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Numerical simulation and optimization of turbulent nanofluids in a three-dimensional rectangular rib-grooved channel☆

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ABSTRACT

In this study, numerical simulations by single and two-phase models of nanofluids turbulent forced convection in a three-dimensional rectangular rib-grooved channel with constant wall temperature are investigated. The elliptical, coupled, steady-state, three-dimensional governing partial differential equations for turbulent forced convection of nanofluids are solved numerically using the finite volume approach. The standard $k-\varepsilon$ turbulence model is applied to solve the turbulent governing equations. The interactive influences of rectangular rib-groove geometrical ratios and nanofluid volume concentration on the average Nusselt number are provided in this study. The average Nusselt number of rib-grooved channel is found to improve more with smaller rib-grooved height ratios, and some ratios of rib-grooved pitch. Furthermore, the numerical results of the single and two-phase models show that there are some differences in simulated flow filed and turbulent convective heat transfer characteristics.

In addition, the optimization of this problem is also presented by using the response surface methodology (RSM) and the genetic algorithm method (GA). The objective function E defined as the performance factor has developed a correlation function with four design parameters. It is found that the objective function E is better at Re = 10,000, and rectangular rib-grooved has an 18.2% enhancement.

1. Introduction

Rib/groove is one of the commonly used passive heat transfer enhancement techniques in single-phase internal flows in a channel solar air heater by placing the rib/groove periodically in the absorber plate. For decades, several engineering techniques have been developed for enhancing the convective heat transfer rate from the channel surface. The turbulators used for the cooling/heating channel or channel solar air heater such as ribs [1], fins [2,3], grooves [4,5] or baffles [6,7] are often encountered in order to increase the convective heat transfer coefficients leading to the compact heat exchanger and increasing the efficiency. The reason of this may be that the use of ribs/grooves completely makes the change of the flow field and thus the distribution of the local heat transfer coefficient. The application of rib-groove into the channel is to provide an interruption of boundary layer development, to increase the heat transfer surface area and to cause the enhancement of heat transfer by increasing turbulence intensity or fast fluid mixing. Therefore, more compact and economic heat exchanger with lower operation costs can be obtained. In general, the geometry parameters of ribs in the channel are among the most important factor in the design of channel heat exchangers which have an effect on both local and overall heat transfer coefficients. In particular, the angled rib, rib blockage ratio (BR = b/H), rib pitch ratio (PR) and rib arrangement are all parameters that influence both the heat transfer coefficient and the overall thermal performance. Several studies have been carried out to investigate the effect of these parameters of ribs on heat transfer and friction loss for two opposite roughened surfaces. Promvonge et al. [8] examined numerically the laminar heat transfer enhancement in a square channel with 45° inclined baffle on one wall and reported that a single stream-wise vortex flow occurs throughout the channel and helps to induce impingement jets on the upper, lower and side walls. Again, Promvonge et al. [9,10] also investigated numerically the laminar flow structure and thermal behaviors in a square channel with 30° or 45° inline baffles on two opposite walls. They found that two stream-wise counter-rotating vortex flows appear along the channel and vortex-induced impinging jets occur on the upper, lower and side walls.

High thermal performance is an important research issue in recent years. The nanofluids compared to the base fluid have better heat transfer, and many researchers have studied nanofluids including experiments and simulations. However, no studies have developed a comprehensive and universal numerical model to investigate the heat transfer effect of nanofluids. Most prior studies assume nanofluids as a single phase flow which is much easier and faster, while the accuracy

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Nomenclature

List of symbols

a	acceleration (m/s^2)
A	bottom area of the heating zone (mm^2)
b	rib-grooved width (mm)
C_1, C_2, C_μ, σ_k, σ_ε	closure coefficients
C_p	specific heat of constant pressure (J/kg K)
d_p	particle diameter (mm)
D_h	hydraulic diameter (mm)
e	rib-grooved height (mm)
E	performance factor
f_{drag}	drag function
g	acceleration of gravity (m/s^2)
G	generation of turbulent kinetic energy (kg/ms^3)
h	enthalpy (J/kg)
H	channel height (mm)
$\overline{h}$	average convection heat transfer coefficient (W/m K)
I	turbulent intensity
k	conduction heat transfer coefficient (W/m K)
k	turbulent kinetic energy (m^2/s^2)
L_1	inlet length (mm)
L_2	length of the heating zone (mm)
L	total length (mm)
$\overline{Nu}$	average Nusselt number
p	rib-grooved pitch (mm)
p	pressure (Pa)
q''	heat flux (W/m^2)
Re	Reynolds number
T	temperature (K)
V_{dr}	drift velocity (m/s)
V_{pf}	relative velocity (m/s)
u, v, w	velocity component (m/s)
V, v	time-mean and fluctuating velocity (m/s)
x, y, z	Cartesian x, y, z-coordinate (mm)

Greek symbols

ρ	density of the fluid (kg/m^3)
μ	dynamic viscosity ($N\ s/m^2$)
ν	kinematic viscosity (m^2/s)
ε	turbulent kinetic dissipation (m^2/s^3)
τ	wall shear stress (Pa)
ϕ	nanoparticle volume concentration

Subscripts

0	smooth channel
bf	base fluid
eff	effective
f	fluid
in	inlet
m	mean
nf	nanofluid
p	particle
w	wall

is low in terms of the results of simulation compared to the experimental data, due to a lack of consideration of nanofluid microscopic phenomena. Therefore, many scholars use the two-phase model to simulate nanofluids to improve the accuracy of simulations. Nanofluids were first used by Choi [11] at the Argon national laboratory. Easterman et al. [12] reported that with low nanoparticle concentrations (1–5 vol.%), the effective thermal conductivity of the suspensions can increase by more than 20% for various mixtures. Lee et al. [13] measured four kinds of nanofluids (CuO/water, Cuo/EG, Al_2O_3/water, Al_2O_3/EG), and showed Cuo/EG increases 20% heat transfer by 4% solid volume fraction. At a low solid volume fraction ($\phi < 5\%$), the thermal conductivity increased linearly with increasing solid volume fraction and the thermal conductivity was also found to be increased with decreasing particle size. Experimental results of Xie et al. [14] show that using the deionized water, ethylene glycol (EG), and pump oil as the base fluid, the heat transfer increased significantly after adding a few nanoparticles (Al_2O_3).

Xuan and Li [15] explored the heat transfer phenomenon of nanofluid (CuO/water) flowing through a pipe with constant heat flux wall, and the Reynolds number ranges from 10,000 to 25,000. Their experimental results showed that nanofluid has a higher heat transfer coefficient than pure water while the nanoparticle concentration is less than 2%. Experiments were conducted to investigate the cooling performance of a microchannel with Al_2O_3/water nanofluid [16], and the results showed the nanofluid-cooled heat sink performed by examining the heat transfer rate and the pressure drop. Murshed et al. [17] found that the heat transfer effects would be enhanced with the increase of volume concentration of TiO_2. Yoo et al. [18] discussed four kinds of nanofluids (TiO_2/water, Al_2O_3/water, Fe/EG, WO3/EG), the results displayed that the thermal conductivity of nanofluids is much better than that of pure water, but they also found that the surface-to-volume ratio was an important factor influencing the thermal conductivity coefficient of nanofluids.

Vajjha and Das [19] experimentally determined the thermal conductivity of three nanofluids (CuO, Al_2O_3, ZnO) and developed new corrections. Maiga et al. [20] showed that heat transfer effect of γ-Al_2O_3/EG is better than γ-Al_2O_3/water. Izadi et al. [21] numerically studied the laminar forced convection of Al_2O_3/water nanofluids in an annulus using a single phase approach, and found that temperature profiles were affected by the particle concentration. Also, a convective heat transfer coefficient increased with the nanoparticle concentration, and the friction coefficient was dependent on the nanoparticle concentration. Heat transfer enhancement due to flows of copper–water nanofluid through a two-dimensional rectangular duct has been studied by Santra et al. [22]. The results showed that there is a little effect of nanoparticles on the flow structure but the isotherms changed and it moved toward the centerline of the channel with an increase in solid volume fraction. The turbulent forced convection flow of a water/Al_2O_3 nanofluid in a square tube subject to constant and uniform wall heat flux was numerically investigated by Vincenzo et al. [23]. Heat transfer enhancement increased with the particle volume concentration, but it was accompanied by increasing wall shear stress values. The optimal Reynolds number was analytically determined and it decreased as particles' concentration increased.

Three kinds of nanofluids (Cu/water, Al_2O_3/water and CuO/water) in the two-dimensional wavy channel were numerically studied by Yang et al. [24]. The results showed that the heat transfer could be improved when using nanofluids. The genetic algorithm for multi-objective optimization was performed to obtain the optimal solutions. Akbari et al. [25] compared the CFD predictions of laminar mixed convection of Al_2O_3/water nanofluids by single phase and three different two-phase models (volume of fluid, mixture, Eulerian). They found that single-phase and two-phase models predicted almost identical hydrodynamic fields but very different thermal ones. The predictions of the three two-phase models were essentially the same. At low volume fractions, comparing with the experimental data, the results simulated by the two phase model were more precious than the single phase model.

In the present study, a numerical approach based on the finite difference method is applied to simulate the turbulent flow of Al_2O_3/water nanofluid in a rib-grooved channel. The main purpose of this study is to optimize the geometries of the forced convective heat transfer in a rib-grooved channel. Effects of volume concentration, rectangular rib-grooved height ratios, rectangular rib-grooved width ratios, rectangular rib-grooved pitch ratios on the fluid flow and heat transfer characteristics are studied and presented. In addition, the optimization of this