International Journal of Heat and Mass Transfer 81 (2015) 563–577

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Turbulent flow and heat transfer enhancement in rectangular channels with novel cylindrical grooves

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ARTICLE INFO

Article history:
Received 26 February 2014
Received in revised form 11 September 2014
Accepted 11 October 2014
Available online 15 November 2014

Keywords:
Cylindrical groove
Rounded transitions
Recirculating flow
Heat transfer enhancement
Thermal performance

ABSTRACT

Turbulent flow characteristics and heat transfer performances in square channels with different cylindrical-shaped grooves are analyzed and compared numerically in this research. The novel groove geometries are conventional cylindrical grooves with rounded transitions to the adjacent flat surfaces and with modifications to their bases. The objective of this work is to determine optimal configuration for augmenting heat transfer rates with minimal pressure drop penalties. The paper documents also provide the flow details near the groove surface. All turbulent fluid flow and heat transfer results are obtained using computation fluid dynamics with a verified v^2f turbulence closure model. Five rectangular channels with different cylindrical groove shapes are computed. Heat transfer enhancement and flow details are analyzed and compared with results for conventional cylindrical groove geometry and for conventional square ribs. This investigation shows that the conventional cylindrical grooves have similar overall heat transfer enhancement with conventional square ribs, but the pressure loss penalty is much decreased from square rib values. The rounded transition of the grooves has a large advantage over conventional cylindrical grooved surfaces in both enhancing heat transfer and reducing pressure loss penalty. For the rounded-transition grooves, recirculating flows inside the groove are reduced and reattachment develops more smoothly and the separating zone is reduced compared with the flow over the conventional cylindrical groove. The velocity magnitude in the near-wall region of grooved surface is much larger compared with that over a ribbed surface, which essentially causes the larger heat transfer enhancement for the groove surfaces. The design for the rounded transitions is shown to improve the overall thermal performance for channel internal cooling.

1. Introduction

Ribbed ducts are usually employed as an internal cooling method for turbine blade, to increase the convective heat transfer. The presence of ribs, also called roughness elements or turbulators, enhances the heat transfer coefficients by creating redevelopment of the boundary layer after flow reattachment between the ribs and by induced secondary flows. Numerical or experimental studies on ribs have paid attention to configuration parameters such as rib shape, aspect ratio (AR), pitch ratio (p/e), blockage ratio (e/D_h), rib angle of attack (α), inclination of ribs, and rib arrangement (staggered or parallel) as well as the channel shape [1–7]. The investigations also showed that the rib-shaped turbulators can effectively enhance heat transfer but with a relatively large pressure loss penalty.

Grooves are also an effective heat transfer enhancement method that is widely used in modern heat exchangers and other cooling equipment. In past years, most research has concentrated on rectangular grooves [8–14]. The distributions of the heat transfer coefficient along the wall inside a channel with periodic transverse grooves were measured by Lorenz et al. [8] for thermally developing and periodic turbulent flow having $10^4 \leqslant Re \leqslant 10^5$. They found that global Nusselt numbers for the grooved wall were augmented by $1.52 \leqslant Nu/Nu_{pl} \leqslant 1.75$ compared to plane channel values. Adachi and Uehara [9] correlated between heat transfer and pressure drop data for channels with periodic rectangular grooved parts. It was found that channels with expanded grooves performed efficiently while the channels with "contracted grooves" behave less efficiently. The "contracted grooves" in their research were similar to conventional rib turbulators. Eiamsa-ard and Promvonge [10] conducted a numerical study on heat transfer in turbulent channel flows over periodic grooves. They found that heat transfer in the channel with periodic grooves could be

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.10.021
0017-9310/

Nomenclature

D	groove depth (m)
p	groove pitch (m)
h	groove width or rib width (m)
D_h	hydraulic diameter (m)
e	rib height (m)
H	channel height (m)
L_H	length of the heated wall (m)
d	moved distance of lowest point
f	friction factor
f/f_0	normalized Fanning friction factor
k	turbulent kinetic energy (m^2/s^2)
Nu	Nusselt number
$Nu(i)$	cell Nusselt number
Nu/Nu_0	normalized Nusselt number
Pr	Prandtl number
A_0	heated area in smooth channel (m^2)
A/A_0	active surface area enhancement factor
q	wall heat flux (W/m^2)
Re	Reynolds number
T	temperature (K)
u_{in}, u, u_i	inlet velocity ($m\ s^{-1}$)
v'^2	velocity variance scale
L	length scale used in v^2f model
S_{ij}	deformation rate tensor
u_x	streamwise velocity
u_y	spanwise velocity
u_z	normal velocity

Greek symbols

ΔP	pressure drop (Pa)
υ	air kinematic viscosity ($m^2\ s^{-1}$)
υ_t	eddy viscosity
ρ	air density ($kg\ m^{-3}$)
ε	rate of energy dissipation (m^2/s^3)
λ	fluid thermal conductivity (W/m K)

enhanced although higher pressure losses were obtained. A thermal enhancement factor of about 1.33 was found at lower Reynolds numbers for the space between grooves when the groove depth/channel height was 0.75. In addition, they investigated the characteristics of turbulent flows on a rib-grooved channel [11]. The rib-groove arrangements significantly enhanced heat transfer rates in comparison with those of a smooth duct. Jain et al. [13] performed a numerical study on shape optimization of rectangular groove micromixers. The superior mixing performance of the optimal design structure which is similar to tortuous gullies could be attributed to the generated transverse flow generated by the featuring which results in higher interfacial area for mass transfer. Grooved surfaces are also applied in film cooling of turbine blades [15,16].

Recently, more attention [17–19] has been drawn to different-shaped grooves seeking the optimal configurations. Bilen et al. [17] investigated the groove geometry effect on heat transfer for internally grooved tubes containing groove shapes of circles, trapezoids and rectangles. In evaluation of thermal performance, the grooved tubes were preferred for flow with Reynolds numbers up to 30,000 with circular and trapezoidal grooves and up to 28,000 for rectangular grooves. Moradi and Floryan [18] maximized heat transfer from micro-channels by the use of grooves parallel to the flow direction. They did so without mixing augmentation. In their research, the optimal groove shape that maximized overall system performance was determined. Ramadhan et al. [19] investigated effects of groove geometry on turbulent heat transfer and fluid flow. From their investigation, the shallow and triangular grooves were recommended based on heat transfer enhancement.

Most heat transfer augmentation affects the boundary layer in such a way as to make it thinner or to partially disrupted, which often results in higher flow resistance. On the other hand, previous research work [20–25] has shown that dimples can provide substantial heat transfer enhancement in confined channels with relatively low pressure loss penalty, compared to that of other types of augmented heat transfer devices such as fins, pins, and rib turbulators. Unlike protruding turbulators, heat transfer of dimpled surfaces is enhanced because vortex structures promote mixing, drawing “cold” fluid from outside the thermal boundary layer to make contact with the heated wall, enhancing convective heat

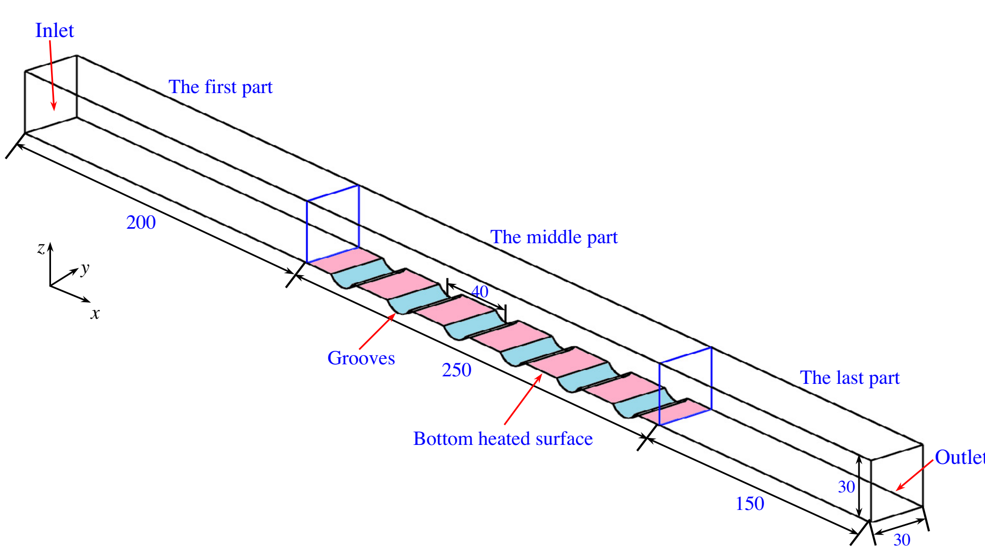

Fig. 1. Schematic diagram of the square channel with three parts. All dimensions are given in millimeters.