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Experimental and numerical investigation of heat transfer and friction performance for turbine blade tip cap with combined pin-fin-dimple/protrusion structure

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ABSTRACT

The blade-tip region of turbine blade exposes to gas with high temperature and high velocity. So the cooling in this area has significant influence on turbine blade safety. The U-shaped cooling channel with 180° turning bend is common in internal cooling of turbine blades, which improves the heat transfer coefficient. Special attention should be paid to the impingement cooling at bend area which is important to the cooling of the blade tip region. Dimples, protrusions and pins which are placed on the bend area are well recognized to enhance the heat transfer in the area. In this paper, the heat transfer and friction performance of the tip-cap are predicted numerically and experimentally. Pin-fin-dimple/protrusion is arranged as the heat transfer augmentation structure at the bend region. It is concluded that, the temperature of solid surface decreases obviously when dimple/protrusion or pin-fin-dimple/protrusion structure is arranged. The area-averaged *Nu* of impingement surface with pin-fin-dimple/protrusion increases by 31.2–127.3%, which implies that the heat transfer performance is prominently better than that on the smooth tip wall. The additional pressure penalty of pin-fin-dimple/protrusion is 16.2% at most. In summary, the arrangement of dimple/protrusion and pin-fin-dimple/protrusion on the blade-tip surface inside the blade can enhance the heat transfer with little increase of friction, indicating an efficient cooling structure.

1. Introduction

The blade-tip region of a turbine is in contact with gas with high temperature and high velocity. Hence, the cooling in this area is of significance for the safety of a turbine blade. Generally, the cooling of blade-tip adopts the combination of internal convection cooling and external film cooling. However, some turbine blades only contain internal cooling channel without external methods such as film cooling. Thus the cooling of blade-tip completely depends on internal convection. A cooling channel of U shape with 180° bend region is more common in internal cooling of a turbine blade. The bend region not only improves the heat transfer coefficient of two channel columns but also achieves better cooling performance of blade-tip on the basis of the impingement cooling around the corner, which deserves special attention by researchers in related area. In common turbine blades, a smooth surface without enhanced structure is employed around the corner. Bunker [1] proposed a pin-fin placed on the bending surface, which obviously enhanced the heat transfer in the area. While Xie et al. [2] presented a structure with large dimples, protrusions achieving the same effect. Van [3], Metzger et al. [4–6] and Chyu et al. [7,8] revealed that the pin height-to-diameter ratio, array orientation (in-line or staggered) and fin cross-sectional shape, etc., are crucial parameters in determining the heat transfer and friction factor. Ligrani et al. [9–11] conducted experimental researches on the transient vortex structure inside dimples and also studied the combined effect of dimples and protrusions on the opposite wall. With the combination heat transfer method presented in this paper, the combination of pin-fin and dimple/protrusion is applied in the bend region as cooling configuration. Detailed heat transfer performance as well as friction of the structure are discussed in detail.

The exhausting structures such as film cooling and slot film cooling are always arranged around leading edge (LE) and trailing edge (TE) of a turbine blade. Usually, the gas flows into leakage chamber by side impingement in the cooling channel near the LE and the TE, and then forms a gas film. The impact on the leakage chamber wall enormously promotes the cooling effect in this area.

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Nomenclature

D	dimple/protrusion diameter
D_h	hydraulic diameter
D_p	fin diameter
f	friction factor
h_p	fin height
H	inlet height of the channel
k	turbulent kinetic energy
L_1	length of the channel
L_2	width of the channel
L_3	clearance width of the turning bend
Nu	Nusselt number
Nu/Nu_0	Heat transfer enhancement factor
P_w	lateral spacing of the dimple/protrusion
P_h	longitudinal spacing of the dimple/protrusion
q''	surface heat flux
Re	Reynolds number
T	temperature
W	inlet width of the channel
y^+	non-dimensional grid spacing at the wall
Greek symbols	
δ	dimple/protrusion depth
Δp	pressure drop
ε	rate of energy dissipation
λ	fluid thermal conductivity
μ	fluid dynamic viscosity
ρ	fluid density
ω	specific dissipation rate
Subscripts	
w	wall
f	fluid

Taslim et al. [12] analyzed the side impingement structure near the LE/TE of a turbine blade and concluded that the position of side hole, the staggered arrangement method, the angle of side groove etc. all greatly influenced the cooling effect. Taslim et al. [13,14] also reported the results of a series of investigations on internal impingement on the leading-edge cavity walls. In consideration of the impingement cooling characteristics of dimple/protrusion structure as target surface, the impingement of dimple/protrusion structure is arranged on the exhausting chamber wall of the turbine blade LE/TE to study the heat transfer performance and friction of the structure. Xie et al. [15] discussed the cooling effect of pins/dimples/protrusions/on turbine blade tip wall at high Reynolds numbers. Rhee et al. [16,17] investigated the effect of vane/blade relative position on heat transfer performance of stationary turbine blade. Varun et al. [18] experimentally investigated combination geometries viz. transverse and inclined discrete ribs, which gives better heat transfer enhancement compared to single roughened geometry. Sahu and Bhagoria [19] conducted the experimental investigation on the effect of 90° broken ribs as roughness elements and found that thermal efficiency is 51–83.5%. Rao et al. [20–22] conducted an experimental and numerical study to investigate the flow and heat transfer characteristics in a pin fin-dimple channel.

Based on the research status mentioned above, the heat transfer and friction performance of U shape cooling channel around the turbine blade-tip are discussed in this paper. The combination of pin-fin and dimple/protrusion is introduced in the bend region of U shape cooling channel near blade-tip to study the enhancement of heat transfer as well as friction feature and obtain the best structure parameter of dimple/protrusion.

2. Research object

As a type of commonly used internal cooling channel, the U shape channel is adopted in this paper. The 180° bend region increases the heat transfer rate and high heat transfer region is formed on account of cooling gas impingement at the top of bend region, which is of great importance to the blade-tip cooling and deserves further study. The cooling channel inside blade-tip is shown in Fig. 1, where it's a representative cooling structure proposed by Han [23] and it shows the inside blade-tip heat transfer surface which this paper concentrates on.

The physical model adopted in this paper is based on the U shape channel tested by Bunker [1], where the aspect ratio (AR = W/H) of channel inlet and outlet section is 1:2. The corresponding hydraulic diameter is D_h. The length of two cooling column L_1 is $10D_h$ and the gap at the bend region L_2, L_3 are 0.95 and 0.27. The main parameters are shown in Fig. 2. Bunker's [1] study adopted pin fin to enhance the heat transfer of bend region tip in the channel, while in this paper, the heat transfer and friction performance with combination of pin-fin and dimple/protrusion are discussed.

It's shown in Fig. 3 that dimple/protrusion or pin-fin-dimple/protrusion is placed on tip region of channel bend region. In this paper, different structures such as dimple/protrusion, dimple/protrusion with different interval density and depth ratio, pin-fin-dimple structure, pin-fin-protrusion structure, etc. are discussed. The interval of sparse dimple/protrusion P_w and P_h are 25 mm.

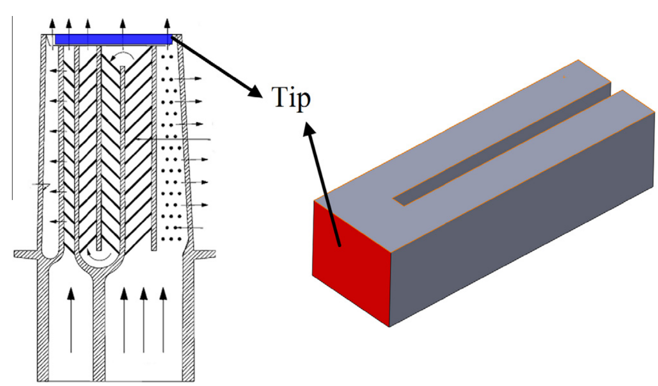

Fig. 1. Representative cooling structure inside turbine blade.

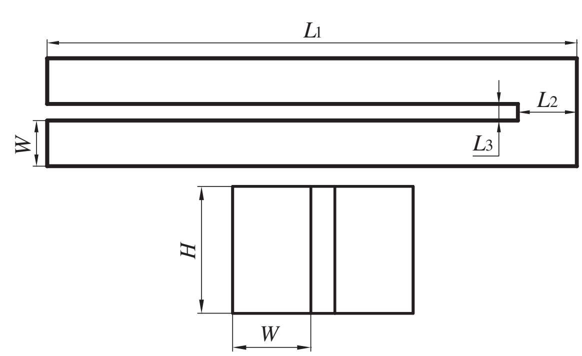

Fig. 2. Main parameters of U shape channel.