Numerical Study on Flow and Heat Transfer Characteristics in Fin-Groove Channels: Postprint

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Abstract

This paper numerically investigates the flow and heat transfer characteristics in a rectangular channel under the combined effects of ribs and grooves, analyzing the influence of rib height distribution along the spanwise direction on the channel' s thermal performance. Five rib structures with different height distributions but identical cross-sectional areas are selected, wherein the rib center height gradually increases from Structure 1 to Structure 5, with Structure 3 featuring a uniform height distribution. The results demonstrate that ribs with non-uniform height distribution along the spanwise direction generate counter-rotating vortex pairs, which can entrain cooling air from the mainstream core region and transport it to the high-temperature wall, while simultaneously sweeping away low-speed hot air within the grooves and increasing the airflow velocity near the groove walls, thereby enhancing the heat transfer performance of the heated surface. Furthermore, the greater the variation in rib height along the spanwise direction, the stronger the vortex structure and the more significant the heat transfer enhancement effect. Structure 5, possessing the highest rib center height, yields the maximum Nusselt number, friction factor, and thermal performance factor.

Full Text

Numerical Investigation on Flow and Heat Transfer Characteristics in Rib-Grooved Channels

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Abstract: This paper numerically investigates the flow and heat transfer characteristics in a rectangular channel with combined rib and groove structures, focusing on the effect of spanwise rib height distribution on thermal performance. Five rib configurations with identical cross-sectional area but different height distributions are examined. From Case 1 to Case 5, the rib center height gradually increases, with Case 3 featuring a uniform spanwise height distribution. The results demonstrate that ribs with non-uniform spanwise height distributions generate counter-rotating vortex pairs that entrain cooler core flow air to the heated walls while sweeping low-velocity hot air out of the grooves, thereby increasing near-wall flow velocity and enhancing heat transfer on the heated surface. Moreover, greater variation in rib height along the spanwise direction yields stronger vortical structures and more significant heat transfer enhancement. Case 5, with the highest rib center height, delivers the maximum Nusselt number, friction factor, and thermal performance factor.

Keywords: ribbed channel; groove structure; heat transfer enhancement; thermal performance; numerical simulation

The continuous increase in gas turbine inlet temperatures poses significant challenges for the safe and reliable operation of high-temperature components. Consequently, developing advanced materials and efficient cooling technologies is critical for next-generation gas turbines. High-temperature turbine blades typically employ internal cooling channels with turbulence promoters to enhance cooling performance. Common turbulence promoters include periodically arranged ribs, dimples/protrusions, pin fins, grooves, and combinations thereof.

Extensive research has been conducted on heat transfer enhancement using ribs, dimples/protrusions, and pin fins. Chi et al. [?] numerically investigated the flow and heat transfer mechanisms in parallel-ribbed internal cooling channels for gas turbine blades. Bi et al. [?] compared the heat transfer enhancement characteristics of dimpled channels, circular-grooved channels, and low-rib channels, finding that dimpled and grooved channels exhibited significantly lower flow losses than low-rib channels, though the latter provided better overall heat transfer performance. Wan et al. [?] experimentally studied impingement cooling on surfaces with pin-fin turbulence promoters, demonstrating that pin-fin surfaces substantially improved overall heat transfer performance compared to smooth surface jet impingement.

Research on flow and heat transfer analysis of groove structures remains relatively limited. Groove structures enhance heat transfer by intensifying near-wall flow disturbance while causing smaller pressure losses than rib structures since they do not protrude into the main flow. Eiamsa-ard and Promvonge [?] investigated the effect of different groove-width-to-cavity-height ratios on channel thermal performance, reporting optimal thermal performance at a ratio of 0.75. Bilen et al. [?] and Ramadhan et al. [?] examined the influence of various groove shapes (circular, rectangular, trapezoidal, triangular) on heat transfer performance and flow losses. Liu et al. [?] enhanced groove surface heat transfer and reduced pressure losses by incorporating arc transition sections at the leading or trailing edges of conventional circular grooves. Zhang et al. [?] placed protrusion structures upstream of circular grooves to study the effects of protrusion quantity and spanwise position on heat transfer and pressure losses in grooved channels.

To further enhance heat transfer, researchers have investigated combined rib-groove structures. Jaurker et al. [?] compared the thermal performance of single rib structures versus rib-groove combinations, finding that the combined configuration exhibited superior thermal performance. Eiamsa-ard and Promvonge [?] studied various rib-groove combinations (rectangular rib-triangular groove, triangular rib-rectangular groove, triangular rib-triangular groove), identifying the triangular rib-triangular groove configuration as yielding the maximum thermal performance factor. Beyond transverse ribs, several scholars [?] have analyzed the heat transfer and resistance characteristics of angled ribs, V-shaped ribs, and wavy ribs combined with grooves.

Current research on rib-groove structures primarily focuses on groove and rib geometries and rib angles. This study investigates the influence of spanwise rib height distribution, employing ANSYS-CFX to numerically examine the effects of five rib height distributions on heat transfer and resistance characteristics in rib-grooved channels.

1.1 Computational Model

Figure 1 [Figure 1: see original paper] presents the computational model and local mesh schematic. The study employs a rectangular channel with hydraulic diameter $D_h = 32$ mm, width $W/D_h = 2.5$, and height $H/D_h = 0.625$. The channel comprises three sections: an inlet extension of length $L_1/D_h = 6.25$, a heated section of length $L_2/D_h = 8.75$, and an outlet extension of length $L_3/D_h = 4.69$. The heated section bottom surface features six equally spaced rib-groove structures arranged streamwise. The grooves have circular cross-sections with depth $\delta/D_h = 0.125$, width $D_p/D_h = 0.5$, and spacing $P/D_h = 1.25$. Ribs are positioned upstream of the grooves at distance $d/D_h = 0.625$, with rectangular cross-sections and width $e/D_h = 0.063$. Rib height varies along the spanwise direction, with five distribution patterns shown in Figure 1(a). Notably, ribs with different height distributions maintain identical cross-sectional areas. Among the five configurations, Case 1 features lowest center height and highest ends, Case 2 has slightly lower center than ends, Case 3 exhibits uniform spanwise height distribution, Case 4 has slightly higher center than ends, and Case 5 has highest center and lowest ends. Figure 1(b) illustrates the local mesh for Case 4. Structured grids were generated using commercial software ICEM-CFD with near-wall refinement to ensure y^+ values remain small.

1.2 Parameter Definitions

The Reynolds number is defined as:

$$Re = \frac{\rho u D_h}{\mu}$$

where ρ is the mainstream density, u is the inlet velocity, D_h is the hydraulic diameter, and μ is the dynamic viscosity.

The local Nusselt number is defined as:

$$Nu_x = \frac{q_w D_h}{(T_{w,x} - T_f)\lambda}$$

where q_w is the heat flux on the heated surface, $T_{w,x}$ is the local wall temperature, T_f is the mass-averaged temperature between the heated section inlet and outlet, and λ is the thermal conductivity of the airflow.

The area-averaged Nusselt number is defined as:

$$\overline{Nu} = \frac{1}{A}\int_A Nu_x \, dA$$

where A is the heated surface area.

The friction factor is defined as:

$$f = \frac{\Delta P D_h}{L \cdot 0.5 \rho u^2}$$

where ΔP is the pressure drop across the heated section and L is the heated section length.

The thermal performance factor is defined as:

$$\eta = \frac{Nu/Nu_0}{(f/f_0)^{1/3}}$$

where Nu_0 and f_0 represent the Nusselt number and friction factor for a smooth channel, respectively. In this study, Nu_0 and f_0 are calculated using the Dittus-Boelter and Blasius correlations.

1.3 Grid Independence Validation

To balance computational accuracy and efficiency, grid independence validation was performed. Results for Case 3 are presented in Figure 3 [Figure 3: see original paper]. When the grid count exceeds 4.08 million, the computed Nusselt number and friction factor remain essentially unchanged. Therefore, subsequent calculations employ a grid of 4.08 million cells.

1.4 Numerical Method Validation

To ensure computational reliability, the numerical method was validated against experimental measurements from a rib-grooved channel [?]. Figure 2 [Figure 2: see original paper] compares the predicted Nusselt numbers and friction factors with experimental data [?]. The results show excellent agreement, with computed values within the experimental error range, confirming that the numerical approach reliably investigates heat transfer and resistance characteristics in rib-grooved channels.

1.5 Boundary Conditions

The working fluid is treated as ideal air with inlet temperature $T_{in} = 300$ K and inlet Reynolds numbers of 5000, 10000, 15000, and 20000. The outlet is specified as static pressure $P = 1$ atm. The rib-grooved heated surface is subjected to constant heat flux $q_w = 1000$ W/m², while other walls are assumed adiabatic and no-slip.

2.1 Flow Characteristics Analysis

Figure 4 [Figure 4: see original paper] compares streamlines and normal velocity distributions on a fixed observation plane for the five configurations. For uniform spanwise rib height (Case 3), the flow primarily exhibits upward and downward motion with flow separation near the groove bottom, while spanwise flow is negligible. For non-uniform spanwise rib heights, the vortical structures induced by ribs significantly affect groove flow, generating pronounced transverse flow in near-wall regions.

For ribs with lower center and higher ends (Cases 1 and 2), airflow at the channel sides is deflected upward by the ribs. The two upward streams reach the channel top, flow along the upper surface toward the center, mix at the centerline, and finally descend back to the heated surface, forming a counter-rotating vortex pair downstream of the ribs. This vortex pair entrains cooler core flow air to the central groove region while sweeping low-velocity hot air toward the groove sides, enhancing groove surface heat transfer. Case 1 exhibits greater spanwise height variation than Case 2, increasing flow differences across the span and strengthening the counter-rotating vortex pair.

For ribs with higher center and lower ends (Cases 4 and 5), center region airflow is deflected upward, impinges on the cavity top, flows toward the channel sides, and descends near the side walls, forming a counter-rotating vortex pair. This vortex pair also entrains cooler core flow air to the groove surface, but concentrates it near the groove sides while sweeping low-velocity hot air toward the groove center, similarly enhancing heat transfer. Case 5 shows greater spanwise height variation than Case 4, producing more significant vortical structures and transverse flow.

Figures 5 and 6 present spanwise and streamwise velocity distributions on fixed observation planes for the five configurations. Figure 5 reveals that for uniform rib height (Case 3), minimal spanwise velocity exists near the wall due to small flow differences across the span. For non-uniform rib heights, significant spanwise velocity appears near the wall because flow differences through the ribs vary substantially with spanwise position. As previously analyzed, ribs with lower center and higher ends (Cases 1 and 2) generate vortex pairs that transport cooler core air to the groove center and sweep hot air sideways, resulting in high spanwise velocity in the central groove region. Conversely, ribs with higher center and lower ends (Cases 4 and 5) produce vortex pairs that deliver cooler air to the groove sides and sweep hot air toward the center, creating high spanwise velocity near the groove sides.

Regarding streamwise velocity distribution (Figure 6), Cases 1 and 2 feature lower rib center heights, resulting in higher gas streamwise velocity through the center region. Their vortex pairs concentrate reattachment flow in the groove center, increasing velocity there. For Cases 4 and 5, lower rib side heights produce higher streamwise velocity through the side regions, with vortical structures concentrating reattachment flow near the groove sides. Case 3 shows minimal spanwise variation in streamwise velocity near the rib and groove surfaces due to constant rib height. Additionally, as spanwise height variation increases, the strengthened vortical structures enhance both spanwise and streamwise velocities near the wall. Among the four non-uniform configurations, Case 5 yields the highest near-wall velocities, followed by Case 1, Case 4, and Case 2.

Figure 7 compares streamlines and dimensionless turbulence kinetic energy distributions on different spanwise planes. All configurations exhibit flow separation after being deflected by ribs, reattachment near the groove trailing edge, and formation of distinct recirculation zones within the grooves. For uniform rib height (Case 3), flow patterns and turbulence kinetic energy distributions are similar across spanwise planes. For non-uniform heights, significant differences emerge. In the center region, ribs with lower center and higher ends shift the reattachment point upstream on the groove surface, while in the side regions, ribs with higher center and lower ends produce the same effect. Comparing turbulence kinetic energy reveals that higher ribs generate more pronounced upward flow and recirculation, creating greater turbulence kinetic energy. Consequently, Cases 1 and 2 exhibit larger turbulence kinetic energy in the side regions, while Cases 4 and 5 produce greater turbulence kinetic energy in the center region, with Case 5 showing notably higher center-region turbulence kinetic energy than other configurations.

2.2 Heat Transfer Characteristics Analysis

Figure 8 presents the streamwise distribution of local Nusselt number at different spanwise positions for the five configurations. The variation trends are similar across all cases. Using the uniform rib height case (Case 3) as an example, the local Nusselt number on the upstream heated surface gradually decreases, reaching a valley at the rib leading edge before peaking in the rib region. This occurs because the boundary layer thickens as cooling air flows along the heated surface, degrading heat transfer, until the air impinges on and is deflected by the rib, locally enhancing heat transfer. The deflected air reattaches at the groove trailing edge, creating a large local Nusselt number. Some reattached flow then moves upstream along the groove surface, forming a low-speed clockwise recirculation between the groove and rib that gradually reduces the Nusselt number with decreasing x/D_h, though a local peak appears at the groove leading edge due to significant geometric transition.

In the channel center region ($z/D_h = 0.16$), Case 1 exhibits near-zero rib height, and unlike other configurations, shows no local Nusselt number peak in the rib region. For ribs with lower center and higher ends (Cases 1 and 2), the induced vortex pair transports cooler core air to the heated surface center while sweeping low-velocity hot air sideways, increasing the local Nusselt number in the center region. Greater spanwise height variation produces stronger vortical structures and transverse flow, yielding higher center-region Nusselt numbers. Therefore, near the channel center ($z/D_h = 0.16$), Case 1 achieves the highest local Nusselt number, followed by Case 2 and Case 3, while Cases 4 and 5 show poorer and nearly identical heat transfer performance.

For ribs with higher center and lower ends, the vortex pair transports cooler core air to the heated surface sides while sweeping low-velocity hot air toward the center, enhancing side-region heat transfer. Greater spanwise height variation strengthens this effect. Consequently, near the channel side walls ($z/D_h = 1.09$), Case 5 provides the best heat transfer, followed by Cases 4 and 3, while Cases 2 and 1 show poorer and nearly identical performance.

Figure 9 [Figure 9: see original paper] compares the area-averaged Nusselt number ratio on the heated surface across Reynolds numbers for all configurations. The area-averaged Nusselt number ratio decreases with increasing Reynolds number for all cases. Uniform spanwise rib height (Case 3) yields the lowest average Nusselt number, indicating that altering the spanwise rib height distribution improves overall heat transfer in rib-grooved channels. As flow analysis revealed, ribs with highest center and lowest ends (Case 5) provide the maximum near-wall velocity, resulting in the highest average Nusselt number, followed by Cases 4, 1, 2, and 3. At $Re = 10000$, Case 5' s area-averaged Nusselt number ratio is approximately 0.14 higher than Case 3. In summary, non-uniform spanwise rib height distributions enhance average Nusselt number, with greater height variation yielding better heat transfer enhancement. When maximizing heated surface heat transfer is the criterion, ribs with higher center and lower ends outperform those with lower center and higher ends.

2.3 Resistance Characteristics and Thermal Performance Analysis

Heat transfer enhancement typically accompanies increased flow losses, necessitating investigation of how spanwise rib height distribution affects channel resistance characteristics.

Figure 10 [Figure 10: see original paper] compares the friction factor ratio in the heated section across Reynolds numbers for all configurations. The friction factor increases with Reynolds number for all cases. Flow analysis indicates that Case 5 generates the highest mainstream turbulence kinetic energy and thus the greatest flow losses, followed by Cases 4, 3, 1, and 2. In summary, compared to uniform spanwise rib height, ribs with higher center and lower ends significantly increase flow losses, while ribs with lower center and higher ends reduce flow losses. Greater spanwise height variation produces larger flow losses.

Figure 11 [Figure 11: see original paper] presents the thermal performance factor across Reynolds numbers for all configurations. While Case 5 provides the best heat transfer, it also creates the highest flow losses. To comprehensively evaluate channel performance and identify the optimal configuration, the thermal performance factor is examined. The factor decreases with increasing Reynolds number for all cases. Uniform spanwise rib height (Case 3) yields the lowest thermal performance factor, confirming that altering rib height distribution improves overall channel performance. At $Re = 10000$, Case 5' s thermal performance factor is approximately 0.065 higher than Case 3. Among all configurations, Case 5 achieves the highest thermal performance factor, followed by Cases 1, 2, 4, and 3, indicating that greater spanwise height variation produces higher thermal performance factors.

3 Conclusions

This study investigates the role of combined rib-groove structures in enhancing channel thermal performance and numerically analyzes the effects of spanwise rib height distribution on heat transfer and resistance characteristics in rib-grooved channels. The main conclusions are:

1) Non-uniform spanwise rib height distributions generate counter-rotating vortex pairs, with greater height variation producing stronger vortical structures.

2) Non-uniform spanwise rib height distributions increase both spanwise and streamwise velocities in near-wall regions, with greater height variation yielding higher near-wall velocities.

3) Non-uniform spanwise rib height distributions enhance both heat transfer performance and thermal performance factors in rib-grooved channels, with larger height variations producing higher Nusselt numbers and thermal performance factors. Ribs with higher center and lower ends increase flow losses, while ribs with lower center and higher ends reduce flow losses. Case 5 (highest center, lowest ends) achieves the highest heat transfer and thermal performance. At $Re = 10000$, Case 5' s Nusselt number ratio and thermal performance factor are approximately 0.14 and 0.065 higher than Case 3, respectively.

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