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Numerical analysis of the heat transfer behaviour of water based Al_2O_3 and TiO_2 nanofluids in a circular pipe under the turbulent flow condition☆

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ABSTRACT

A numerical investigation has been carried out applying single phase approach on turbulent forced convection flow of water based Al_2O_3 and TiO_2 nanofluids flowing through a horizontal circular pipe under uniform heat flux boundary condition applied to the wall. The effect of volume concentrations, Brownian motion and size diameter of nanoparticles on flow and heat transfer have been examined for Reynolds number, $Re = 10 \times 10^3$ to 100×10^3, Prandtl number, $Pr = 7.04$ to 20.29, nanoparticle volume concentration, $\chi = 4\%$ and 6% and nanoparticles size diameter, $d_p = 10$, 20, 30 and 40 nm respectively. Results reveal that the small size of nanoparticles with their Brownian motion has the highest average shear stress ratio, heat transfer rate and thermal performance factor for $\chi = 6\%$. Besides, it is found that the heat transfer rate increases as the particle volume concentration and Reynolds number increase with a decrease of nanoparticles size diameter. Moreover, Al_2O_3–water nanofluid shows a higher heat transfer rate compared to that of TiO_2–water nanofluid. Finally, a conclusion has been drawn from the present analysis that the heat transfer performance is more affected by the size diameter and Brownian motion of nanoparticles than the thermal conductivity of nanofluid. Results of the non-dimensional fully developed velocity and turbulent kinetic energy, frictional factor and average Nusselt number for pure fluid (water) as well as the result of average Nusselt number for Al_2O_3 and TiO_2–water nanofluid have been validated with published experimental results as well as with available correlations where a reasonable good agreement has been achieved.

1. Introduction

Nanofluids are new kind of heat transfer fluids which are derived by stably suspending nanoparticles in conventional heat transfer fluids usually liquids, and the volumetric fraction of the nanoparticles is usually below 5 to 10%. Various applications of nanofluids are found in cooling electronic components [1], transportation [2], industrial cooling [3], heating buildings and reducing pollution [4], nuclear systems cooling [5], space and defence [6,7], energy storage [8], solar absorption [9], friction reduction [10], magnetic sealing [11], antibacterial activity [12], nanodrug delivery [13], intensify micro reactors [14], microbial fuel cells [15] and so on. Hence, research is in progress to introduce nanofluids in many thermal applications where the conventional fluids such as ethylene glycol, engine oil and water are not capable of improving the rate of heat transfer as expected. For the first time, Choi [16] at Argonne National Laboratory used nanoparticles suspended in a conventional heat transfer fluid known as nanofluid and proposed that the addition of nanometer size particles into the base fluid helps to increase the thermal conductivity and hence enhances the heat transfer rate of nanofluid.

Numerous experimental and numerical investigation have been carried out by researchers on different types of pipes or tubes using nanofluids under turbulent flow regime using nanofluid with single phase approach. Qiang and Yimin [17] investigated experimentally the heat transfer characteristics of nanofluid in a circular tube under both laminar and turbulent flow regime. They have measured the heat transfer coefficient and Darcy friction factor of Cu–water nanofluid and showed that the heat transfer rate increased because of addition of nanoparticles in the base fluid, while the Darcy friction factor remained unchanged for different volume fractions. Mansour et al. [18] investigated experimentally the effect of physical properties of nanofluid flowing through a tube under constant and uniform heat flux boundary condition. They have demonstrated that the physical parameters vary considerably with the thermophysical properties of the nanofluid. Xuan and Li [19] investigated experimentally the flow and heat transfer behaviour of Cu–water nanofluid. They mentioned that enhancement of heat transfer rate depends on the increase of thermal conductivity or the random movement of the nanoparticles in nanofluid. They introduced

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Nomenclature

$A_0, A_1, C_1, C_2, C_\mu$	model constant
C_p	specific heat capacity (J/kg K)
D	Einstein diffusion coefficient
D_h	diameter of a pipe (m)
d_f	fluid molecular diameter (m)
d_p	diameter of nanoparticle (nm)
f	Darcy friction factor
f_μ	dumping function
G_k	generation of turbulent kinetic energy
I	turbulent intensity
L	length (m)
M	molecular weight of the base fluid
$\dot{m}$	mass flow rate (kg/s)
N	Avogadro number
N_x, N_r	number of grid distribution in axial and radial directions
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure (N/m^2)
Pr	Prandtl number
$\dot{q}_s$	heat flux of the pipe (W/m^2)
R	radius of a pipe (m)
Re	Reynolds number
r	radial coordinate (m)
S	modulus of the mean rate of strain tensor
T	temperature (K)
T_{fr}	freezing point of the base fluid (K)
T_w	temperature at the wall (K)
T_m	mean temperature of a fluid (K)
u_B	nanoparticle particle mean Brownian velocity (m/s)
u_τ	friction velocity (m/s)
V_m	mean fluid velocity (m/s)
v	velocity (m/s)
x	axial coordinate (m)

Greek symbols

ρ	density (kg/m^3)
μ	dynamic viscosity (kg/ms)
λ	thermal conductivity (W/m K)
κ	turbulent kinetic energy (m^2/s^2)
μ_t	turbulent molecular viscosity
ϵ	dissipation rate of turbulent kinetic energy (m^2/s^3)
χ	nanoparticle volume concentration
ξ	thermal performance factor
τ_D	time (s)
$\overline{\tau_\tau}$	ratio of average shear stresses
Γ	exchange coefficient for general transport
σ_t	constant of turbulent Prandtl number
σ_κ	effective Prandtl number for turbulent kinetic
σ_ϵ	effective Prandtl number for rate of dissipation

Subscripts

in	inlet
f	base fluid
nf	nanofluid
p	nanoparticle
w	wall
m	mean
eff	effective

a correlation to evaluate the average heat transfer rate of nanofluid under turbulent flow regime. Kim et al. [20], on the other hand, studied experimentally the effect of nanofluid on heat transfer flowing through a circular horizontal tube under both laminar and turbulent flow regime. Their investigation revealed that average heat transfer rate increases to 15% and 20% for Al_2O_3–water nanofluid at 3 vol.% under both laminar and turbulent flow condition, respectively.

Fotukian and Esfahany [21] investigated experimentally the turbulent heat transfer of Al_2O_3–water nanofluid in a circular tube. Their results indicated that insertion of small amounts of nanoparticles into the base fluid augmented heat transfer remarkably. Sajadi and Kazemi's [22] experimental results on TiO_2–water nanofluid in a circular pipe also showed the same behaviour. Torii [23] however observed that the forced convective heat transfer rate increased with the volume fraction of nanoparticle flowing through a straight circular tube under constant heat flux boundary condition. Sundar et al. [24] investigated experimentally the convective heat transfer and flow behaviours of Fe_3O_4 nanofluid inside a circular tube. It is found that addition of magnetic nanoparticle in the base fluid enhanced the heat transfer rate significantly compared to the other types of nanofluids.

Maiga et al. [25] studied numerically the flow and heat transfer behaviours of Al_2O_3–water nanofluid at various nanoparticle volume concentrations in a circular tube under turbulent flow regime. In this study, $Re = 10^4$ to 5×10^5 and the fluid inlet temperature of 293.15 K are considered. Also effect of nanoparticle volume fraction and Reynolds number are presented and a new correlation is proposed. Their numerical outcomes revealed that the inclusion of nanoparticles into the base fluid enhanced the heat transfer rate with the increase of nanoparticle volume fraction. The similar investigation is carried out by Bianco et al. [26] using both single phase and multiphase approaches and it is found that the accuracy of the multi-phase mixture model is better than the single phase model. However, Namburu et al. [27] analysed numerically the forced convective flow and heat transfer behaviour EG-water based CuO, Al_2O_3 and SiO_2 nanofluids flowing through a circular tube. It is shown that nanofluids have higher viscosity, thermal conductivity and heat transfer rate compared to the base fluid. On the other hand, Kumar [28] studied numerically the heat transfer behaviour of Al_2O_3–water nanofluid using the single phase approach covering both laminar and turbulent flow regime. It is observed that heat transfer rate significantly enhanced in the turbulent flow regime compared to that in the laminar flow regime.

In a practical situation, almost all of the flows are turbulent, and many of these demonstrate extremely high Reynolds numbers e.g. flow in aircraft wings, cars, ships, submarines, turbine blades and large pipe. In order to develop models for energy efficient applications, it is important to understand the phenomena of high Reynolds number turbulence. Therefore, present investigation, which has a particular focus on the thermal energy application, is carried out to explore the effect of Brownian motion and various sizes of nanoparticles of TiO_2–water and Al_2O_3–water nanofluids under the turbulent flow condition for $Re = 10 \times 10^3$ to 100×10^3. In the present investigation, Prandtl number, Pr, ranges from 7.04 to 20.29, the particle volume concentration of 4% and 6% and diameter of the nanoparticles of 10, 20, 30 and 40 nm are considered. To the best of our knowledge, no investigation is carried out to understand the effect of Brownian motion and size of different nanoparticles of Al_2O_3 and TiO_2–water nanofluids considering the above parameters. Hence, the aim of our study is to examine the effect of nanoparticles volume concentration, diameter size and Brownian motion of the nanoparticles on convective heat transfer for Al_2O_3 and TiO_2–water nanofluids using a single phase model.

2. Mathematical modelling

Two approaches have been used by the researchers to investigate the effect of inclusion of nanoparticles into the base fluid [26,29,30]. The first approach is the single phase model in which both the fluid