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Numerical study of nanofluid forced convection flow in channels using different shaped transverse ribs☆

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ABSTRACT

A numerical investigation is performed to study the effects of different rib shapes and turbulent nanofluid flow on the thermal and flow fields through transversely roughened rectangular channels with Reynolds number ranging from 5000 to 20000 and uniform heat flux of 10 kW/m^2. Considering single-phase approach, the two-dimensional continuity, Navier–Stokes, and energy equations were solved by using the finite volume method (FVM). The optimization was carried out by using various rib shapes (rectangular shape, triangular shape, wedge pointing upstream, and wedge pointing downstream) in two arrangements (in-line and staggered) and three different aspect ratios ($w/e = 0.5$, 2, and 4) to reach the optimal geometry with maximum performance evaluation criterion (PEC). The main aim of this study is to analyze the effects of nanoparticle types (Al_2O_3, CuO, SiO_2, and ZnO), concentration (1–4%), and nanoparticle diameter (30–80 nm), on the heat transfer and fluid flow characteristics. Simulation results show that the ribbed channels' performance was greatly influenced by rib shapes and their geometrical parameters. The highest PEC was obtained for the in-line triangular ribs with $w/e = 4$ at $Re = 5000$. It is found that the water–SiO_2 shows the highest heat transfer enhancement compared with other tested nanofluids. The Nusselt number through the ribbed channels was enhanced with the increase of the particle volume fraction and Reynolds number, and with the decrease of nanoparticle diameter.

1. Introduction

Conventional sources of energy are being depleted at an alarming rate, which makes future sustainable development of energy use very difficult. On the other hand, in recent years, the issue of providing more efficient and reliable thermal systems in terms of reducing the size, weight, cost, and saving of energy has received substantial attention. In order to fulfill these demands, many engineering techniques have been investigated over the years. Employing ribs or grooves on the inner surface of heat exchangers has been one of the frequent passive approaches to break the laminar sub-layer and create local wall turbulence due to flow separation and reattachment between successive corrugations, which reduces the thermal resistance and significantly enhances heat transfer. The ribbed channel, because of its effectiveness in heat transfer, is a good candidate for engineering applications such as cross-flow heat exchanger, gas turbine airfoil cooling design, solar air heater blade cooling system, and gas cooled nuclear reactor [1–3].

Shokouhmand et al. [3] numerically analyzed heat transfer characteristics of turbulent incompressible air flows in grooved parallel-plate channels. Two cases were examined: (i) arc-shaped grooves and (ii) rectangular grooves. In most cases, at equal Reynolds numbers, arc-shaped grooved channels had larger values of mean *Nu* in comparison with rectangular ones. Manca et al. [4] performed a 2-D numerical investigation on turbulent air forced convection in a channel with transversal ribs mounted on the lower wall. The Nusselt number increased almost linearly as Reynolds rose for all the values of dimensionless pitch (p/e). For square and rectangular ribs with $p/e = 12$ and for triangular ones with $p/e = 10$, the maximum Nusselt numbers were obtained. The heat transfer rate was 1.93 times higher than the smooth duct at least at $Re = 20000$. Kamali and Binesh [5] carried out a numerical investigation into the importance of rib shape effects on turbulent local heat transfer and flow friction characteristics of square duct with various-shaped ribs (square, triangular, trapezoidal with decreasing height in the flow direction, and trapezoidal with increasing height in the flow direction) placed on one wall. The results showed that the duct equipped with trapezoidal ribs with decreasing height in the flow direction has the largest full region of heat transfer enhancement.

Promvonge and Thianpong [6] carried out an experimental study to assess turbulent forced convection heat transfer and friction loss behaviors for air flow through a constant heat flux channel with three different shaped ribs: triangular, wedge, and rectangular. According to the

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Nomenclature

A	Cross-section area (m^2)
Cp	Specific heat capacity (J/kg.K)
CFD	Computational fluid dynamic
D_h	Hydraulic diameter (m)
d_p	Nanoparticle diameter (nm)
d_f	Equivalent diameter of a base fluid molecule
e	Rib height (m)
E	Total energy (J)
f	Friction factor
h	Average heat transfer coefficient ($W/m^2.K$)
H	Height of the channel (m)
K	Kelvin
k	Thermal conductivity (W/mK)
k	Turbulent kinetic energy (J/kg)
L_1	Upstream length (m)
L_2	Test section length (m)
L_3	Exit section length (m)
M	Molecular weight (g/mol)
N	Avogadro number (mol^{-1})
Nu	Nusselt number
P	Pressure (N/m^2)
P	Ribs pitch (m)
Pr	Prandtl number
ΔP	Pressure drop (N/m^2)
P_h	Wetted perimeter of the cross-section (m)
q''	Heat flux (KW/m^2)
R_{np}	Nanoparticle radius (nm)
Re	Reynolds number
T	Temperature (K)
u	Flow velocity component (m/s)
$\bar{u}$	Velocity correction (m/s)
$\acute{u}$	Fluctuated velocity (m/s)
u^*	Initial guessed velocity (m/s)
u_m	Mean velocity (m/s)
V	Velocity (m/s)
w	Rib width (m)
x	Coordinate direction
y^+	Dimensionless distance from the cell center to the nearest wall

Greek symbols

K	Boltzmann constant
ρ	Density (kg/m^3)
μ	Dynamic viscosity (Ns/m^2)
ε	Turbulent dissipation rate (m^2/s^3)
β	Fraction of the liquid volume which travels with a particle
$\varnothing$	Noparticle volume fraction
τ	Shear stress (kg/m^2)

Subscript

av	Average
bf	Base fluid
eff	Effective
in	Inlet
m	Mean
nf	Nanofluid
np	Nanoparticle
s	Smooth channel
t	Turbulent
w	Wall

results, the highest heat transfer rate was around 440% for in-line wedge rib pointing downstream. Thianpong et al. [7] experimentally investigated the turbulent heat transfer and friction loss behavior of airflow through a channel fitted with different heights of isosceles triangular ribs. Two rib arrangements, namely, in-line and staggered arrays, were used. The results showed that the use of non-uniform rib height was an inefficient heat transfer enhancement method compared to the uniform rib height method. The staggered triangular rib with $e/H = 0.13$ had higher thermal performance. Jansangsuk et al. [8] experimentally studied the heat transfer and pressure drop in a channel with periodic triangular V-ribs. The ribs were tested by pointing downstream to the flow direction. A uniform heat flux was applied to the upper plate of channel and air was used as the working fluid with Reynolds number between 5000 and 20000. In the case of $e/H = 0.20$, PR = 3, the thermal enhancement factor was higher in comparison with the other cases, due to lower friction loss.

Eiamsa-ard and Promvonge [9] investigated the air turbulent forced convection heat transfer in a 2-D channel flow over periodic transverse grooves numerically. The grooves were on the lower channel wall subjected to a constant heat flux condition while the upper wall was insulated. The analysis showed that the groove-widths to channel-height ratio of $B/H = 0.75$ has thermal enhancement factor of about 1.33. Eiamsa-ard and Promvonge [10] carried out an experimental study to examine the combined effects of rib-grooved turbulators on the turbulent forced convection heat transfer and friction characteristics in a rectangular channel under a uniform heat flux boundary condition. It was reported that for the TR–TG, the enhancement index has the highest value and reduces with increasing Reynolds number. Turbulent flow in a channel with transverse square rib roughness on one wall was studied by Cui et al. [11]. Rib roughness was divided into d-type (with a pitch ratio of 1), intermediate (with a pitch ratio of 4), and k-type (with a pitch ratio of 9) based on their spacing. For intermediate and k-type roughness, strong dependency on roughness height has been seen. Chaube et al. [12] analyzed the heat transfer and flow characteristics in a high aspect ratio (7.5) rectangular duct of a solar air heater which was mounted with ribs on the lower wall. The study was conducted for different geometric rib shapes (rectangular, chamfered, semicircular, and circular). The results showed that chamfered ribs had the highest Nusselt number but rectangular rib of size 3×5 mm had the best performance index.

Apart from geometric parameters of a roughened channel, working fluid plays a significant role on the heat transfer enhancement. Nanofluids are a colloidal mixture of nanoparticles smaller than 100 nm, a term proposed by Choi [13]. Water, oil, and ethylene glycol are conventional heat transfer fluids used for cooling of thermal systems. Nanofluids have superior thermophysical properties compared to those of base fluids [14]. First, Maxwell proposed a theoretical work which showed the possibility of enhancing thermal conductivity of liquids by mixing micron-sized solid particles [15]. However, problems such as rapid sedimentation, erosion, clogging, and high-pressure drop caused by these particles have kept the technology far from practical use.

Nanofluids have valuable applications in the area of heating buildings through hydronic coils, cooling automotive engines through radiators and in heat exchangers in all types of industries. In all these applications, the fluid flow is generally in the turbulent regime, because higher heat transfer is achieved through turbulent flow.

Several studies [16,17] revealed the great thermal transport characteristics of nanofluids in heat exchangers. Salman et al. [18] conducted a numerical study of fluid flow and heat transfer characteristics in a two-dimensional microtube to examine the effects of using different types of nanoparticles including Al_2O_3, CuO, SiO_2, and ZnO which are suspended in pure ethylene glycol (EG) as a base fluid. The results were presented for the Reynolds number range of 10–1500, nanoparticle concentration of 0–4%, and nanoparticle diameter of 25–85 nm. Throughout this study, it was found that using EG–SiO_2 as the working fluid with volume