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Flow structure and heat transfer in a square passage with offset mid-truncated ribs

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ABSTRACT

The enhancement of heat transfer attributed from rib turbulators relative to the increased pressure drop in the channel is a crucial design parameter. Thus, the design of the truncated ribs (whose length is less than the passage width) provides options to address such cooling requirements when the pressure loss is a critical factor. Considering different types of truncated ribs, mid-truncated ribs (which are truncated in the central part of the rib) have been proved to show better thermal performance than other types of truncated ribs. A numerical study of mid-truncated ribs with different offset placements or angles on turbulent heat transfer inside a non-rotating cooling passage of a gas turbine blade is performed for inlet Reynolds number ranging from 10,000 to 50,000. The overall performance characteristics of six different types of mid-truncated ribbed arrangements are also compared: Cases A1, A2, A3 utilize mid-truncated spanwise ribs with different relative rib stagger positions at different spanwise locations; Cases B, C, D utilize mid-truncated angled ribs with the ribs oriented at ±45° (Case B), +45°/+45° (Case C), and ±135° (Case D). In all cases, a gap is present between the ribs placed on opposite spanwise parts of the channel, to provide the mid-truncation. It is found that the 135° mid-truncated rib (Case D) has the highest heat transfer coefficient, while the 90° mid-truncated ribs with no offset placement (Case A1) behave best in reducing pressure loss penalty. Although Case A shows larger heat transfer augmentation, Case D is advantageous for augmenting side-wall heat transfer when the pressure loss is considered and the Reynolds number is comparatively large. Case C exhibits the best overall thermal performance over the largest range of experimental conditions when the pressure drop is also considered. Staggered arrangement for 90° mid-truncated ribs can enhance heat transfer efficiently and makes a good overall performance at low Reynolds numbers. Case A1 can be used in practical operation because of reduced weight and good thermal performance at high Reynolds numbers. This is the first study on various offset mid-truncated ribs aiming to improve the heat transfer of turbine blade internal cooling passages with reduced pressure loss penalty.

1. Introduction

To improve thermal efficiency, gas-turbine stages are being designed to operate at increasingly higher inlet temperatures. To achieve higher thermal efficiency and power output in advanced gas turbines, the rotor inlet temperatures are required to exceed the melting point of the blade material. In order to allow the gas turbine designer to increase the turbine inlet temperature while maintaining an acceptable material temperature, sophisticated cooling methods are thus required. There are many heat transfer enhancement and cooling methods used for turbine blades to protect the blade material from exceeding the maximum allowable temperature, e.g., film cooling, impingement cooling, rib turbulated cooling and pin–fin cooling.

For the internal cooling of the blades, ribbed ducts are usually employed to increase the convective heat transfer. The presence of ribs, also called roughness elements or turbulators, enhances the heat transfer coefficients by creating redevelopment of the boundary layer after flow reattachment between the ribs and because of induced secondary flows. Therefore, it is meaningful to accurately predict the heat transfer and related friction characteristics. Numerical or experimental studies on ribs have paid attention to configuration parameters such as rib shape, aspect ratio (AR), pitch ratio (p/e), blockage ratio (e/D_h), rib angle of attack

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Nomenclature

A	wall surface area (m^2)
D_h	hydraulic diameter (m)
e	rib height (m)
f	friction factor
f/f_0	normalized Fanning friction factor
H	channel height (m)
K	turbulent kinetic energy (m^2/s^2)
L	length of the side-wall (m)
l	length of the rib (m)
Nu	Nusselt number
$Nu(i)$	cell Nusselt number
P	rib pitch (m)
Pr	Prandtl number
q	wall heat flux (W/m^2)
Re	Reynolds number
S_{ij}	deformation rate tensor
t	truncated space (m)
T	temperature (K)
T_f	local mixed-mean fluid temperature (K)
u_i	spatially-averaged inlet velocity (m/s)
u_x, u_y, u_z	streamwise, spanwise, normal velocity component (m/s)
W	channel width (m)
v'^2, f	velocity variance scale, variable related to turbulent energy redistribution
x, y, z	streamwise, spanwise, normal coordinates (m)

Greek symbols

ε	rate of energy dissipation (1/s)
Δp	pressure drop (Pa)
μ	fluid dynamic viscosity (kg/ms)
υ	air kinematic viscosity (m^2 s^{-1})
ρ	air density (kg m^{-3})
λ	fluid thermal conductivity (W/m K)

(α), inclination of ribs, and arrangement (staggered or parallel) as well as channel shape [1–10]. The results showed that the rib shape affects the pressure drop more than the heat transfer and angled ribs or inclined ribs are effective from both heat transfer and pressure drop considerations.

There have been many numerical studies on heat transfer and cooling performance of ribbed passages with different turbulence models. For example, Saidi and Sunden [11] examined the ability of two low-Re k–ε turbulence models to predict the local and mean thermal–hydraulic characteristics in rib-roughened ducts having square cross sections. They found that the eddy viscosity model (EVM) and Explicit Algebraic Stress Model (EASM) had similar ability to predict the average Nusselt number, and the EVM offered friction factors in closer agreement with the experimental data. Wongcharee et al. [12] studied the effects of different shapes of ribs with the Shear Stress Transport (SST) k–ω and Renormalization Group (RNG) turbulence model. Lin et al. [13] considered the heat transfer in a smooth and ribbed U-Duct with and without rotation using the Shear Stress Transport (SST) turbulence model, which can account for the near wall low-Reynolds number effects. They found that the SST model eliminated the dependence on free-stream k and has a limiter to control overshoot in k with adverse pressure gradients. Liu and Wang [14] carried out an investigation on synthetic performances of fluid flow and heat transfer of semi-attached rib-channels by the Reynolds stress model (RSM) turbulence model and they found that semi-attached ribs can fully eliminate the areas with low heat transfer. Iacovides et al. [15,16] applied the low-Re model to compute flow and heat transfer in stationary and rotating ducts with rib-roughened walls. The results showed that the low-Re turbulence models are necessary to predict heat transfer in ribbed ducts properly, and the low-Re RSM model yields thermal predictions superior to those of the low-Re eddy viscosity models. Ooi et al. [17] demonstrated that the v^2f model is very accurate and promising when applied to the near-wall region. The v^2f model predicts very well heat transfer on the ribbed side wall of transverse-ribbed ducts, while the prediction is not so good for the smooth side wall of 3D ribbed ducts. However, Hermanson et al. [18] used successfully the v^2f model for heat transfer in inclined-ribbed 3D ducts: this might be because the secondary flow is mainly driven by the inclined ribs, instead of by the anisotropy of the Reynolds stresses. Jia et al. [19] studied square ducts with V-shaped ribs using the v^2f model and Large Eddy Simulations (LES) were also employed to evaluate the accuracy and reliability of Reynolds-averaged Navier–Stokes (RANS) methods.

Previous experimental and numerical studies show that truncated ribs can reduce pressure drop penalties, compared to channels with ribs without truncations [20–24]. Compared these past studies [20–24], the present investigation considers ribs with different geometric arrangements, especially in regard to the use of mid-truncation. In particular, the present investigation is different from the study of Xie et al. [23] because that study only utilized truncated ribs oriented normal to the bulk flow direction, with truncations generally applied between the ribs and the side walls of the channel. The present study uses ribs which are truncated in the central part of the ribs, with six different rib configurations, with both normal and angled orientations relative to the bulk flow direction. These configurations are utilized because better thermal performance is expected, compared to other types of rib truncation arrangements [20–24].

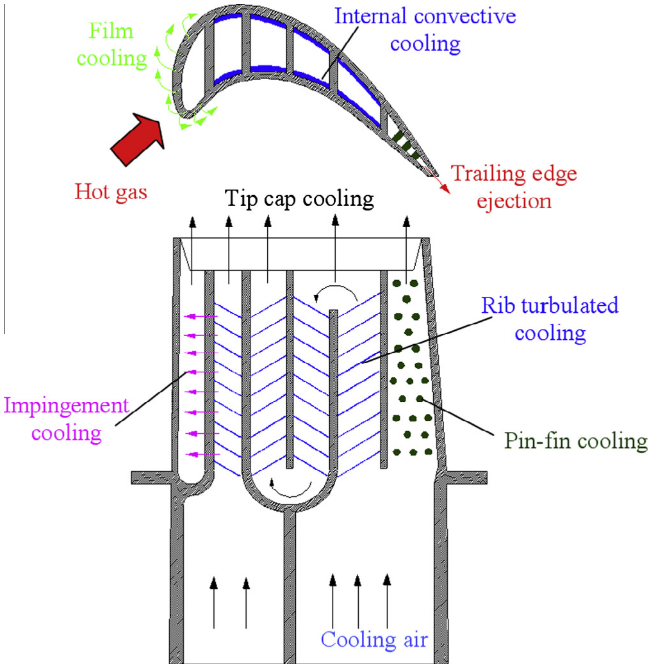

Fig. 1. Common cooling methods for a turbine blade: in the middle section of the blade the continuous ribs are replaced with mid-truncated ribs in order to decrease pressure loss.