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Heat transfer in a two-inlet rotating rectangular channel with side-wall fluid extraction

Hongwu Deng, Yanan Chen, Zhi Tao, Yang Li, Lu Qiu *

National Key Laboratory of Science and Technology on Aero-Engine Aero-thermodynamics and Collaborative Innovation Center of Advanced Aero-Engine, Beijing University of Aeronautics and Astronautics, Beijing 100191, China

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ABSTRACT

The convective heat transfer in a rotating rectangular channel with an aspect ratio of 4:1 is investigated. Two branches of coolant enter the channel from the inlets at the top and bottom of the channel, encounter each other in the middle of the channel, and then exit the channel through eight sidewall slots. The channel is assembled in a rotating facility, and the two streams of flow are radial-outward and inward respectively. The mass flow rate of the major inlet is kept at a constant ($Re = 20{,}000$), whereas the inlet mass flow ratio (*MR*, second inlet mass flow rate/major inlet mass flow rate) changes from 0 to 0.6. The general *MR* is found to be a good parameter to describe the flow status in the two-inlet channel. However, with the local *MR*, the heat transfer data at different locations converge into the same trend, indicating that the local *MR* should be the dominate parameter. In the non-rotating channel, the Nusselt number ratio is oscillating against local *MR*, three extreme values can be distinguished at three critical local *MR* regardless of the location. In the rotating channel, a different kind of critical *MR* phenomenon is observed. After the critical point, the heat transfer on the leading surface exceeds the trailing one. A lower critical inlet *MR* is observed at a higher radius location, but the corresponding critical local *MR* is independent of location. The rotation suppresses the radial-inward flow and in turn results in a higher critical *MR*.

1. Introduction

Regarding the modern advanced gas turbines, the developments of the cooling technology of the high pressure turbine rotor blade motivate the scientific researches of the flow and heat transfer in the rotating system [1]. As a simplified model of the internal cooling passage of turbine blade, the heat transfer in the rotating channels have been extensively investigated. Recently, the advanced experimental techniques were employed to measure the flow field and heat transfer in the rib-roughened rotating channels [2,3]. The rotation could promote or weaken the heat transfer of the trailing or leading surface (pressure or suction side) in a radial-outward flow at low rotation numbers [4]. However, the heat transfer on the leading surface was elevated by rotation after a critical rotation number, which was a function of the dimensionless location [5,6]. At high rotation numbers, the buoyancy force was strong enough to generate the reverse flow on the leading surface, therefore, a critical rotation number was observed. The rotating square channel was treated as the model of cooling passage in the middle part of a turbine blade. However, when it came to the trailing tail of the blade, the geometry was very unique. The cross section of the channel was trapezoid or wedge-shaped, the channel was orientated with a large angle respect to the rotating plane, and the flow were extracted from the lateral slots [7,8].

In the channel with lateral fluid ejections, the local mass flow rate reduced along the channel. It was difficult to determine the local Reynolds number and bulk temperature. One possible solution was measuring the pressure drops of ejection holes to calculate the local mass flow rate [9]. The overall heat transfer was reduced compared to the non-ejection case [10,11]. But the heat transfer inside the channel was not influenced by the length of the holes. The ejections elevated the mass transfer rate in the region close to the holes but presented negative effects in the opposite inner region [12]. Similar observations were also reported in the investigations of rectangular or wedge-shaped channels [13,14]. The outer surface presented the most significant heat transfer enhancement compared to the non-ejection cases. The effects of lateral-to-total flow ratio on heat transfer of a wedge-shaped pin–fins arrayed channel were studied. The worst overall heat transfer rate was observed as the flow ratio was around 0.3–0.4 depended on the shape of pin–fins [15,16].

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* Corresponding author.
E-mail addresses: denghw@buaa.edu.cn (H. Deng), chenyanan@buaa.edu.cn (Y. Chen), tao_zhi@buaa.edu.cn (Z. Tao), buaalzw@126.com (Y. Li), qiulu@buaa.edu.cn (L. Qiu).

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Nomenclature

English symbols

A	area (m^2)
Buo	buoyancy number
C_p	heat capacity at constant pressure (J/(kg·K))
D_h	hydraulic diameter (m)
h	heat transfer coefficient (w/(m^2·K))
I	current of heater (A)
L	length of the channel (m)
$\dot{m}$	mass flow rate (kg/s)
MR	mass flow rate ratio, see Eq. (4)
Nu	Nusselt number
P	heat transfer measured point in X-direction, see Fig. 2
Pr	Prandtl number
r	the rotation radius (m)
R	resistance of each heater (Ω)
Re	Reynolds number
Ro	rotation number
T	temperature (K, °C)
TR	temperature ratio
U	mean velocity (m/s)
WP	wetted perimeter (m)
X, Y	coordinates, see Fig. 2

Greek symbols

α	wall-to-environment heat-loss coefficient (w/K)
β	angle from the channel symmetrical plane to the rotation plane (°)
μ	viscosity of coolant (Pa·s)
Ω	rotational speed (rad/s)
λ	heat conductivity coefficient (w/(m·K))
ρ	density of the coolant (kg/m^3)

Subscripts

1	the parameters of the major stream (bottom inlet)
2	the parameters of the second stream (top inlet)
ave	average parameter
b	bulk parameter
e	environment parameter
eff	effective parameter based on total inlet mass flow rate
i	number of the measured point in the X-direction
in	inlet
$loss$	loss
net	net
out	outlet
s	stationary
w	wall
x	local parameter
0	fully-developed turbulent flow in circular pipe with smooth wall

The high aspect ratio ($AR > 1$) rectangular channel could be considered as the model of the turbine blade trailing edge internal cooling passage. It was observed that the heat transfer on both the leading and trailing surfaces could be enhanced by rotation [17]. The aspect ratio gave rise to influence the magnitude of Coriolis force induced secondary flow, and in turn affected the heat transfer characteristics [18]. The leading-to-trailing heat transfer difference could be reduced by increasing the aspect ratio at the cost of significant increase in pressure loss [19], or varying the channel orientation from 90° to 135° [20]. In the rectangular channel with $AR = 4$, a critical rotation number was observed, after which the increasing trend of the heat transfer was reversed on the trailing wall of the radial-outward channel or the leading wall of the radial-inward channel [21]. High span-wise heat transfer variation could be formed in an $AR = 10$ channel on both leading and trailing surfaces [22]. The rotation enhanced the heat transfer on both leading and trailing surface in the smooth or pin–fins roughened channel with an aspect ratio of $AR = 4$ or 8. The outer region on the trailing surface presented the greatest heat transfer enhancement in the smooth channel. The rotational effects were weaker in the channel with a higher aspect ratio [23]. The similar observations were made in the rotating wedge-shaped channels. Due to the 135° channel orientation, the heat transfer on both leading and trailing surfaces was enhanced by rotation, and the heat transfer in the inner region of the channel was affected by rotation significantly [24]. Adding the lateral ejection holes to the wedge-shaped channel strengthened the heat transfer in the outer narrower region because of the turbulent mixing created by the slot holes [25], whereas the pin–fins or ribs promoted the overall heat transfer and reduced the effects of rotation by increasing the heat transfer area and promoting the turbulence mixing [26,27]. However, the heat transfers were reduced by the fluid extraction in both rotating and non-rotating wedge-shaped channels [28]. Besides, the channel with mixed rib and pin–fin turbulators was also investigated. The heat transfer and flow field were explained with the simulation results in detail [29].

Recently, it was found that the channel orientation played an important role in influencing the heat transfer of a rotating channel with lateral fluid extractions [8,30]. With a larger angle of channel orientation, the Coriolis force of the radial outward flow directed to the sidewall slots, which reduced the local Reynolds number in the opposite inner region of the channel. On the contrary, Coriolis force could drag the main flow to the inner side at some other channel orientations. The rotation increased or decreased the heat transfer when the angle was lower or higher than a critical value. However, in a typical turbine blade trailing edge configuration (around $\beta = 135°$), the rotation abated the downstream heat transfer significantly. A hot spot was observed at the inner top corner. Therefore, a second inlet was added, which improved the local heat transfer significantly and compensated the effects that induced by the rotation [8]. Compared with the non-rotating case, the overall averaged heat transfer could be enhanced by the second inlet once the second-to-major inlet mass flow ratio was around 0.3 [7].

As mentioned above, injecting the second stream of coolant at the top of the rotating channel benefited the channel heat transfer significantly in a wedge-shaped channel with lateral fluid extraction. Two streams of coolant encountered each other in the middle of the channel, presenting the distinguished heat transfer characteristics. However, the wedge-shaped cross section, the injection induced jet impingement, and the sudden expansion of the second stream made the flow field complicated. Therefore, a rectangular channel with two rectangular inlets is employed in this work to investigate the heat transfer characteristics of the counteracting flow in both non-rotating and rotating conditions.

2. Experimental facility

The rotating experimental platform is illustrated in Fig. 1. The test channel was encapsulated in a pressure vessel which was fixed on the rotating arm. In order to mimic the real configuration of the turbine blade trailing tail, the symmetrical plane of the rectangular channel orientated at an angle of 135° with respect of the rotation