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Numerical study on heat transfer of turbulent channel flow over periodic grooves ☆

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ABSTRACT

A numerical investigation of turbulent forced convection in a two-dimensional channel with periodic transverse grooves on the lower channel wall is conducted. The lower wall is subjected to a uniform heat flux condition while the upper wall is insulated. To investigate turbulence model effects, computations based on a finite volume method, are carried out by utilizing four turbulence models: the standard $k-\varepsilon$, the Renormalized Group (RNG) $k-\varepsilon$, the standard $k-\omega$, and the shear stress transport (SST) $k-\omega$ turbulence models. Parametric runs are made for Reynolds numbers ranging from 6000 to 18,000 with the groove-width to channel-height ratio (B/H) of 0.5 to 1.75 while the groove pitch ratio of 2 and the depth ratio of 0.5 are fixed throughout. The predicted results from using several turbulence models reveal that the RNG and the $k-\varepsilon$ turbulence models generally provide better agreement with available measurements than others. Therefore, the $k-\varepsilon$ model is selected to use in prediction of this complex flow. In addition, the results of the heat transfer coefficient, friction factor, skin friction coefficient and thermal enhancement factor are also examined. It is found that the grooved channel provides a considerable increase in heat transfer at about 158% over the smooth channel and a maximum gain of 1.33 on thermal performance factor is obtained for the case of $B/H=0.75$. This indicates that the reverse/re-circulation flow in a channel with transverse grooves can improve the heat transfer rate.

1. Introduction

The improvement of convective heat transfer in thermal systems is needed in many engineering applications with a view to reducing the size, weight and cost of heat exchangers. Attempts have been made to enhance heat transfer in the heat exchangers by using roughen surfaces or turbulators such as rib, groove and helical rib in disturbing the flow and in providing transverse/longitudinal vortices or three-dimensional mixing. Comprehensive reviews on heat transfer enhancement by periodic surfaces mounted obstacles have rarely been found because of the wide variability of geometric parameters. A review of measurements of global heat transfer coefficient and pressure drop for various rib configurations was given by Dalle Donne and Meyer [1]. Martin and Bates [2] presented velocity field and the turbulence structure in an asymmetrically ribbed rectangular channel with one rib configuration of square ribs and varying channel height. Hong and Hsieh [3] investigated the influence of rib alignment on forced convection in a channel at different rib alignments, either staggered or in-line, on the internal surfaces of rectangular or square channels. Jaurker et al. [4] reported the heat transfer and friction characteristics of rib–grooved artificial roughness on one broad heated wall of a large aspect ratio duct. Distributions of the heat transfer coefficient and the pressure drop along the wall inside an asymmetrically ribbed channel measured for thermally developing and turbulent flow over periodic grooves were studied by Lorenz et al. [5].

Numerical investigations on turbulent flow friction and heat transfer enhancement in ducts or channels with rib, groove or rib–groove turbulators have been carried out extensively. Chaube et al. [6] investigated the flow and heat transfer characteristics of a two-dimensional rib roughened (rectangular/chamfered rib) rectangular duct with only one principal heating wall by using the shear stress transport $k-\omega$ turbulence model. Saidi and Sunden [7] studied the thermal characteristics in a duct with rib turbulators by using a simple eddy viscosity model and an explicit algebraic stress model and reported that the algebraic stress model has some superiority over the eddy viscosity model for only velocity field structure prediction. Tatsumi et al. [8] investigated numerically the flow around a discrete rib attached obliquely to the flow direction onto the bottom wall of a square duct and found that noticeable heat transfer augmentation was obtained downstream of the rib, produced by a strong secondary flow motion. Yang and Hwang [9] conducted numerically to examine the heat transfer enhancement in rectangular ducts with slit and solid ribs mounted on one wall using the $k-\varepsilon$ turbulence model.

Luo et al. [10] reported the turbulent convection behavior in a horizontal parallel-plate channel with periodic transverse ribs using the standard $k-\varepsilon$ model and a Reynolds stress model. They found that

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Nomenclature

B	distance between grooves, m
C_f	friction coefficient
C_μ	turbulence model constant
D_h	hydraulic diameter of channel, (=2H)
e	rib height or groove depth, m
f	friction factor
H	channel height, m
h	convective heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
L	channel length of test section, m
Nu	Nusselt number
p	static pressure, Pa
Re	Reynolds number
s	rib land/length, m
T	temperature, K
u	mean velocity, m s^{-1}
u'_i	fluctuation velocity components, m s^{-1}

Greek letter

μ	kinematic viscosity, kg $s^{-1}m^{-1}$
μ_t	eddy viscosity, kg $s^{-1}m^{-1}$
τ_{ij}	Reynolds stress, m^2 s^{-2}
τ_w	wall shear stress, Pa
η	thermal enhancement factor, $(=(Nu/Nu_s)/(f/f_s)^{1/3})$
ω	turbulent specific dissipation rate, s^{-1}
ε	turbulent dissipation rate, m^2 s^{-3}
ρ	density, kg m^{-3}

Subscript

ave	average
s	smooth

the anticlockwise vortex was observed in the downstream region of a rib while the length and relative strength of the vortex predicted by these two models were significantly different. Kim and Lee [11] presented an optimal design of a square channel with V-shaped square ribs extruded on both walls to enhance turbulent heat transfer by using the shear stress transport (SST) model.

Apart from using different turbulence models as mentioned earlier, large eddy simulation (LES) was also introduced to investigate turbulent flows in periodically grooved channel by Yang [12] and in a ribbed tube by Vijiapurapu and Cui [13] and found that the large-scale turbulent structures are significantly affected by the geometry of the groove or the rib.

Several recent studies cited above reveal that the grooved channel flows have been examined only for heat transfer coefficients or the flow field and turbulence structure from different groove pitches/heights with rarely varying groove sizes. In the present work, heat transfer (Nu), friction factor (f), skin friction coefficient (C_f Re) and thermal enhancement factor ($(Nu/Nu_s)/(f/f_s)^{1/3}$) characteristics in a perodic grooved channel with different groove widths are studied numerically. The main goals of the present work are (1) to examine the performance of the four turbulence models (standard $k-\varepsilon$ turbulence, Renormalized Group (RNG) $k-\varepsilon$ turbulence, standard $k-\omega$ turbulence and SST $k-\omega$ turbulence models) in prediction of heat transfer in turbulent grooved channel flows and (2) to investigate the effect of groove-width ratio (B/H) on heat transfer, flow friction and thermal enhancement characteristics.

2. Geometry of the present problem

The system of interest is a horizontal plane channel with nine periodic grooves (eight ribs) along the lower channel wall as shown in Fig. 1. The channel height is set to H=40 mm while the channel length, rib land (s) and groove width (B) were set to 47H, H and H, respectively. To ensure a fully developed flow, the first groove was located at the distance of 20H downstream of the entrance while the last groove was set to 10H upstream of the exit. The grooved channel having eight ribs with a test section length of L=680 mm (17H), 20 mm rib height (e=0.5H), 40 mm rib length (s=H) and 40 mm channel clear height (H) as depicted in Fig. 1. The dimension of the constant heat flux test section mentioned above is the same as the grooved channel of Lorenz et al. [5] used for validation. To examine an effect of the groove size on heat transfer and friction loss in the channel, the groove width ratio, (B/H), is varied to be B/H=0.5, 0.75, 1.0, 1.25, 1.5 and 1.75, for each test run of calculations.

A uniform rectangular mesh with grid adoption for $y^+\approx 2$ at an adjacent wall region is used to resolve the laminar sub-layer and is shown in Fig. 2. To obtain grid independence solution, the number of cells is varied between 50,900 and 155,992 meshes. The mean inlet velocity between 1.19 and 3.58 m/s based on Reynolds number cited above, zero pressure gradients at the exit and no slip wall boundary conditions are taken for the present computation. In previous research, Chaube et al. [6] suggested that the calculation with 2-dimensional flow model yields the results closer to measurements as compared that with 3-dimensional flow. In this work, the 2D flow is therefore carried out for saving computer memory and computational time.

3. Mathematical modeling

3.1. Flow governing equations

The phenomenon under consideration is governed by the steady 2-Dimensional form of the continuity, the time-averaged incompressible

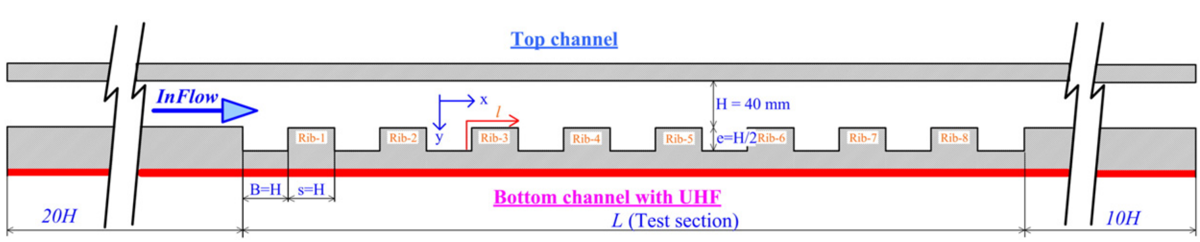

Fig. 1. Grooved channel flow configuration.