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Heat transfer enhancement and turbulent flow in a high aspect ratio channel (4:1) with ribs of various truncation types and arrangements

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A R T I C L E I N F O

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A B S T R A C T

Ribs are often employed in internal cooling passages of turbine blades to augment heat transfer with cooling air flowing through the internal ribbed passages. The present work concentrates on truncated ribs to improve thermal performances with continuous ribs in a high aspect ratio channel. With various truncation types and arrangements of truncated ribs, the optimized thermal performance of ribbed channels is attempted for by taking both heat transfer and pressure drop into consideration. Eight different ribbed channels with various truncation types and arrangements are investigated. Liquid Crystal Thermography (LCT) is employed to measure surface temperature and derive heat transfer coefficients over the ribbed surfaces in the tested channels. The turbulent flow details are presented by numerical calculations with an established turbulence model, i.e. the *k-ω* SST. From the obtained results, it is found that truncated ribs can reduce the pressure loss penalty without reducing the heat transfer enhancement in the tested channels. By changing the configurations to staggered arrangements, the heat transfer can be further enhanced associated with a moderate pressure drop. The truncated ribs generate transverse vortices at the truncation gaps and reduce the recirculating flow behind the ribs. Enhanced flow mixing contributes to the increased heat transfer. By the staggered arrangement, the flow path becomes more complex and the flow mixing is further enhanced. Truncated ribs are promising for applications in the high aspect ratio channel of the turbine blades and the enhancement factor is about 10%.

1. Introduction

To increase the efficiency of a gas turbine, the common approach is to increase the turbine inlet temperature. In order to allow the gas turbine designers to increase the turbine inlet temperature while maintaining an acceptable temperature for the structures, advanced cooling methods are developed. Ribbed passages are widely used in internal cooling of turbine blades, as shown in Fig. 1.

In the past several years, ribbed passages are commonly used to increase the convective heat transfer by creating flow reattachment between two adjacent rib rows and inducing secondary flows. Studies on ribs have paid attention to many configuration parameters of ribbed channels, such as rib shape, aspect ratio, pitch ratio (p/e), blockage ratio (e/D_h), rib angle of attack (α), inclination of ribs, rotation of ribs and arrangement (staggered or parallel) [1–6]. The results have shown that the rib shape affected the pressure drop more than the heat transfer. Recently, Chung et al. [7] investigated augmented heat transfer with intersecting rib in rectangular channels having different aspect ratios. As an intersecting rib was present, additional vortices were generated at every point of the intersection with the angled ribs and the heat/mass transfer performance was significantly enhanced. Abraham et al. [8] measured heat transfer and pressure drops in a square cross-section converging channel with V and W rib turbulators. They found that the local variation of the in heat transfer coefficients in the cross stream direction on the ribbed wall was more significant for the V ribs than for the W ribs. Yang et al. [9] conducted an experimental study on the heat transfer characteristics of a high blockage ribbed channel. They found that the heat transfer coefficient of symmetric arranged ribs is higher than for staggered ribs, but the pressure losses of the symmetric arranged ribs is larger than

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Nomenclature

D_h	hydraulic diameter (m)
e	height of ribs (m)
H	channel height (m)
h	heat transfer coefficient (W/m^2·K)
k	turbulent kinetic energy (m^2/s^2)
L	total length of the channel (m)
ΔL	truncated length (m)
L_{front}	length of the upstream extended channel (m)
L_{back}	length of the downstream extended channel (m)
L_{heated}	length of the heated foil (m)
Nu	Nusselt number
Nu_0	Nusselt number of a smooth channel
P	pitch distance (m)
P_{ref}	reference pressure (Pa)
q_{w}	wall heat flux (W/m^2)
q_{loss}	heat loss (W/m^2)
Re	Reynolds number
T	temperature (K)
T_f	fluid temperature (K)
T_w	wall temperature (K)
u	flow velocity (m/s)
x	streamwise direction (m)
y	spanwise direction (m)
z	normal direction (m)
W	channel width (cm)

Greek symbols

Δp	pressure drop (Pa)
λ	thermal conductivity (W/m·K)
μ	fluid dynamic viscosity (Pa·s)
ρ	fluid density (kg/m^3)

Subscripts

m	average/overall
max	maximum
w	wall

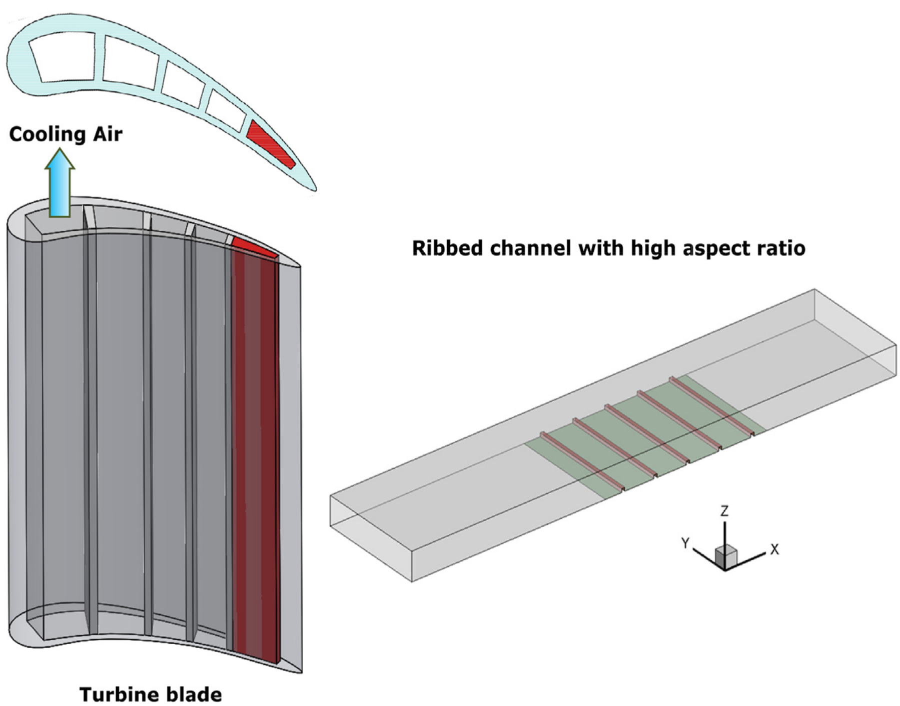

Fig. 1. Ribbed channels in the internal cooling of a turbine blade.

the staggered arrangement ribs. Singh et al. [10,11] studied characteristics of heat transfer enhancement and frictional losses in a two-pass square duct featuring unique combinations of rib turbulators and cylindrical dimples. It was observed that 45° angled and V compound configurations resulted in higher heat transfer augmentation as well as higher thermal hydraulic performance compared to corresponding configuration of ribs alone and dimples alone. Alfarawi et al. [12] measured the heat transfer enhancement in a rectangular duct with hybrid ribs. They found that the hybrid ribs provide mostly higher values for the efficiency indices compared with those of the rectangular and semi-circular ribs cases.

There are many numerical studies on heat transfer and cooling performance of ribbed passages using various turbulence models [13–19]. Saidi and Sunden [13] examined the ability of two low-Re k-ε turbulence models to predict the local and mean thermohydraulic characteristics in rib-roughened ducts. They found that the Eddy Viscosity Model (EVM) and Explicit Algebraic Stress Model (EASM) had similar abilities to predict the average Nusselt number, but the EVM offered friction factors in closer agreement with the experimental data. Lin et al. [14] compared the heat transfer in smooth and ribbed U-Ducts with and without rotation using the Shear Stress Transport (SST) turbulence model, which can account for near wall, low-Reynolds number effects. They found that the SST model eliminated the dependence on free stream turbulent kinetic energy k and had a limiter to control the overshoot in k with