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Augmented heat transfer in a turbulent channel flow with inclined detached-ribs

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ABSTRACT

This paper presents the results of numerical study of turbulent flow and heat transfer in a channel with inclined detached-ribs. The computations based on the finite volume method, and the SIMPLE algorithm have been implemented. The study encompasses the Reynolds number (based on the hydraulic diameter of a channel) range from 4000 to 24,000. The heat transfer, pressure loss and thermal performance of the inclined detached-ribs with different attack angles (θ) of 0°, 15°, 30°, 45°, 60°, 75°, 105°, 120°, 135°, 150° and 165° are examined and compared with those of the typical transverse attached rib with θ of 90°. The computational results reveal that, at high Reynolds number, the inclined ribs with θ=60° and 120° yield comparable heat transfer rates and thermal performance factors which are higher than those given by the ones with other angles. On the other hand, at low Reynolds number, the effect of rib attack angle is insignificant.

1. Introduction

Rib-roughened walls are extensively applied for heat transfer augmentation in cooling passages. The heat transfer augmentation by ribs relies on induced turbulence in the flow. Several researchers reported the effects of rib geometries (channel aspect ratio, rib height-to-passage hydraulic diameter or blockage ratio, rib angle of attack, rib pitch-to-height ratio and shape, the manner in which the ribs are positioned (in-line, staggered, oblique, one-wall, and opposite two-walls)) on the heat transfer enhancement, pressure drop and thermal performance. Momin et al. [1] presented the thermal behaviors in a solar air heater channel fitted with V-shaped ribs for e/D=0.02–0.034 and the angle of attack (α)=30–90°. Aharwal et al. [2] investigated the heat transfer characteristics in a solar air heater channel with inclined square split-rib with a gap on one wall. They observed that the gap in the inclined rib helped to enhance the heat transfer in the channel. Tanda [3] studied the forced convection heat transfer in a rectangular channel with angled rib turbulators inclined at 45°. The angled ribs were deployed with parallel orientations on one or two surfaces of the channel. The effects of ratio of rib height to hydraulic diameter, rib spacing, rib pitch-to-height ratios (p/e) on the thermal performance were examined. Lanjewar et al. [4] examined the heat transfer and friction factor characteristics in a rectangular duct roughened with W-shaped ribs pointing downstream (W-down) and upstream (W-up) to the flow. Promvonge et al. [5] investigated the effects of the combined ribs (isosceles triangle rib) and delta-winglet type vortex generators on heat transfer and pressure drop characteristics in a solar air heater channel for Reynolds numbers between 5000 and 22,000. Promvonge and Thianpong [6] reported the thermal

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performance of wedge ribs pointing upstream and downstream, with triangular and rectangular ribs in a channel. Their results reveal that the in-line wedge rib pointing downstream yielded the highest heat transfer rate while the staggered triangular rib offered the best thermal performance. Liu et al. [7] investigated the forced convection heat transfer in microchannel by using the CFD and lattice Boltzmann approaches. Influences of the microchannel geometric shape (ridge-shaped groove, V-shaped groove, shield-shaped groove, and straight slot groove) on thermal performance were also described. Liu and Wang [8] studied the heat transfer and friction factor characteristics in channel with semi-attached ribs. The ribs were perforated at the rib corners to form two rectangular holes, so a portion of the fluid could pass through the holes. Effects of the width ratios of channel to hole, transverse rib and 45° angled ribs on flow structure were also reported. Wongcharee et al. [9] studied the thermal performance in a channel fitted with concave–concave/convex–concave/long convex-short concave/long concave-short concave ribs. It was found that the modified ribs with convex surfaces (convex–concave and long convex-short concave ribs) gave lower Nusselt numbers and friction factors but higher thermal performance factors than the one with both concave surfaces (concave–concave and long concave-short concave ribs). Sriromreun et al. [10] studied the effect of 45° Z-baffles on the thermal performance factor in a rectangular channel which aligned in series on the isothermal-fluxed top wall. They found that the thermal performance factor for the in-phase 45° Z-baffles was higher than those for the out-phase 45° Z-baffles. In addition, heat transfer rate and friction loss increased as baffle height increased while thermal performance factor increased as baffle pitch length decreased. Recently, Promvonge et al. [11] reported the flow and heat transfer characteristics in a square duct fitted diagonally with 30° angle-finned tapes at different fin-to-duct height ratios. As compared with typical wire coil and twisted tape, the finned tape gave significantly higher thermal performance factor.

The main aim of the present work is to extend the numerical data availability in heat transfer enhancement by inclined detached-ribs with different attack angles ($\theta = 0°$, 15°, 30°, 45°, 60°, 75°, 105°, 120°, 135°, 150° and 165°). In the present report, the numerical computations for channel flows over inclined detached-ribs mounted on the bottom channel wall are conducted to analyze the fluid flow, temperature field and thermal performance. All of the numerical calculations were carried out in a turbulent region with the Reynolds number based on the hydraulic diameter (Re), from 4000 to 24,000. In addition, the results of the detached-ribs are subjected to compare with those of typical transverse attached-ribs ($\theta = 90°$).

2. Mathematical foundation

The numerical model for fluid flow and heat transfer in a channel was developed under the following assumptions:

- Steady two-dimensional fluid flow and heat transfer.
- The flow is turbulent and incompressible.
- Constant fluid properties.
- Negligible radiation heat transfer, body forces and viscous dissipation.

Based on the above assumptions, the channel flow is governed by the continuity equation, the Navier Stokes equations and the energy equation. In the Cartesian tensor system these equations can be written as follows:

Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum equation:

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{2}$$

Energy equation:

$$\frac{\partial}{\partial x_i}[u_i(\rho E + p)] = \frac{\partial}{\partial x_j}\left(k_{eff}\frac{\partial T}{\partial x_j}\right) \tag{3}$$

$$E = h - \frac{p}{\rho} + \frac{u^2}{2} \tag{4}$$

The Reynolds-averaged approach to turbulence modeling requires that the Reynolds stresses, $-\rho\overline{u_i' u_j'}$ in Eq. (2) be appropriately modeled. A common method employs the Boussinesq hypothesis to relate the Reynolds stresses to the mean velocity gradients

$$-\rho\overline{u_i' u_j'} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t\frac{\partial u_k}{\partial x_k}\right)\delta_{ij} \tag{5}$$