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Numerical optimization of heat transfer enhancement in a wavy channel using nanofluids ☆

Yue-Tzu Yang, Yi-Hsien Wang *, Po-Kai Tseng

Department of Mechanical Engineering, National Cheng Kung University, Tainan 70101, Taiwan

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ABSTRACT

In this study, a multi-parameter constrained optimization procedure integrating the design of experiments (DOE), full factorial experimental design (FFED), genetic algorithm (GA) and computational fluid dynamics (CFD) is proposed to design two-dimensional wavy channel with nanofluids (Cu/water, Al_2O_3/water and CuO/water). The elliptical, coupled, steady-state, two-dimensional governing partial differential equations for laminar forced convection of nanofluids are solved numerically using the finite volume approach. Some important parameters for the influences of heat transfer enhancement such as the Reynolds number ($250 \leqq Re \leqq 1000$), the particle volume concentration ($0\% \leqq \phi \leqq 5\%$), the wavy channel amplitude ($0.1 \leqq \alpha \leqq 0.3$) and the wavy numbers ($3 \leqq \beta \leqq 12$) on the enhancement of nanofluid heat transfer have been investigated.

The numerical results with a single-phase model are first validated with the available data in the literature. The maximum discrepancy is within 8%. Results of a further extension to a two phase model are also validated. The numerical results indicate that the thermal enhancement can achieve 15%, 24% in the wavy channel flow compared with pure fluid, with the particle volume concentration of $\phi = 3\%$ and $\phi = 5\%$ of Cu/water nanofluids. In addition, after the validation of the numerical results, the numerical optimization of this problem is also presented by using a full factorial experimental design and the genetic algorithm (GA) method. The objective function E which is defined as thermal performance factor has developed a correlation function with three design parameters. The predicting performance factor E ($\alpha = 0.278, \beta = 3, \phi = 5\%$) of regression function is closely agreed with those from the CFD computational results within 4.6% difference. The combination of parameters is considered as the optimal solution.

1. Introduction

Nanotechnology is considered by many researchers to be one of the significant forces that drive the next major industrial revolution of this century. A significant research effort has been committed to exploring the thermal transport properties of colloidal suspensions of nanosized solid particles (nanofluids). The presence of the nanoparticles in the fluids increased appreciably the effective thermal conductivity of the fluid and consequently enhanced the heat transfer characteristics. Nanofluids have a distinctive characteristic which is quite different from those of traditional solid–liquid mixtures in which milli-meter or micro-meter sized particles are involved. Thus, nanofluids are best for applications in which fluid flows through small passages because nanoparticles are small enough to behave similar to liquid molecules. The application of nanofluids is not confined to heat transfer purpose. The numerous applications include tribology, chemistry, environmental areas, coating and medical applications or even in fuel cells.

Nanofluids were first used by Choi [1] at the Argon national laboratory. Several researches [2,3] have presented that with low (1–5% by volume) nano-particle concentrations, the thermal conductivity can be increased by about 20%. Xuan et al. [4] experimentally obtained thermal conductivity of copper-water nanofluid up to 7.5% of solid volume fraction. Experiments were conducted to investigate the cooling performance of a microchannel with Al_2O_3/water nanofluid [5], and the results showed the nanofluid-cooled heat sink outperformed the water-cooled one by examining the heat transfer rate and the pressure drop. Interesting contributions on the use of nanofluids were presented by Pantzali et al. [6,7]. They found that the considered nanofluids (CuO/water) could be used as potential substitutes for conventional coolants in a micro-scale equipment in laminar flow conditions, while in some application the use would be somewhat compromised because of increased viscosity. It was noted that the type of flow conditions inside a heat exchanging device is an important factor to evaluate the performance of the nanofluid as a working fluid. Hojjat et al. [8] experimentally investigated the forced convection heat transfer under laminar flow conditions for three types of nanofluids in a circular tube with constant wall temperature. It was found that the increase in convective heat transfer is higher than the increase caused by the augmentation of the effective thermal conductivity.

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* Corresponding author.
E-mail addresses: ytyang@mail.ncku.edu.tw (Y.-T. Yang), eshangw@hotmail.com (Y.-H. Wang).

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Nomenclature

List of Symbols

A	wave amplitude (mm)
C_p	specific heat (J/kg·K)
C_f	Friction coefficient
D_h	hydraulic diameter (mm)
f_{drag}	drag function
k	thermal conductivity (W/m·K)
L_h	channel height (mm)
L_w	wavelength of the wavy channel (mm)
Nu	average Nusselt number
Nu_o	Nusselt number of the smooth channel
P	static pressure (Pa)
ΔP_o	pressure drop of the smooth channel (Pa)
ΔP	pressure drop (Pa)
E	performance factor
Re	Reynolds number ($Re = u_{in}D_h/\nu$)
S	the curved length of bottom wall
T	temperature (K)
T_{in}	inlet temperature (K)
V	velocity component (m/s)
u_{in}	inlet velocity (m/s)
x	Cartesian *x*-coordinate (mm)
y	Cartesian *y*-coordinate (mm)

Greek symbols

α	channel aspect ratio ($\alpha = A/L_h$)
β	wave numbers
ρ	density of the working fluid (kg/m^3)
μ	dynamic viscosity ($N\cdot S/m^2$)
ν	kinematic viscosity (m^2/s)
ϕ	volume fraction

Subscripts

dr	drift
eff	effective
f	base fluid
m	mixture
nf	nanofluid
p	solid particle
w	wall

Santra et al. [9] reported that heat transfer due to laminar flow of copper-water nanofluid through a two-dimensional channel with constant temperature walls. They conclude that the rate of heat transfer increases with the increase in flow of the Reynolds number as well as the increase in solid volume fraction of the nanofluid. Izadi et al. [10] 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 are affected by the particle concentration. Also, a convective heat transfer coefficient increases with nanoparticle concentration. However, when the order of magnitude of heating energy is much higher than the momentum energy, the friction coefficient depends on the nanoparticle concentration. Forced convection flow of Al_2O_3/water nanofluid in a radial flow cooling system was simulated in the studies [11,12]. Results showed that the Nusselt number increases with the increase of Reynolds number and nanoparticle volume fraction, though the increase in pressure drop is more significant with the increase of particle concentration. Besides, under a fixed pumping power the nanofluid exhibited no higher heat transfer rate than water at lower values of heat flux, while the enhancement using a nanofluid becomes more remarkable as the heat flux increases. Conjugate heat transfer approach was used to numerically study the laminar forced convective heat transfer characteristics of Al_2O_3/H_2O nanofluid flowing in a silicon microchannel heat sink of rectangular cross-section using thermal dispersion model [13]. Results indicated that the use of nanofluid improves MCHS performance by reducing fin (conductive) thermal resistance. In the study of Ho et al. [14], significant difference in the effective dynamic viscosity enhancement of the nanofluid calculated from different formulas, other than that in the thermal conductivity enhancement, was found to play as a major factor which leads to contradictory results concerning the heat transfer efficacy of using nanofluid in the enclosure. Ghasemi and Aminossadati [15] numerically studied the problem of natural convection heat transfer in an inclined enclosure filled with a CuO/water nanofluid. The enclosure filled with the nanofluid is associated with higher velocities compared to the enclosure with pure water. Moreover, for high Rayleigh numbers, there is an optimum value for the solid volume fraction which maximizes the heat transfer enhancement. Abu Nada et al. [16] investigated the heat transfer enhancement in a differentially heated enclosure using variable thermal conductivity and variable viscosity of Al_2O_3/water nanofluids. The results demonstrated that the average Nusselt number of Al_2O_3/water nanofluid at high Rayleigh numbers is reduced by increasing the volume fraction of nanoparticles above 5%, while at low Rayleigh numbers it is slightly enhanced by increasing the volume fraction of nanoparticles. It was also found that at high Rayleigh numbers the average Nusselt number is more sensitive to the viscosity models than to the thermal conductivity models. The periodic natural convection in an enclosure filled with nanofluids was examined [17]. A periodic behavior was found for the flow and thermal fields as a result of the oscillating heat flux, and the utilization of nanoparticles, in particular Cu, enhances the heat transfer especially at low Rayleigh numbers. Kahveci [18] numerically studied the heat transfer enhancement of water-based nanofluids in a differentially heated, tilted enclosure for a range of inclination angles, nanoparticle radii, solid volume fractions, and Rayleigh numbers. It was concluded from the results that suspended nanoparticles substantially increase the heat transfer rate and the average Nusselt number is nearly linear with the increase of solid volume fraction. Ho et al. [19] conducted experiments to examine the natural convection heat transfer of a nanofluid in vertical square enclosures, and the results showed systematic heat transfer degradation for the nanofluids containing nanoparticles of volume fraction higher than 2%. However, for the nanofluid containing much lower particle fraction of 0.1 vol.%, a heat transfer enhancement of around 18% compared with that of water was found. Angue Mintsa et al. [20] examined the effective thermal conductivity of alumina-water and copper oxide-water nanofluids, and the relative increase in thermal conductivity was observed to be more important at higher temperatures.

Xuan and Roetzel [21] analyzed nanofluids with the dispersion model and derived correlations for predicting the Nusselt number based on the assumption that the nanofluid behaves more like a fluid rather than a conventional solid–fluid mixture. The heat transfer and viscous pressure loss characteristics of alumina-water and zirconia-water nanofluids in laminar flow regime were studied experimentally [22]. The heat transfer coefficients in the entrance region and in the fully developed region were found to increase by 17% and 27%, respectively, for alumina-water nanofluid at 6 vol.% with respect to pure water. The zirconia-water nanofluid heat transfer coefficient increases by approximately 2% in the entrance region and 3% in the fully developed region at 1.32 vol.%. The results showed that both the measured nanofluid heat transfer coefficient and pressure loss agree with the traditional model predictions for laminar flow. This suggested that the nanofluids behave as homogeneous mixtures.

Laminar copper-water nanofluid flow and heat transfer in a two-dimensional wavy wall channel are numerically investigated in Ahmed et al. [23]. They show that the friction coefficient and the Nusselt

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