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Heat transfer augmentation in the straight channel by using nanofluids

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ABSTRACT

Heat transfer enhancement of nanofluids under turbulent flow through a straight square channel under constant heat flux conditions at the upper and lower walls is studied numerically. The nanofluids are prepared as solid nanoparticles of CuO, TiO_2 and Al_2O_3 suspended in water. CFD analysis by FLUENT software using the finite volume method is conducted. The boundary conditions are applied under a heat flux of 5000 W/m^2, Reynolds numbers of 10^4–10^6 and a constant volume concentration of 1–4%. The results show that the heat transfer rates and wall shear stress increase with an increase of the nanofluids' volume concentration. It seems that the CuO nanofluid significantly enhances heat transfer. The results show good agreement with results of other researchers by a 10% deviation.

1. Introduction

Many applications of heat transfer enhancement using nanofluids to get the cooling challenge necessary such as the photonics, transportation, electronics, and energy supply industries [1–4]. Hussein et al. [5] studied the effect of the SiO_2 nanofluid on an automotive cooling system. Both experiments and simulations by FLUENT software have been adopted. Results showed significant enhancement of the heat transfer with the nanofluids and agreed with the available literature data. Bahiraei et al. [6] examined the effect of temperature and volume fraction on the viscosity of TiO_2–water nanofluid. The results were recorded and analyzed within the temperature range of 25–70 °C and the volume fractions 0.1%, 0.4%, 0.7% and 1%. The viscosity of two different materials, single wall carbon nanohorn (SWCNH) and titanium dioxide (TiO_2), suspended in water was measured experimentally by Bobbo et al. [7]. Empirical correlation equations of viscosity against nanofluid volume fraction have been developed. The forced convection turbulent flow of Al_2O_3–water nanofluid inside an annular tube with variable wall temperatures was investigated experimentally by Prajapati et al. [8]. The results showed that the heat transfer was enhanced due to the nanoparticles dispersed in the fluid. Horizontal double-tube heat exchanger counter turbulent flow was studied numerically by Bozorgan et al. [9]. Al_2O_3–water nanofluid of 7 nm with volume concentration up to 2% was selected as the coolant fluid. The results showed that the pressure drop of the nanofluid is slightly higher than water and increases with the increase of volume concentrations. A double tube coaxial heat exchanger heated by solar energy using aluminum oxide nanofluid was presented experimentally and numerically by Luciu et al. [10]. The results showed that nanofluids have a higher performance of heat transfer than base fluids. The turbulent flow of (CuO, Al_2O_3 and TiO_2) nanofluids with different volume concentrations flowing through a two-dimensional duct under constant heat flux conditions has been analyzed numerically by Rostamani et al. [11].

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Nomenclature

C	specific heat [W/kg °C]
D	diameter [m]
E	energy [W]
f	friction factor
htc	convection heat transfer coefficient [W/m^2 °C]
k	thermal conductivity [W/m °C]
Nu	Nusselt number [$htc\,D/K_{nf}$]
P	pressure [N/m^2]
Pr	Prandtl number [$C\mu/K_{nf}$]
Re	Reynolds number [$\rho_{nf}D_h u/K_{nf}$]
u	velocity [m/s]
μ	viscosity [N s/m^2]
ρ	density [kg/m^3]
τ	shear stress [N/m^2]
ϕ	volume concentration

Subscripts

f	liquid phases
p	solid particle
nf	nanofluid
h	hydraulic

In this study, heat transfer enhancement in a straight square channel is carried out. This work contributed to the knowledge of heat transfer enhancement for many industrial applications. CFD analysis by FLUENT software using the finite volume method is adopted. The heat flux, Reynolds numbers and volume concentration are 5000 W/m^2, 10^4–10^6 and 1–4%, respectively. Three types of nanofluids (Al_2O_3, TiO_2 and CuO) dispersed in water are utilized. The results are compared with experimental data available in the literature to be validated.

2. Thermal properties

The density (ρ_{nf}), specific heat capacity (C_{nf}), thermal conductivity (k_{nf}) and viscosity (μ_{nf}) of the nanofluid are obtained by the corresponding relations [12]

$$\rho_{nf} = \left(\frac{\phi}{100}\right)\rho_p + \left(1-\frac{\phi}{100}\right)\rho_f \tag{1}$$

$$C_{nf} = \frac{\frac{\phi}{100}(\rho C)_p + \left(1-\frac{\phi}{100}\right)(\rho C)_f}{\rho_{nf}} \tag{2}$$

$$k_r = \frac{k_{nf}}{k_f} = 0.8938\left(1+\frac{\phi}{100}\right)^{1.37}\left(1+\frac{T_{nf}}{70}\right)^{0.2777}\left(1+\frac{d_p}{150}\right)^{-0.0336}\left(\frac{\alpha_p}{\alpha_f}\right)^{0.01737} \tag{3}$$

$$\mu_r = \frac{\mu_{nf}}{\mu_f} = \left(1+\frac{\phi}{100}\right)^{11.3}\left(1+\frac{T_{nf}}{70}\right)^{-0.038}\left(1+\frac{d_p}{170}\right)^{-0.061} \tag{4}$$

The assumption of the problem undertaken is that the nanofluid behaves as a Newtonian fluid for a concentration of less than 4.0%. For conditions of dynamic similarity for flow of the two media, nanoparticles and base liquid water, in the channel, the ratio of friction coefficients can be written as follows:

$$f_r = \frac{f_{nf}}{f_f} = \left[\frac{C2}{C3}\right]\frac{Re_f^m}{Re_{nf}^p} \tag{5}$$

For base fluid water [13]

$$f_f = \frac{0.316}{Re^{0.25}} \tag{6}$$

The system of governing criteria can be written as

$$f_r = \frac{f_{nf}}{f_f} = F\left[\frac{\rho_{nf}}{\rho_f}, \frac{\mu_{nf}}{\mu_f}\right] \tag{7}$$

The empirical correlation obtained from experimental data of a number of investigators [14–18] is

$$f_r = \frac{f_{nf}}{f_f} = 1.078\left[\left(\frac{\rho_{nf}}{\rho_f}\right)^{-0.514}\left(\frac{\mu_{nf}}{\mu_f}\right)^{-0.1248}\right] \tag{8}$$

Forced convection heat transfer coefficient under turbulent flow may be estimated by the Dittus–Boelter correlation (Eq. (9)) for pure water in the range of Reynolds number $1\times10^4 < Re < 1\times10^5$.

$$Nu = \frac{h_f}{k_f}D = 0.023\,Re^{0.8}\,Pr^{0.4} \tag{9}$$