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Numerical investigation of turbulent flow and heat transfer in two-pass ribbed channels

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ABSTRACT

In this study, the heat transfer and friction characteristics of four different rib geometries- 45° angled, V-shaped, W-shaped and M-shaped ribs in a two-pass stationary channel have been numerically investigated. The aspect ratio (Height to Width) of the cooling channel was 1:1 (square). The rib pitch-to-rib height ratio (p/e) and the rib-height-to-channel hydraulic diameter ratio (e/D_h) were 16 and 0.125 respectively. The Reynolds number was varied from 20,000 to 70,000. For the computations, the Reynolds averaged Navier–Stokes (RANS) equations were solved with the commercial software ANSYS Fluent using the realizable version of k-ε (RKE) model. The heat transfer results were benchmarked with experiments on a test rig with similar geometries and flow conditions. Detailed analysis of the flow characteristics in the two-pass channel was carried out so as to understand the interaction of the rib-induced secondary flows and the bend-induced secondary flows and their contribution to heat transfer enhancement. The heat transfer enhancement provided by V-shaped ribs was 7% higher than 45° ribs, 28% higher than W-shaped ribs and 35% higher than M-shaped ribs. However, the pressure penalty for V-shaped ribs was 19% higher than 45° ribs, 24% higher than W-shaped ribs and 28% higher than M-shaped ribs. On comparing the overall thermal hydraulic performance, V-shaped and 45° ribs were observed to perform significantly better than W-shaped and M-shaped ribs.

1. Introduction

Modern gas turbines are operated at elevated turbine inlet temperatures, as high as 1600 °C, which exceed the melting temperature of the super-alloy metals used in the construction of the hot gas path components. Under such extreme conditions, the vanes and blades are subjected to high thermal stresses. It is therefore imperative to provide adequate cooling for the hot gas path components so as to prolong their life and ensure safe and reliable operation. A widely used method for cooling the blades involves passing coolant air bled from the compressor through serpentine internal passages inside the airfoils. The internal cooling passages consists of a series of straight ducts connected by 180° bends forming a multi-pass channel. The aspect-ratio and shape of the cooling channels depend on the aerodynamic profile and the portion of the vane where they are located. So as to enhance the heat transfer between the coolant and the hot walls, roughness elements or turbulence promotors (ribs) are installed on the walls of the serpentine passages. The ribs breakdown the laminar sublayer and cause re-development of the boundary layer which helps in enhancing the heat transfer. When the ribs disturb the incoming boundary layer, they create local wall turbulence which facilitates the heat dissipation from the near-wall fluid to the mainstream owing to turbulent mixing. Although the complex flow field generated by the ribs provides significant heat transfer enhancement, the presence of these roughness elements results in pressure penalty. In the past, numerous experimental and numerical studies have been carried out to assess the thermal-hydraulic performance of the roughening features.

Han et al. [1] presented a comprehensive overview about internal cooling with various roughness elements like ribs, pin fins etc. Taslim et al. [2] experimentally investigated the heat transfer and friction characteristics of 90°, 45°, V-shaped and discrete angled ribs. They observed that 45° and V-shaped ribs provide higher heat transfer enhancement than discrete angled and 90° ribs. Ekkad and Han [3] used transient liquid crystal technique to obtain detailed Nusselt number distribution for a two-pass square channel with different rib turbulators. Lee et al. [4] experimentally investigated the heat transfer distribution in a high aspect ratio rotating ribbed channel with V-shaped and angled ribs. V-shaped

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Nomenclature

D_h	Hydraulic diameter [m]
e	Rib height [m]
f	Friction factor
f_0	Friction factor for fully developed tube flow
f_s	Friction factor for smooth channel
h	Heat transfer coefficient [W/m^{2}K]
k	Thermal conductivity [W/mK]
L	Channel Length [m]
Nu	Nusselt number
Nu_0	Nusselt number from Dittus-Boelter equation
Nu_s	Nusselt number for smooth channel
P	Rib pitch [m]
p	Pressure [Pa]
p^*	Normalized pressure $(p-p_{in})/(0.5\rho u_{in}^2)$
Pr	Prandtl number
q''	Heat flux [W/m^2]
Re	Reynolds number $(u_{in}D_h/\nu)$
s	Distance in streamwise direction along the two-pass channel [m]
T	Temperature [K]
T^*	Normalized temperature (T/T_{in})
T_{bulk}	Bulk fluid temperature [K]
T_{in}	Fluid temperature at inlet [K]
T_w	Wall temperature [K]
TKE	Turbulent kinetic energy [m^2/s^2]
TKE*	Normalized turbulent kinetic energy (TKE/u_{in}^2)
u	Total fluid velocity [m/s]
u_m	Mean fluid velocity in the channel [m/s]
u^*	Normalized velocity (u/u_{in})
ρ	Density (kg/m^3)
ν	Kinematic viscosity (m^2/s)
η	Thermal hydraulic performance factor

ribs were observed to provide a higher heat transfer enhancement than angled ribs for both the stationary and rotating cases. Mochizuki et al. [5] studied the heat transfer and friction characteristics in a two-pass channel with different rib configurations. They concluded that the orientation of the ribs before and after the bend results in significant differences in the pressure drop and thermal performance of the two-pass channel due to interactions between the rib-induced and bend-induced secondary flows. Han et al. [6] carried out heat transfer and pressure measurements in square channels with parallel, crossed and V-shaped ribs. They reported that V-shaped ribs provide the best performance amongst the configurations studied. Kumar and Amano [7] compared the performance of different arrangements of 60°-V and 60°-V broken ribs in a two-pass channel. Lamont et al. [8] compared the heat transfer characteristics of 90°, W-shaped and M-shaped ribs in a developing channel flow at a Reynolds number of 12,000 using transient liquid crystal technique. Maurer et al. [9] investigated the heat transfer and pressure drop characteristics of V and W-shaped ribs for different rib pitch-to-rib height ratios. They observed that the thermal hydraulic performance of W-shaped ribs was better than V-shaped ribs. Wright et al. [10] investigated the thermal-hydraulic performance of different continuous and discrete ribs in a high aspect-ratio rotating channel with Reynolds number ranging from 10,000 to 40,000. They observed that discrete V-shaped and W-shaped ribs performed better than the other configurations studied.

Several numerical studies have been conducted to study the flow and heat transfer characteristics in two-pass ribbed cooling channels. Lin et al. [11] performed computations to study the flow and heat transfer in a smooth and ribbed U-shaped duct under rotating and non-rotating conditions using the k- ω SST turbulence model. They observed the interaction of rib induced secondary flows with the Dean-type secondary flows induced by the bend. Shih et al. [12] numerically investigated the three-dimensional flow and heat transfer in a ribbed U-shaped wall under rotating and non-rotating conditions using the k- ω SST model. In the absence of rotation, the heat transfer in the bend was observed to be dominated by the bend induced pressure gradients at low Reynolds number and by the rib-induced secondary flows at high Reynolds number. Al-Qahtani et al. [13] numerically predicted the flow and heat transfer for a two-pass rectangular channel with 45° rib turbulators using a multi-block RANS method under stationary and rotating conditions. Su et al. [14] performed computations to study the three-dimensional flow and heat transfer in a rectangular channel with 45° V-shaped ribs. Jia et al. [15] numerically studied the flow and heat transfer in a straight square duct with V-shaped ribs pointing upstream and downstream using the low-Reynolds number k-ε turbulence model. Bonhoff et al. [16] numerically studied the flow characteristics in a stationary square ribbed coolant channel with various turbulence models and validated it against PIV measurements. They observed that the results obtained with RSM model were most consistent with the experimental results amongst the models studied. Shevchuk et al. [17] investigated the heat transfer distribution in a two- pass varying aspect ratio channel with different divider wall-to-tip wall distances at a Reynolds number of 100,000. They reported good agreement between their computations and PIV measurements thereby illustrating that RANS models are capable of predicting the flow and heat transfer in a two-pass channel reasonably. Similar studies were carried out by Siddique et al. [18] and Pape et al. [19] who investigated the effect of divider-to-tip wall distance on the heat transfer enhancement and pressure drop in a two- pass channel using realizable k-ε model with enhanced wall treatment.

The objective of the present study is to assess the thermal-hydraulic performance of four different rib configurations- 45° angled, V-shaped, W-shaped, and M-shaped using numerical simulations. Although V-shaped and 45° ribs have been well documented in the literature, studies pertaining to flow and heat transfer characteristics of W-shaped and M-shaped ribs are sparse. To the authors' knowledge, detailed flow and heat transfer analysis of the investigated rib configurations in a two-pass channel are limited. Furthermore, while most of the previous studies have focused on rib pitch-to-height ratios lesser than or equal to 10, this study is directed at exploring the performance of the different rib shapes at larger rib pitch-to-height ratios ($p/e = 16$). This could be helpful in designing two-pass ribbed channels for high Reynolds number flows (land based gas turbines) in which case the pressure penalty at low rib pitch-to-height ratios could be significant. Also, this study examines the performance of the different rib configurations in a developing channel flow which is common in internal cooling channels.

2. Computational methodology

In this section, an overview of the computational methodology including details about the computational domain, grid generation, solver, turbulence model and boundary conditions has been presented.