The flow finally redirected to radial outward by the 180° hub turn and discharges through the slot configuration at the third passage. Data measurements are conducted in the second and third passages (includes the hub turn regions). The first passage is not instrumented and serves as flow inlet only. The effects of rotation on the heat transfer coefficients (HTC) were investigated at rotation numbers (*Ro*) up to 0.32 and Reynolds numbers (*Re*) from 10,000 to 40,000. This study concludes that the rotating utilizes a positive and negative effect on HT on the radial inward flow leading and trailing surfaces respectively. A reverse trend is concluded for radial outward flow. Rotation also suppresses HT in the turn portion. The effect is most severe at the hub turn side wall. The effect of turning vane slightly reduces and increases HT on all interested surfaces in radial inward and outward flow passages respectively. The turning vane effect is diluted in the hub turn area under rotation. Radial outward flow (third passage) HT is substantially impacted by the channel orientation. Combine with the discharge configuration, under rotating scheme, HT levels in $\beta = 45°$ is significant lower then $\beta = 90°$. Regional HTCs are correlated with rotation numbers for multi-pass rectangular smooth channel with hub turning vane and trailing edge ejection.

1. Introduction

Gas turbines are used for aircraft propulsion and land-based power generation or industrial applications. Thermal efficiency and power output of gas turbines increase with increasing turbine rotor inlet temperatures (RIT). Current advanced gas turbine engines operate at turbine RIT (1500 °C) far higher than the yielding point of the blade material (1000 °C); therefore, turbine blades are cooled by compressor discharge air (650 °C). Since this extraction from compressor air incurs a penalty on the thermal efficiency and power output of the gas turbine engine, it is important to fully understand and optimize the cooling technology for a given turbine blade geometry under engine operating conditions. Gas turbine blade/vane cooling method can be characterized into two categories; namely, internal and external (film) cooling methods. Internal cooling is achieved by passing the coolant through several rib-turbulated serpentine passages inside of the blade. Both jet impingement and pin-fin configurations are also employed in internal cooling passage design. External cooling is achieved by discharging the internal coolant air through discrete holes to generate a coolant film to protect the outside surface of blade/vane from high temperature combustion gas. The engine cooling system must be designed to ensure that the maximum blade surface temperatures and temperature gradients during operation are compatible with the allowable blade thermal stress for the life of the design. The major parameters that would affect internal cooling passage HT have been identified as channel aspect ratio, channel shape, 180° sharp turn, entrance geometry, rib configuration, *Re* number, Ro number, buoyancy parameter (Bo) [1] as well as designs of turning vanes and the trailing edge ejection. This study focuses on the HT phenomenon of a typical turbine blade

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Nomenclature

A	area [m^2]
AR	aspect ratio
As	cross section area of ejection slot [m^2]
Box	local buoyancy parameter $Bo_x = (\Delta\rho/\rho_{b,x})(Ro)^2(R_x/D_h)$
c	specific heat at constant pressure
CD	discharge coefficient
Dh	hydraulic diameter [m]
DR	bulk-to-wall density ratio $DR = \Delta\rho/\rho_b$
e	rib height [m]
h	regionally averaged heat transfer coefficient (HTC) [W/m^2 K]
H	channel height [m]
i	designates a given region in the test model
I	electric current [A]
k	thermal conductivity of air [W/m K]
L	height of turning vane [m]
m	mass flow rate [kg/s]
Nu	Nusselt number
Pm	perimeter of flow channel [m]
Pv	perimeter of turning vane [m]
Pr	Prandtl number of air
Q	heat transfer rate [W/m^2]
R	radius of rotation [m]
ri	radius of inner wall in turn region[m]
ro	radius of hub wall in turn region[m]
RH	heater electrical resistance [Ω]
Re	Reynolds number
Ro	Rotation number
T	temperature [K]
U	stream wise velocity [m/s]
V	electrical potential applied to heater [V]
Vi	velocity in ejection slot [m/s]
W	channel width [m]

Greek symbols

β	angle of channel orientation
μ	air viscosity [kg/ms]
ρ	air density [kg/m^3]
Ω	rotation speed [rpm]
ΔPi	pressure difference through ejection slot i

Subscripts

b	bulk air
e	exit
f	film
h	hydraulic
htr	heater
in	inlet
l	loss
n	net
o	fully developed turbulent flow in stationary smooth pipe
p	projected
s	stationary
t	total
w	wall
x	local

three-passage internal cooling with smooth surface with hub turning vane and trailing edge ejection test model as shown in Fig. 1.

1.1. Channel aspect ratio effects

In the previous experimental studies, channels with various rectangle cross sections are used to simulate internal cooling channel design. Due to geometrical limitations from the blade profile, the cooling channels cross-section ought to change along the cord length, and it can be characterized as three categories viz. near leading edge, middle blade, and near trailing edge area. The internal cooling channels near the blade leading edge have been modeled as narrow rectangular channels with AR = 1:4 and 1:2. In the middle of the blade, the channels are closer to square in shape. Towards the trailing edge, the channels have wider aspect ratios of AR = 2:1 and 4:1. An experimental study on the effects of the buoyancy parameter in various aspect ratio channels was performed by Fu et al. [2]. The study considered five different aspect ratio channels (AR = 1:4, 1:2, 1:1, 2:1, and 4:1) with a fully developed flow inlet condition. The results showed that the overall levels of HT enhancement (Nu/Nu_o) for all the ribbed channels of different aspect ratios were comparable. However, significant differences arose in the pressure losses incurred in each of the channels. The 1:4 channel incurred the lowest pressure penalty; therefore, the thermal performance of the 1:4 channel was superior to the 1:2, 1:1, and 2:1 channels. In addition, they found that rotation has more effect on 1:4 and 1:2 channels as compared with 4:1 and 2:1 aspect ratio channels.

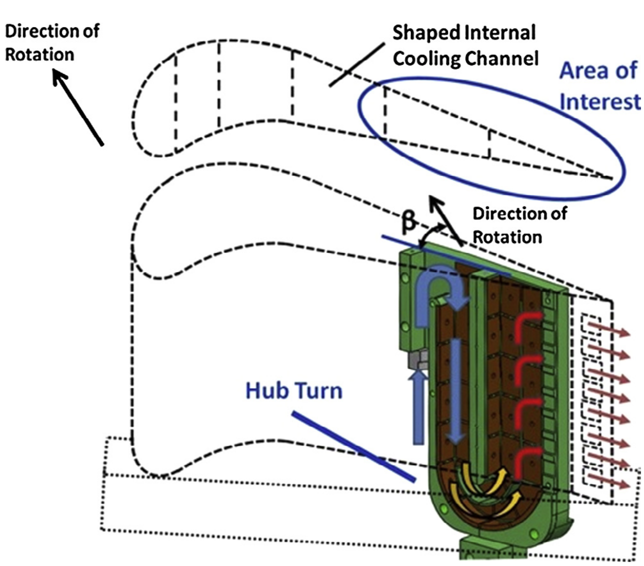

Fig. 1. Study concept and test section schematics.

1.2. Rotation effects

Rotation induces Coriolis and centrifugal forces which produce cross-stream secondary flow in the rotating coolant passages; therefore, HTC in rotor coolant passages are very much different from those in non-rotating frames. *Ro* number is a non-dimensional parameter that researcher utilizes while evaluating the rotation effect. It is defined as the ratio of Coriolis force to inertial force. As Han et al. [1] documented, the most important conclusion from recent research is that rotation can greatly enhance HT on one side of the cooling channel while reduce HT on the opposite side due to rotating-induced secondary flow, depending on the radial outflow or inflow of the cooling passages. Without considering rotational effect, the coolant passage would be over-cooled on