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Detached eddy simulation of turbulent flow and heat transfer in cooling channels roughened by variously shaped ribs on one wall

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ABSTRACT

Delayed Detached Eddy Simulations with the k-ω-SST turbulence model were conducted for 8.0 MPa pressurized helium-gas flow in cooling channels with rib arrays on one wall at a Reynolds number of $Re = 1.05 \times 10^5$. Turbulent flow and heat transfer were determined for arrays of eight variously configured V-shaped and transverse ribs. The relative roughness was $e/D_h = 0.0638$ and 0.0652 and the rib pitch was $p/e = 10$. The results showed that for ribs not extended over the total channel width, form drag was reduced and flow stagnation regions with a low heat transfer at the rib corners on the sides disappeared, whereas heat transfer by forced convection increased. Compared to smooth channel flows, the Nusselt numbers were increased by a factor of 1.6–1.8 and 2.2–2.5 for the transverse and V-shaped ribs, respectively. The corresponding friction factors were enhanced by a factor of 2.4–2.9 and 2.8–3.7, respectively. Evaluation of the thermal performance of structured cooling channels in comparison with smooth cooling channels revealed that thermal performance was best for the upstream directed 60° V-shaped ribs. The results showed that secondary flow motion induced by a V-shaped rib configuration caused an outward convective fluid transport within the recirculation region behind the rib. Vortical structures associated with local heat transfer deterioration behind the rib could be eliminated by appropriate designs of rib cross sections. Both lateral convective fluid transport and the elimination of vortical structures deteriorating heat transfer were found to lead to a significant heat transfer enhancement in the leeward rib region for the V-shaped ribs with modified cross section.

1. Introduction

Rib-turbulators are widely used for heat transfer devices to provide effective cooling performance in high temperature applications. In general, heat transfer enhancement is caused by inducing secondary flow motion, increasing the forced convective heat transfer and rising the turbulent mixing. Therefore, turbulent flow and heat transfer in cooling channels roughened by rib arrays have been investigated extensively for decades. Han [1,2] and Han et al. [3] systematically studied heat transfer coefficients and friction factors of turbulent flow in uniformly heated rectangular channels with square ribs on two opposite walls at varying pitch-to-rib-height-ratios ($5 \le p/e \le 40$), rib-height-to-hydraulic-diameter-ratios ($0.0021 \le e/D_h \le 0.102$), and channel aspect ratios ($1/4 \le W/H \le 4$) at Reynolds numbers of $7 \times 10^4 \le Re \le 9 \times 10^4$. The results showed that heat transfer at the rib-roughened wall and the friction factor increased with increasing relative roughness e/D_h and decreased with increasing rib pitch p/e. Similar results were obtained from flow experiments in channels with square ribs ($e/D_h = 0.063, 0.081, 0.106$; $p/e = 10, 15, 20$) on two opposite walls at Reynolds numbers of $5.0 \times 10^3 \le Re \le 5.4 \times 10^4$ by Liou and Hwang [4]. They reported that Nusselt number and friction factor decrease with increasing relative rib pitch at a constant rib height and increase with increasing relative roughness at a constant Reynolds number. Here, the relative rib pitch of $p/e = 10$ provides for maximum heat transfer. Local Nusselt number deterioration occurred in the vicinity of the rib's rear surface. Labbé [5] performed Large Eddy Simulation (LES) to determine turbulent flow in a one-sided rib-roughened channel ($e/D_h = 0.3$, $p/e = 10$) at Reynolds numbers of $Re = 4.0 \times 10^4$. It was found that local heat transfer deterioration was caused by a secondary recirculation vortex trapped between the elongated primary recirculation vortex and the rear rib surface. It resulted in a downward fluid motion that inhibited convective energy transport from the near-wall flow to the core flow. The results of Detached Eddy Simulations (DES) for turbulent flow and heat transfer in two-sided rib-roughened channels at $Re = 2.0 \times 10^4$ performed by Viswanatha and Tafti [6]

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showed that turbulence intensities were reduced in the region behind the rib, and so was turbulent mixing. Rau et al. [7] reported turbulent flow and heat transfer in oppositely two-sided and one-sided rib-roughened cooling channels with square ribs ($e/D_h = 0.1$; $6 \leq p/e \leq 12$) at $Re = 3.0 \times 10^4$. Measurement results revealed that the location of maximum heat transfer coincided with peak vertical velocities and peak turbulent fluctuations in the reattachment zones behind and in front of the ribs. Compared to smooth channel flows, heat transfer was increased by about a factor of 2.1 and 2.4 and the friction factor was increased by about the factor of 3.5 and 5.0 for the one-sided and two-sided rib-roughened channel, respectively. With the objective of designing efficient ribs for heat transfer applications, recent studies covered (time-resolved) Particle Image-Velocimetry (PIV) measurements to obtain deep insights into the complex flow motion of shear layer formation, vortex shedding, and mixing processes. Cardwell et al. [8] performed measurements in a square channel rib-roughened on two opposite sides with staggered square ribs ($e/D_h = 0.12$; $p/e = 8$) at Reynolds numbers of $Re = 2.5 \times 10^3$, 1.0×10^4 and 2.0×10^4. They found that vortices shed from the rib interacted with the rib wake. Counter-rotating vortices were formed and produced an intermittent high velocity jet in wall-normal direction, which displaced the shear layer. Colleti et al. [9] investigated the unsteady turbulent flow field in a channel with square ribs ($e/D_h = 0.1$; $p/e = 10$) on one wall at a Reynolds number of $Re = 1.5 \times 10^4$. It was shown that the shear layer flow was dominated by clockwise-rotating vortices which developed during the roll-up process of shear layer formation. Shear layer flapping influenced the recirculation region, resulting in an alternation of the instantaneous shear layer reattachment point. The analysis of turbulence quantities revealed that highest shear stresses occurred in the separated shear layer and that the turbulent flow field within the near-wall layer and at the rib top was highly anisotropic.

The flow field and heat transfer in channels with ribs applied on the channel walls are significantly affected by the ribs' cross sectional shape and the rib configuration. Turbulent flow and heat transfer in a channel roughened by transverse ribs ($e/D_h = 0.08$; $8 \leq p/e \leq 20$) with triangular, semicircular, and square cross sections at Reynolds numbers of $7.8 \times 10^3 \leq Re \leq 5.0 \times 10^4$ were studied by Liou and Hwang [10]. The results showed that the most uniform local heat transfer distribution resulted for the semicircular ribs, while highest heat transfer peaks were obtained for the square ribs. The highest deterioration of local heat transfer occurred for the square ribs. The averaged heat transfer at the rib-roughened wall was increased by about 60–110%, 70–120%, and 90–170% for the semicircular, triangular, and square ribs and the corresponding averaged friction factor was increased by a factor of about 4–8, 5–10, and 7–15, respectively. Similar results were reported by Ahn et al. [11]. They conducted LES of turbulent flow in a duct with transverse ribs ($e/D_h = 0.1$, $p/e = 10.$) of square or semicircular cross section on two opposite walls at a Reynolds number of $Re = 3.0 \times 10^4$. The time-averaged results showed that vortices in the backward-facing and forward-facing rib corners were reduced for the semicircular rib. Consequently, local heat transfer peaks in the vicinity of the ribs were weaker for the semicircular ribs than for the square ribs. For both rib cross sections, the heat transfer maximum was reached about a rib height upstream of the reattachment location of $x/e = 4.5$. The instantaneous results revealed that the upstream location of the heat transfer maximum was caused by vortical motion. The cold fluid entrained by the clockwise-rotating vortices moved backwards after shear layer reattachment and shifted the cold fluid upstream. The averaged Nusselt number was in a comparable range for the square and semicircular ribs, but the reduced friction factor of the latter yielded an increased thermal performance. Friction factors and Nusselt numbers in a rectangular channel (2:1 aspect ratio) with upstream directed 45° V-shaped ribs ($e/D_h = 0.0625$ and 0.2, $p/e = 10$) on one or on two channel walls at Reynolds numbers of $9.5 \times 10^4 \leq Re \leq 5.0 \times 10^5$ were analyzed by Maurer et al. [12]. The results showed that the friction factor ratios increase with increasing Reynolds numbers, whereas the Nusslet Number ratios converge to a constant value. Similar to the results for transverse ribs reported by Chandra et al. [13,14], the heat transfer was slightly enhanced with the introduction of a second rib-roughened wall, but the corresponding huge pressure drop causes an efficiency decrease. Thus, best thermal performance was obtained for the one-sided rib-roughened channels with the lower blocking. Ruck et al. [15] investigated the friction factor and heat transfer in channels roughened by variously shaped ribs on one wall at Reynolds numbers of $5.0 \times 10^4 \leq Re \leq 2.5 \times 10^4$. It was shown that round-edged ribs reduced both the friction factor and the heat transfer for transverse and V-shaped ribs. Wang and Sundén [16] investigated the effect of the pitch-rib ratio ($8 \leq p/e \leq 15$) and the Reynolds number ($8.0 \times 10^3 \leq Re \leq 2.0 \times 10^4$) on the Nusselt number and friction factor in a channel with ribs applied on one wall ($e/D_h = 0.1$). The rib cross section was square, equilateral-triangular, and trapezoidal with rising and declining rib height in mean flow direction. It was found that local heat transfer immediately downstream of the rib was strongly influenced by the rib shape, but less dependent on the inter-rib spacing. Averaged heat transfer varied for the rib shapes and heat transfer and pressure drop were highest for the trapezoidal ribs with decreasing rib height. Liou et al. [17] compared the thermal performance of twelve differently configured rib turbulators ($e/D_h = 0.12$, $p/e = 10$) in single rib configuration at a Reynolds number of $Re = 1.2 \times 10^4$. The results of liquid crystal thermography, LDV and pressure drop measurements showed that heat transfer at the rib-roughened wall was dominated by rib-induced secondary flows. According to previous studies, high heat transfer coincided with regions of downward flow velocities and reduced heat transfer occurred in regions of upward flow velocities behind the rib. The upstream directed 45° V-shaped rib and a 45° delta wing rib produced the best thermal performance. Nusselt number distributions and friction factors of flow in square channels with ribs on one and two opposite walls were investigated by Jia et al. [18]. Reynolds-averaged Navier-Stokes (RANS) simulations were carried out for the upstream and the downstream directed 45° V-shaped ribs ($e/D_h = 0.0625$, 0.125; $p/e = 10$) with an inline and a staggered arrangement at Reynolds numbers of $1.0 \times 10^4 \leq Re \leq 3.2 \times 10^4$. LES with a Smagorinsky subgrid-scale (SGS) model were conducted for the 60° V-shaped ribs ($e/D_h = 0.1$; $p/e = 10$) at a Reynolds number of $Re = 6.24 \times 10^4$. The V-shaped rib-induced secondary flow forms a counter-rotating vortex pair. The vortex rotation direction depends on the upward or downward direction of the rib. Depending on the relation between local heat transfer and secondary flows reported by Liou et al. [17], the local Nusselt number on the rib-roughened surface varied significantly. The region of high heat transfer within the inter-rib spacing was located centrally for the upstream directed ribs and shifted towards the side walls for the downstream directed ribs. Fang et al. [19] investigated turbulent flow around upward directed V-shaped ribs (30°, 45°, and 60°, $e/D_h = 0.1$, $p/e = 8$) in a square channel at a moderate Reynolds number by means of PIV under isothermal conditions. A counter-rotating vortex pair was formed by secondary flow motion as a result of the interaction of different mean vorticity components. Ejection events which were identified by Wang et al. [16] by PIV measurements ($e/D_h = 0.2$, $p/e = 10$, $Re = 2.2 \times 10^4$) as the main contributors to the Reynolds shear stress at the leading edge of transverse ribs were found to be significantly suppressed for the V-shaped ribs. Furthermore, it was found that for the V-shaped ribs, turbulence kinetic energy mainly originated from the extra mean shear components and Reynolds normal stresses, whereas