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Analysis of single phase, discrete and mixture models, in predicting nanofluid transport

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ABSTRACT

A numerical investigation of developing forced convective heat transfer and pressure drop of nanofluid flow inside a tube subject to a constant wall heat flux boundary condition is presented. The single-phase homogenous and two different two-phase models: Lagrangian-Eulerian model or (discrete phase model) and mixture model are utilized with both constant and temperature dependent properties to further investigate and clarify the differences and evaluate the assumption of the single-phase model. The obtained results were subjected to an intensive comparison with the available experimental data and numerical works in the literature. The influence of some important parameters such as, source and sink terms, injected particle mass flow rate, slip velocity, particle forces, Reynolds number, constant or temperature dependent properties and particle concentration on the heat transfer and flow characteristics of nanofluids were determined and discussed in detail. It was observed that the two phase Lagrangian-Eulerian model (DPM) overestimated the heat transfer coefficient values and the results from the mixture model displayed an unrealistic increase in heat transfer particularly for high particle volume fraction. The proposed single phase approach revealed a very good agreement with the experimental data and the maximum difference in the average heat transfer coefficient between the single-phase and DPM was found to be 5.9% considering variable properties. The results also revealed that increasing the injected particle mass flow rate does not have a significant effect on the heat transfer coefficient values and that the particles move with the same velocity of the fluid. Furthermore, the heat transfer coefficient increases as the particle volume fraction and Reynolds number increases, but it is accompanied by a higher pressure drop and wall shear stress values. DPM model provides a reasonable prediction for the thermal behavior of the nanofluids transport, the single-phase approach with temperature dependent viscosity and thermal conductivity is an accurate way to analyze the transport of nanofluids while requiring less CPU usage and memory for predicting the enhancement in nanofluids convective heat transfer.

1. Introduction

Nanofluids have shown better heat transfer enhancement and energy saving over base fluids in thermal applications [1,2]. Typical nanofluids are mixture of conductive solid particles 1–100 nm in diameter suspended in a base fluid which can be used in several applications such as electronic cooling, heat exchangers, automotive and air conditioning. The thermal conductivity of the particle materials, such as Al_2O_3, CuO, Cu are typically several orders-of-magnitude higher than the base fluid. As such, even at low concentrations, they have shown significant increases in the heat transfer coefficient [2–6].

Numerical and experimental studies were carried out by many researchers to evaluate the effect of utilizing nanofluids as the working fluid to enhance the thermal performance. Some analytical and experimental results [4,7] show that using a nanofluid as the working fluid is an efficient method to reduce the thermal resistance and entropy generation in a heat pipe. Other experimental studies [8–11] have shown that nanofluids possess higher heat transfer characteristics than the base fluid particularly for small particle diameters. It has been observed [9] that the enhancement in the heat transfer coefficients in the developing region is higher than that in the developed region. However, classical correlations for pure fluids cannot properly estimate the enhancement in the forced convective heat transfer of nanofluids for both constant wall temperature and constant heat flux boundary conditions [12,13].

Numerical investigation of forced convective heat transfer for water-Al_2O_3 nanofluid inside a circular tube under constant wall

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Nomenclature

$\vec{a}$	particle's acceleration
C_p	specific heat transfer, J/kg K
cst.	constant properties
D	tube diameter, m
d	nanoparticle diameter, m
F	body force, N
g	gravitational acceleration, m/s^2
Gz	Graetz number, $VD^2/\alpha L$
H	total enthalpy, kJ/kg
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/mK
L	tube length, m
m	mass, kg
Nu	Nusselt number, hD/k
P	pressure, Pa
Pr	Prandtl number, $C_p\mu/k$
q	wall heat flux, W/m^2
r	radial coordinate, m
r_0	tube radius, m
Re	Reynolds number, $\rho VD/\mu$
S_m, S_e	source and sink terms
T	fluid temperature, K
T^*	dimensionless temperature, $(T - T_w)/(T_b - T_w)$
t	time, s
V	velocity vector, m/s
V_{dr}	drift velocity, m/s
δV	cell volume, m^3
var.	variable properties
z	axial coordinate, m

Greek letters

α	thermal diffusivity, m^2/s
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
Φ	particle volume fraction
τ	wall shear stress, Pa
k_B	Boltzmann constant, 1.3807×10^{-23} J/K
υ	kinematic viscosity, m^2/s

Subscripts

av	average
b	bulk mean
bf	base fluid
i	inlet
m	mixture
n	total number of particles
nf	nanofluid
p	nanoparticle
w	wall
0	reference to inlet condition

heat flux were presented by several investigators [14–16]. A new concept of combined/hybrid nanofluids based on CNTs + Al_2O_3, was introduced by Nuim Labib et al. [17]. They used two-phase mixture model to study forced convective heat transfer under constant wall heat flux. Their results showed that the combined mixture tends to enhance the convective heat transfer significantly because CNTs shows higher shear thinning behavior which results in a thinner boundary layer. In addition, using Ethylene Glycol as a base fluid instead of water appears to be more efficient in enhancing the heat transfer. Moghadassi et al. [18] investigated Al_2O_3/water and hybrid nanofluids with 0.1% volume concentration flowing inside a horizontal tube for steady state laminar region (*Re* < 2300). Khanafer et al. [19] presented a critical investigation to study the effect of nanoparticle addition, temperature and nanoparticle size-dependence on the specific heat capacity of both conventional and molten salt-based nanofluids. A general correlation for Al_2O_3-water nanofluids that takes into account the effect of temperature, volume fraction and nanoparticle size was developed and verified. Buongiorno [20] theoretically studied the effect of nanoparticle thermal dispersion on the energy transfer of nanofluids by considering seven slip mechanisms that can produce a relative velocity between the nanoparticles and the base fluid.

In our study, we investigate forced convective flow of nanofluids inside a circular tube under constant wall heat flux boundary condition. Ansys Fluent software [21] is used to solve the governing equations by means of a finite volume method. Three models were carried out for the simulation: single-phase and two phase (which included both Eulerian-Lagrangian and mixture models) to evaluate the percentage difference in predicting the nanofluid heat transfer coefficient between the investigated models and the physical effects of some important parameters on the flow behavior for nanoparticles volume fraction from 1% to 4%, taking into account constant and temperature dependent thermophysical properties. The results were compared with the experimental data of Wen and Ding [9], Kim et al. [11] and the numerical work of Bianco et al. [14].

2. Thermophysical properties of the nanofluid for a single-phase model

Conventional heat transfer fluids such as water have inherently low thermophysical properties as compared to solids. Therefore, dispersing colloidal small conductive solid particles such as $AL_2O_3 \leq 100$ nm in diameter can enhance the thermophysical properties for the base fluid. The thermophysical properties for the base fluid and alumina particles are given in Table 1. Researchers have proposed several correlations that can allow calculating properties such as thermal conductivity, density, viscosity and heat capacity, but there are still issues [5] regarding the proper correlations for predicting thermal conductivity and viscosity within an acceptable range. Therefore, further studies need to be conducted in this field.

2.1. Nanofluid density and specific heat

Solid-liquid mixture equations for estimating the density and specific heat capacity of nanofluids were employed from the following equations [5,22–25]:

$$\rho_{nf} = (1-\phi)\rho_{bf} + \phi\rho_p \quad (1)$$

$$Cp_{nf} = (1-\phi)Cp_{bf} + \phi Cp_p \quad (2)$$

Table 1
Physical properties of the base fluid and nanoparticles at T_i = 293 K.

Properties	Water	Al_2O_3
C_p (J/kg K)	4182	733
k (W/m K)	0.6	36
ρ (kg/m^3)	998.2	3880
μ_{water} = 0.001003 kg/m s		