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Effect of nanoparticle shapes on the heat transfer enhancement in a wavy channel with different phase shifts

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ABSTRACT

A numerical investigation is performed to study the effects of different nanofluids on the thermal and flow fields through transversely wavy wall channels with different phase shifts between the upper and lower wavy walls. Reynolds numbers are considered in the turbulent range of $6000 \leq Re \leq 18{,}000$ and a uniform wall temperature of 400 K is applied on the walls. The two dimensional continuity, Navier–Stokes and energy equations are solved by using finite volume method (FVM). The optimization was carried out by using various phase shifts ($\theta = 0°$, 30°, 60°, 90° and 180°) and three different wavy amplitudes ($\alpha = 0.5$, 1 and 1.5 mm) to reach the optimal geometry with the maximum performance evaluation criterion (PEC). The main aim of this study is to analyze the effects of SiO_2 nanoparticles, its concentration (1–4%), and nanoparticle shapes (i.e. blades, platelets, cylindrical, bricks, and spherical), on the heat transfer and fluid flow characteristics. Simulation results show that the wavy channel performance was greatly influenced by changing the phase shift and the wavy amplitude. The highest PEC was obtained for the phase shift of $\theta = 30°$ with $\alpha = 0.5$ at $Re = 6000$. It is found that the SiO_2-EG nanofluid with platelets nanoparticle shape gives the highest heat transfer enhancement compared with other tested nanofluids.

1. Introduction

In the recent years, the issue of heat transfer enhancement has received substantial attention in thermal devices. In order to have more efficient and cost-effective heat exchangers, several approaches have been investigated over years. Employing ribs or grooves on the inner surface of the heat exchangers has been one of the frequent 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 the heat transfer. The main aim of the current research is to find the technique which has the lowest pressure drop and highest heat transfer rate. It is found that the wavy channel can be used in compact heat exchanging devices to improve the thermal–hydraulic performance.

Some numerical and experimental studies on the fluid flow and heat transfer in the wavy channels have been investigated by many authors. Rush et al. [1] experimentally investigated the flow behavior and local heat transfer in sinusoidal wavy passages for laminar and transitional regions. It was seen that both Re number and the channel geometry have significant effects on the position of the onset of mixing and local heat transfer enhancement. Wang and Vanka [2] studied numerically convective heat transfer in periodic wavy passages. It was found that the flow remains steady for Reynolds numbers less than 180 after which a significant increase in heat transfer is observed, due to a transition to chaotic flow. Naphon [3] carried out a numerical study on turbulent air flow to examine the effect of wavy plate geometry configurations on the heat transfer and flow distributions. Higher heat transfer enhancement was observed on the sharp edge of the wavy plate.

A numerical investigation on turbulent forced convection flow in a wavy-wall channel was performed by Wang and Chen [4]. It was seen that as the wavy amplitude–wavelength ratio and the Reynolds number enhance, the local Nusselt number increases noticeably in the converging section of the channel. Alawadhi [5] presented a numerical research on forced convective air flow in a wavy channel. The walls of channel were kept at uniform temperature and the Reynolds numbers were considered from 125 to 1000. The results showed that linearly increasing waviness at the entrance region of channel decreases the pressure drop significantly and increases the average Nusselt number slightly. Ničeno and Nobile [6] numerically analyzed the hydrodynamic and heat transfer characteristics of two-dimensional steady and time-dependent laminar air flow in periodic wavy channels. It was observed that a significant heat transfer occurs beyond the critical Reynolds number in unsteady regimes. Bahaidarah et al. [7] numerically conducted a two-dimensional study to assess fluid flow and heat transfer in a periodic wavy passage using finite-volume technique. In this study, sinusoidal and arc-shaped configurations were adopted. They found that the average Nusselt number increases with the increase in Reynolds number for both configurations.

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Nomenclature

C_f	skin friction coefficient
C_k	thermal conductivity ratio
C_μ	turbulence model constant
Cp	specific heat capacity, (J/kg.K)
D_h	hydraulic diameter, (m)
d_{np}	nanoparticles diameter, (nm)
d_f	equivalent diameter of a base fluid Molecule
f	friction factor
h	average heat transfer coefficient, $(W/m^2.K)$
H	height of the channel, (m)
k	thermal conductivity, $(W/m.K)$
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)
Pr	Prandtl number
ΔP	pressure drop, (N/m^2)
r	surface geometry function
Re	Reynolds number
T	temperature, (K)
u	flow velocity component, (m/s)
u'	fluctuated velocity, (m/s)
x	axial direction

Greek symbols

α	wavy amplitude, (m)
β	fraction of the liquid volume which travels with a particle
Γ	molecular thermal diffusivity
Γ_t	turbulent thermal diffusivity
ε	turbulent dissipation rate, (m^2/s^3)
θ	phase shift, (degrees)
K	Boltzmann constant
λ	wavelength of the wavy wall, (m)
μ	dynamic viscosity, (Ns/m^2)
ρ	density, (kg/m^3)
τ	shear stress, (kg/m^2)
$\varnothing$	nanoparticles volume fraction

Subscript

av	average
bf	base fluid
eff	effective
i, j	components
in	inlet
m	mean
nf	nanofluid
np	nanoparticle
t	turbulent
w	wall

Yin et al. [8] studied numerically the thermal-hydraulic characteristics of air in corrugated sinusoidal wavy channels for different phase shifts between the upper and lower wavy walls. It was observed that as the phase shift increases, the friction factor and Nusselt number decrease. The optimal performance resulted in lower Reynolds number region for the channel of phase shift $\varphi = 0°$. A three-dimensional numerical simulation on laminar water flow and heat transfer in wavy microchannels was carried out by Sui et al. [9]. According to the results, utilizing wavy microchannels has better heat transfer performance and smaller pressure drop penalty as compared with straight baseline microchannels. Assato and de Lemos [10] investigated numerically the performance of linear and nonlinear eddy-viscosity models to foresee the turbulent flow in periodically sinusoidal-wave channels. It was concluded that using nonlinear models and high Reynolds wall treatment is more stable and easier to be obtained, even with coarser grids and greater relaxation parameters.

Nanofluids are colloidal mixture of nanoparticles smaller than 100 nm, a term proposed by Choi [11]. 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 [12]. Firstly, Maxwell has proposed a theoretical work that showed the possibility of enhancing the thermal conductivity of liquids by mixing micron-sized solid particles [13]. However, due to the problems of rapid sedimentation, erosion, clogging and high-pressure drop caused by these particles, his theory was kept far from practical use. Compared to the existing techniques for enhancing heat transfer, the nanofluids show a superior potential for increasing heat transfer rates in heat exchangers. Several studies [14–23] revealed the great thermal transport characteristics of nanofluids.

Mohammed et al. [24] numerically examined the heat transfer and laminar water flow characteristics in wavy microchannel heat sink (MCHS) with various wavy amplitudes using finite-volume method. They found that the wavy microchannels have much better heat transfer performance and much smaller pressure drop penalty in comparison with conventional straight microchannels. Furthermore, the heat transfer coefficient, wall shear stress, pressure drop and friction factor increase across the wavy MCHS with the increase of wavy amplitude. The effect of forced convective copper–water nanofluid on heat transfer and flow field in heated sinusoidal-wall channel was numerically investigated by Heidary and Kermani [25]. It was concluded that using both nanofluid and wavy horizontal walls can enhance the heat transfer by 50%.

Different types of nanoparticles such as ZnO, Al_2O_3 and SiO_2 with different base fluids, higher volume fractions and smaller nanoparticles size, have been found to increase the overall heat transfer rate [26]. Hence, only SiO_2–water nanofluid with volume fraction in the range of 0–4% and $d_{np} = 25$ nm, is considered for the first objective of this study. It can be noticed from the previous literature review that there are no numerical studies on turbulent convective flow in a wavy channel with different phase shifts between the upper and lower walls using nanofluid.

In most of the aforesaid numerical studies, spherical nanoparticle shape has been considered to analyze the effect of utilizing nanofluids on heat transfer augmentation in corrugated channels. According to the recent research [27–31], nanoparticles can have different shapes. The nanoparticle shape may have considerable effect on the effective viscosity and thermal conductivity of the nanofluids, which in turn, may influence the rate of heat transfer enhancement. Therefore, investigating the role of different nanoparticle shapes (i.e. blades, platelets, cylindrical, bricks, and spherical) on the thermal and hydraulic characteristics of 2D turbulent forced convective nanofluids flow is the second objective of the present study. To examine this objective, ethylene glycol (EG) with a concentration of 4% is considered as a base fluid.

Results of interests such as Nusselt number, friction factor coefficient, skin friction coefficient, performance evaluation criterion and pressure drop for turbulent forced convective in a wavy channel are reported to illustrate the effects of wavy channel amplitude, phase shifts and nanoparticle shape on these parameters.