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A new dispersion model for thermal properties of nanofluids in flat tubes

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ABSTRACT

In this paper, a new dispersion model has been presented and evaluated for the thermal properties of nanofluids in flat tubes. First, by using the results of a multi-objective optimization, which has been implemented by combining the CFD techniques and optimization methods, a new dispersion model is presented for thermal properties of nanofluid in flat tubes, which of course is applicable to circular tubes by setting the tube flattening to zero. This model is a complete function of the important parameters of nanofluid flow in flat tubes, which include the tube flattening, flow rate, volume fraction of nanoparticles and the diameter of nanoparticles. In the next step, the capability and performance of the introduced model is evaluated through the numerical simulations of the nanofluid flow in flat tubes using FORTRAN programming language. The obtained results indicate that the presented dispersion model has a high capability in predicting the thermal properties of different nanofluid flows in flat tubes.

1. Introduction

The use of nanofluids is one of the most effective mechanisms for increasing the amount of heat transfer in tubes. Nanofluid is a mixture created from adding nanoparticles, such as Al_2O_3 or CuO to a base fluid and it gives rise to increasing the mixture thermal conductivity as well as heat transfer in tubes. In recent years, many experimental and numerical studies have been done in the field of nanofluids [1–4]. Teng et al. [3] investigated the effects of various parameters such as nanoparticle size, temperature and weight fraction on the Al_2O_3-water nanofluid thermal conductivity in a series of experimental tests. At the end, they proposed a correlation indicating the nanofluid thermal conductivity as a function of mentioned parameters.

In addition to the expensive experimental studies, numerical ones are considered as the effective way to identify the thermal and hydrodynamics flow field in nanofluids. Normally, for the numerical simulation of nanofluid flows, there are two general approaches known as single phase and two phase method. Although, the two phase method (such as the mixture or Eulerian-Eulerian method) enjoys higher accuracies compared to the single phase method, they have longer computation times instead [5,6]. The homogeneous and the dispersion methods are two of the single phase approaches. In the homogeneous method, all the properties of the base fluid are replaced by the equivalent properties of the nanofluid. The homogeneous method usually has much error and its results are not as reliable [7]. On the other hand, the dispersion method, relative to the homogeneous approach, benefits from an extra mechanism for the increase in thermal properties, which improves its accuracy. By using an appropriate model in the dispersion method, in addition to have a shorter computation time (due to the use of a single phase model), a higher accuracy can also be achieved in the prediction of the nanofluid thermal field. Unfortunately, in recent years, very few models have been introduced to use the dispersion method for nanofluid flow, and these few models have been specifically developed for circular tubes [7–9]. In this paper, by using the results of a multi-objective optimization, which was performed by combining the CFD techniques and optimization methods [10], a new dispersion model is introduced and evaluated for the thermal properties of nanofluids in flat tubes, which is applicable to circular tubes as well by setting the tube flattening to zero.

Flat tubes, by having smaller and more useful cross sections relative to circular tubes, have a greater compactness and a higher heat transfer rate, which can make their utilization in heat exchangers very effective. In the field of using flat tubes in which the

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Nomenclature

a	acceleration (m s^{-2})
C	constant in Eq. (34)
C_d	dispersion coefficient
C_f	skin friction coefficient
C_p	specific heat (J kg^{-1} K^{-1})
d_p	diameter of nanoparticles (m)
g	gravitational acceleration (m s^{-2})
h	heat transfer coefficient (W m^{-2} K^{-1})
H	internal Height of Flat tube (mm)
k	thermal conductivity (W m^{-1} K^{-1})
k_B	boltzmann constant (=1.3807 × 10^{-23} J K^{-1})
Nu	nusselt number (=hD_h/k)
P	perimeter of flat tubes (mm)
Q	volumetric flow rate (m^3/hr)
q''	heat flux (W m^{-2})
Re	reynolds number (=VD_h/ν_m)
T	temperature (K)
V	velocity (m s^{-1})
W	width of flat tubes (mm)

Greek symbol

α	thermal diffusivity (=$k/\rho C_p$)
β	volumetric expansion coefficient (K^{-1})
δ	distance between particles (m)
ϕ	nanoparticles volume fraction
μ	dynamic viscosity (N s m^{-2})
ρ	density (kg m^{-3})
τ_w	wall shear stress (Pa)
ω	clustering ratio
η	coordinate in grid generation step
ζ	coordinate in grid generation step

Subscripts

d	dispersion
dr	drift
f	fluid
i	inlet conditions
m	mixture
p	nanoparticle phase
w	wall

nanofluids are flowing, very few studies have been conducted so far [11,12]. Razi et al. [11] considered CuO-Oil nanofluid experimentally in various flat tubes and finally presented some correlations for Nusselt number and pressure drop of nanofluid flow in horizontal flat tubes. Vajjha et al. [12] investigated nanofluid flow in a single flat tube of an automobile radiator using the single phase numerical method. They used convection heat transfer coefficient for the wall boundary condition and finally presented the correlation for local Nusselt number and friction factor of the automobile flat tube.

In this paper, by using the results of a multi-objective optimization, which was performed by combining the CFD techniques and optimization methods [10], a new dispersion model is introduced and evaluated for the thermal properties of nanofluids in flat tubes.

2. Presenting a new dispersion model for thermal properties of nanofluids

For mathematical modeling of dispersion model in the porous media, assume that irregular movements of ultrafine particles induce small perturbations of both the velocity and temperature of the nanofluid mixture, i.e., $\vec{u'}$ and T', respectively. Thus, the averages of each phase are given as [8]:

$$\vec{u} = \overline{\vec{u}} + \vec{u'} \tag{1}$$

$$T = \overline{T} + T' \tag{2}$$

where

$$\overline{\vec{u}} = \frac{1}{V_f}\int_{V_f} \vec{u}\, dV_f \tag{3}$$

$$\overline{T} = \frac{1}{V_f}\int_{V_f} T\, dV_f \tag{4}$$

It is obvious that the volumetric average of T' is zero.

$$\frac{1}{V_f}\int_{V_f} T'\, dV_f = 0 \tag{5}$$

Using the procedure described by some researchers [13,14] and by assuming that the boundary surfaces between the fluid and the particles are small that can be neglected, the energy equation is expressed as:

$$\frac{\partial \overline{T}}{\partial t} + \overline{\vec{u}}\cdot\nabla\overline{T} = \nabla\cdot\alpha_f\nabla\overline{T} - \nabla\left(\overline{u'T'}\right) \tag{6}$$

The second term in right hand side of Eq. (6) shows the thermal dispersion effects. Using turbulence theories, this term is expressed as:

$$\overline{u'T'} = -k_d\cdot\nabla\overline{T} \tag{7}$$

where k_d is the dispersed thermal conductivity. Thermal dispersion diffusivity (α_d) in porous media is dependent upon the following parameters [14]:

$$\frac{\alpha_d}{\alpha_f} = function\left(\mathrm{Re},\ \mathrm{Pr},\ \varepsilon,\ structure, \frac{k_s}{k_f}, \frac{(\rho C_P)_s}{(\rho C_P)_f}\right) \tag{8}$$

So far, very few researches have been conducted on the use of the dispersion method in nanofluids, and these few investigations have been confined to tubes with circular cross sections [7,8]. In this paper, a new dispersion model will be presented for the simulation of nanofluids flow in flat tubes. One of the first relations in the area of the dispersion method was presented by Xuan and Roetzel [8]. By applying the concepts of porous medium, they derived the conductivity coefficient of nanofluids in circular tubes by means of two separate relations, as follows:

$$k_d = C_d(\rho C_P)_{nf} uR \tag{9}$$

$$k_d = C_d(\rho C_P)_{nf} uRd_P\phi \tag{10}$$

One of the most complete relations for the calculation of the