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Parameters study and analysis of turbulent flow and heat transfer enhancement in narrow channel with discrete grooved structures

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ABSTRACT

The influence of discrete grooved structures on heat transfer enhancement in a narrow channel has been investigated numerically. In the present work, three groove configurations including P-type grooves, V-type grooves and W-type grooves are considered with various geometrical parameters, four longitudinal groove-pitch ratios, three transversal groove-pitch ratios, three groove-depth ratios and five groove-inclined angles. The numerical results reveal that Nusselt number value for the P-type grooves is enhanced by 45.8–65.4% and friction factor for the P-type grooves is increased by 95.1–114.8% compared to plain duct with the Reynolds number range (*Re*) between 4016 and 10,709. To obtain an optimum thermal performance condition, the effect of geometrical parameters on the heat transfer and friction factor in the channel is examined. The results of parameters study show that the case of P-type grooves with $p_h = 1.2$, $f_h = 2.6$, $e_h = 1$, $\alpha = 30^\circ$ provides the best overall thermal performance factor (TPF) at $Re = 4016$. Finally, empirical correlations evaluating the Nusselt number and friction factor of three groove configurations are also generated to assist design activities.

Keywords: Heat transfer enhancement; Grooved channel; Correlation; Nusselt number; Computational fluid dynamics; Thermal performance

1. Introduction

Heat exchangers, which enable the heat transfer between two flows, had been extensively used in many engineering areas such as chemical engineering, power production, waste heat recovery and air conditioning etc. Heat transfer augmentation techniques are currently used in heat exchanger systems in order to enhance heat transfer and improve the thermal performance (Bergles, 1973; Webb, 1994). Several techniques such as rib turbulators, pin arrays, arrays of shaped roughness elements and grooves have been used in heat transfer enhancement. In past decades, many studies of convective heat transfer enhancement have been reported. In order to improve the compactness and efficiency of heat exchangers, both the reduction of the pressure loss and enhancement of the heat transfer capacity are necessary. Among various techniques, rib shows better heat transfer performance than groove because of stronger secondary flow. However, the large wake region and strong flow separation cause an increase of pressure drop penalty (Kakac and Shah, 1987). Thus, groove is one of the most promising techniques due to its good thermo-hydraulic performances.

A lot of experimental investigations on the heat transfer enhancement by means of grooves and ribs have been extensively reported. Grooves and ribs are commonly imprinted on the heat transfer surface to promote the fluid mixing between central region and the region closer to the wall. Most of the experimental investigations focused on geometrical parameters, arrangement and flow conditions (Bilen et al., 2009; Satta et al., 2012; Tanda, 2011; Zhang et al., 2013). Jaurker et al. (2006) reported the heat transfer and friction characteristics of rib-grooved artificial roughness on one broad heated wall of a large aspect ratio duct. Wang and Sunden (2007) conducted an experimental study on the heat transfer performance of square ribs, equilateral-triangular ribs, trapezoidal ribs with decreasing height in the flow direction. It was reported that the trapezoidal-shaped ribs with decreasing height in the flow direction give the best heat transfer enhancement performance. Martin and Bates (1992) studied velocity field and flow structure in an

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Nomenclature

A	heat transfer area (m^2)
D_e	hydraulic diameter (m)
q	heat flux (W/m^2)
Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number
Q	heat transfer rate (W)
u	mean velocity (m/s)
f	friction factor
f_h	transversal groove pitch ratio
l	groove length (mm)
L_h	length of groove surface (mm)
G_k	generation of turbulent kinetic energy
ΔP	pressure drop (Pa)
x	coordinates (mm)
y	coordinate (mm)
z	coordinates (mm)
T	temperature (K)
W	channel width (mm)
p	longitudinal groove pitch (mm)
e	groove depth (mm)
h	heat transfer coefficient ($W/m^2\,K$)
w	groove width (mm)
e	groove depth (mm)
H	channel height (mm)
F_1	blending function

Geek symbols

α	inclined angle of groove (°)
α_1	coefficient for generation of specific dissipation rate
β	inclined angle of groove side wall (°)
β_1	constant for turbulent dissipation
ε	dissipation rate of turbulent kinetic energy (m^2/s^3)
η	thermal enhancement factor
ω	specific dissipation rate (1/s)
k	turbulence kinetic energy ($m^2\,s^{-2}$)
ρ	density ($kg\,m^{-3}$)
ν	kinetic viscosity (m^2/s)
σ	temperature gradient (K/m)
μ	molecular viscosity (kg/m s)

Subscripts

b	bulk
i	inlet
m	mean
eff	effective
o	outlet
p	plain duct
w	wall
t	turbulence

asymmetrically ribbed rectangular duct at different rectangular duct heights. San and Huang (2006) experimentally investigated the heat transfer enhancement of the transverse ribs in circular tubes with a length-to-diameter ratio of 87. Eiamsa-ard (2010) conducted a series of experiments on thermal and fluid flow characteristics in turbulent channel inserted by multiple twisted tape vortex generators with three different twist ratios (y/w = 2.5, 3.0 and 3.5). It was found that the channel with the smaller twist ratio (y/w) and free-spacing ratio (s/w) provides higher heat transfer rate and pressure loss than those with the larger of twist ratio and free-spacing ratio. The effects of angled ribs on heat transfer of heat transfer and pressure drop in a narrow channel were studied by Gao and Sundén (2004). Hwang et al. (2010) studied the local heat transfer and thermal performance on periodically dimple-protrusion patterned walls for compact heat exchangers by using a transient TLC (Thermochromic Liquid Crystal) technique.

Detailed analysis of flow and heat transfer in ribbed or grooved channel by means of numerical methods is also important. Chaube et al. (2006) 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–ω turbulence model. Tatsumi et al. (2003) numerically investigated 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 (2004) numerically studied the heat transfer enhancement in rectangular ducts with slit and solid ribs mounted on one wall using the k–ε turbulence model. Eiamsa-ard and Promvonge (2008) numerically predicted the turbulent forced convection in a two-dimensional rectangular duct with periodic transverse grooves by utilizing k–ε turbulence model and 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. Ramadhan et al. (2013) numerically studied effects of groove geometry on turbulent heat transfer and fluid flow. Four geometric groove shapes (circular, rectangular, trapezoidal and triangular) were selected to perform the study. It was concluded that the best performance is obtained with the lower depth-groove ratio, whereas it was found that the grooved tube provides a considerable increase in heat transfer at about 64.4% over the smooth tube and a maximum gain of 1.52 on thermal performance factor is obtained for the triangular groove with e/D = 0.1. Bi et al. (2013) numerically investigated heat transfer enhancement in mini-channel heat sinks with dimples and cylindrical grooves by using the field synergy principle.

According to the above literature survey, it is suggested that most previous studies just focus on the flow and heat transfer in channel with continuous grooved structures, while few papers have been published to investigate heat transfer and fluid flow characteristics in a narrow channel with inclined discrete grooves. Therefore, a newly designed enhanced structure with inclined discrete grooves is proposed in this work. In the present study, the effects of groove configurations, longitudinal grooves-pitch ratios (p_h), transversal groove-pitch ratios (f_h), groove-depth ratios (e_h), and groove-inclined angles (α) on heat transfer, friction factor and thermal performance factor (TPF) were numerically investigated. Moreover, new correlations were developed for predicting the heat transfer and friction factor. In the first part of this paper, the validation experiment is described. In the second part, the simulation results are discussed.

The channels for heat exchange used in the current study are built up by two rows of discrete inclined grooves. From the literature review, it is expected that the discrete groove induces the flowing fluid washing the heating surfaces continuously, and it provides almost uniform temperature distribution throughout the heat exchanger core due to turbulent mixing. Moreover, the wake region is smaller, leading to less pressure drop. Thus inclined discrete groove probably provides higher overall thermal performance over the conventional grooved or ribbed channel.

2. Heat transfer enhanced surface with inclined discrete grooves

Grooved surfaces used in the present experimental work were made of stainless steel with thickness δ = 1 mm by stamping forming technology. The channel (test section) has 41 mm in width (W), 165 mm in length (L) and 20 mm in height (H). In channels, eight grooves in two rows oblique to the main flow direction are imprinted and uniformly arranged