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Heat transfer and flow characteristics of U-shaped cooling channels with novel wavy ribs under stationary and rotating conditions

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ABSTRACT

Wavy rib is a kind of novel turbulator that can effectively improve the ribbed wall heat transfer of cooling channel and produce acceptable friction loss. Meanwhile, it has the advantage of simple structure. In this paper, the effects of wavy ribs on the heat transfer distributions of ribbed walls, side walls, and top wall are numerically studied in stationary and rotating U-shaped channels. The flow characteristics of cooling air are also analyzed. Taking the 45° V-shaped ribs as the reference scheme, the high-performance wavy ribs that have better heat transfer performance on ribbed wall and induce the same friction loss are selected. The channel aspect ratio is 1, with the height of 12.7 mm. The investigated Reynolds number is 25,000, and the rotation number is 0, 0.2, 0.3 and 0.4. Rib height (e-$3e$), rib round radius (0–5 mm), and rib angle (20–55°) are the three major geometrical parameters of wavy rib. The results show that, the diversion effect of wavy ribs on cooling air is the reason of friction loss suppression. On the one hand, the wavy ribs confine the fluid disturbance on side walls, leading to the heat transfer reduction. On the other hand, the impingement of cooling air on the channel top wall is strengthened, which improves the wall heat transfer. In stationary and rotating conditions, the high-performance wavy ribs increase the heat flux on heated surface corresponding to the ribbed wall by 5–21% and 4–24% respectively, and weaken the effect of Coriolis force on the heat transfer of the first pass. With the increase of rotation number, the friction penalty and heat transfer of leading side ribbed wall decrease, while the heat transfer of trailing side ribbed wall slightly increases, showing that those high-performance wavy ribs have a good versatility at multiple rotation numbers.

1. Introduction

In the design of advanced gas turbine, higher and higher turbine inlet temperature is a development trend to improve the overall performance of the engine, such as thrust and efficiency. Since the existing blade materials are far from being able to withstand the erosion of hot gas, effective cooling structures are critical to the safe and stable operation of turbine blades. Inside the turbine blade, the U-shaped channel with ribs is a typical cooling structure. Rib turbulators can effectively enhance the heat transfer of blade by strengthening the cooling air disturbance to increase wall heat transfer coefficient and expanding the area to improve heat transfer rate. Therefore, rib turbulators are always the research focus in the turbine blade cooling design and are also the concern of this paper.

Researchers have been studying the cooling design of turbine blades for a long time, to guarantee the growing cooling requirement. Han et al. [1–6] conducted a comprehensive and in-depth study of the gas turbine heat transfer and cooling technology through a series of experiments and summary of other researchers' valuable work. And the works of Han is a valuable reference and guide for the relevant designers. In 2014, Wright and Han [7] summarized the key advances in turbine blade cooling in the last decade, including the different combinations of cooling technologies already available and some new design concepts. Ligrani et al. [8] investigated the effects of typical cooling structures such as pin-fins, dimpled surfaces, rib turbulators and swirl chambers on the heat transfer enhancement and fluid flow in the cooling channel of the turbine blade.

As a common method of enhancing heat transfer, rib turbulators are widely used in the low Reynolds number flow of industrial heat exchangers. It provides some reference to the internal cooling design of turbine blade at high Reynolds number condition. Dewan et al. [9] reviewed the progress made in the passive heat transfer enhancement, including twisted tapes, wire coils, rib turbulators, fins, and dimples. They found that twisted tapes are suitable for laminar flow and wire coils are good at heat transfer augmentation

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Nomenclature

d	heated plate thickness (mm)
$d1$	min distance between wavy rib and side wall (mm)
D	hydraulic diameter (mm)
e	rib height of 45° inclined rib in literature[18] (mm)
f	friction coefficient
h	heat transfer coefficient (W m^{-2} K^{-1})
he	rib height of wavy rib (mm)
H	channel height (mm)
$L1$	entrance region length (13 D)
$L2$	channel length (12 D)
$L3$	exit region length (13 D)
N	grid number
Nu	Nusselt number
p	static pressure (pa)
P	rib spacing of 45° inclined ribs in literature [18] (mm)
Pr	Prandtl number of cooling air
q	heat flux (W m^{-2})
Q	heat transfer rate (W)
r	rib round radius of wavy rib (mm)
R	radius of rotation (mm)
Re	Reynolds number of channel inlet
th	rib thickness of wavy rib (mm)
T	temperature (K)
T_{bulk}	mass flow averaged temperature (K)
T_w	wall temperature (K)
U	velocity in streamwise direction (m s^{-2})
W	channel width(mm)

Greek symbols

α	rib angle of wavy rib (°)
k	thermal conductivity of cooling air (W m^{-1} K^{-1})
μ	viscosity of cooling air (kg m^{-1} s^{-1})
ρ	density of cooling air (kg m^{-3})

in turbulent flow, both are two promising heat transfer structures. Alam et al. [10] summarized the heat transfer improvement performance and pressure drop penalties of various turbulators in air ducts and listed the correlations of heat transfer and friction loss obtained by many researchers. It was found that the perforation in turbulators is an effective method to further increase the heat transfer improvement, and delta winglet also leads to a good heat transfer performance. Bhushan et al. [11–13] collected almost all types of rib turbulators that could be used to enhance the heat transfer of solar heaters and listed their heat transfer performance and friction losses respectively. Moreover, the influences of geometrical parameters of rib and channel on the rib performance are presented. Sharma et al. [14] also introduced the CFD approach in predicting the flow behavior of roughened walls with different ribs, including the meshing method and turbulence model selection. The works are helpful for the numerical study of rib turbulators by other researchers.

In the cooling channels, the rib turbulators could strengthen the wall heat transfer, meanwhile, the flow resistance is lifted which is adverse to the channel downstream cooling. Therefore, heat transfer improvement and friction penalty are the two most important indices to evaluate the performance of rib turbulators. Thus, different ribs layouts are invented according to the needs of operating conditions. From the above reviews [1–14], it can be concluded that the rib shape, including rib spacing, rib height, rib angle, rib cross-section, etc., and rib arrangement, such as cross or parallel, continuous or discrete, etc., are important factors that determine the rib performance. In addition, this performance is also affected by the cooling channel geometry, Reynolds number and rotation number.

Inclined ribs are the most commonly used turbulators in the cooling channels of turbine blades. Han et al. [1–7] obtained the typical arrangement of inclined ribs after summing up a large number of research results: ribs are installed in parallel on the opposite walls in the internal cooling channel, with the square rib cross-section, the relative rib height e/D is 5–10%, the rib spacing P/e is 7–15, and the rib angle is 30–60°. Moon et al. [15] compared the performance of sixteen ribs with different cross-sections. It was found that the new boot-shaped ribs provide the best heat transfer improvement and induce the same friction loss as the square-shaped ribs. Lei et al. [16,17] studied the effect of rib spacing on the heat transfer of a rotating rectangular channel. It can be seen that when the rib spacing is 10, the heat transfer is the best while the pressure loss is acceptable. When the rib spacing further reduces, the increase of heat transfer improvement is suppressed and the pressure loss grows up rapidly. Cho et al. [18] found that the discrete ribs produce a more uniform heat transfer distribution than the continuous ribs. In addition, the form of discrete performs better in 45° inclined ribs than in transverse ribs. The experimental results of Karwa [19] showed that the V-shaped rib has the best heat transfer augmentation, followed by the inclined rib, the lowest is the transverse rib, and the friction penalty is proportional to the heat transfer performance. For the V-shaped rib, the discrete arrangement performs better in heat transfer enhancement than the continuous arrangement, which proves the advantage of discrete ribs again. Besides, the V-shaped rib pointing downstream possess better heat transfer improvement and lower pressure drop than those of the V-shaped rib pointing upstream. Wright [20] conducted the performance comparison of inclined ribs, V-shaped ribs, and W-shaped ribs in the form of discrete and continuous. It was found that W-shaped ribs do the best in improving heat transfer as well as lifting friction loss, while the inclined ribs show the worst heat transfer enhancement. The results of Lee et al. [21] also demonstrated that discrete ribs are better than continuous ribs in producing uniform heat transfer distribution. However, the cooling structure also becomes slightly complicated. Peng et al. [22] experimentally and numerically investigated the performance of transverse ribs and V-shaped ribs. The results showed that the heat transfer performance and pressure loss of V-shaped ribs are all higher than those of straight ribs, and the thermal performance is also better. This result further illustrates that the V-shaped rib is a high-performance turbulator. The studies by Rao et al. [23] revealed that the application of V-shaped ribs and W-shaped ribs in impingement cooling have substantially the same heat-transfer improvement, but the latter provides slightly lower pressure loss. Al-Hadhrami et al. [24] discussed the heat transfer performance of a rotating U-shaped channel with 45° inclined ribs at different channel orientation angles. It can be seen that the heat transfer performance of ribbed wall decreases as the channel orientation angle increases from 90° to 135°.

Coriolis force is the main factor that affects the heat transfer distribution in the rotating cooling channel. Experimental studies of Azad et al. [25] showed that Coriolis force caused by rotation dominates the overall heat transfer performance of different ribbed walls in a U-shaped channel. On two opposite ribbed walls, the 45° inclined ribs in parallel produce a better heat transfer performance