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Investigation of the characteristics of nanofluids flow and heat transfer in a pipe using a single phase model

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ABSTRACT

Single phase model has been used to investigate the flow characteristics of Al_2O_3–water and TiO_2–water nanofluids in a horizontal pipe under constant heat flux boundary condition. SST $\kappa - \omega$ model has been applied to simulate the flow and thermal fields for a number of physical, thermal and nanofluid conditions. Results generally reveal that the enhancement of heat transfer and entropy generation is dependent on the concentrations, size of nanoparticles and flow Reynolds number. However, the heat transfer rate is predicted to be little bit higher for the Al_2O_3–water nanofluid than that of the TiO_2–water nanofluid. It is also found that there exists no optimal Reynolds number for which the total entropy generation could be optimised. Some new correlations have been proposed and used them to calculate the average Nusselt number using single phase model.

1. Introduction

Reynolds [1] found the transition flow behaviour to change unpredictably between the laminar and turbulent flow. It is observed in this research that the laminar flow can be sustained at high Reynolds numbers if different types of disturbances in the flow are eluded (Cengel [2]). Later on, Ekman [3] and Pfenniger [4] performed experimental investigations and stated that the laminar flow could have been maintained up to a Reynolds number of 40,000 and 100,000 respectively by reducing the flow disturbances. Cengel [2] also suggested, that it was better to have some specific values of Reynolds number for laminar, transitional and turbulent flows in a smooth pipe. But this was tricky since flow disturbances were generated by various mechanisms such as surface roughness, noise, and vibrations. In most cases, the flow in a smooth pipe is said to be laminar when $Re < 2300$, fully turbulent when $Re > 10{,}000$ and transitional when $2300 \le Re \le 10{,}000$. Cengel [2] however stated that even though transitional flow exists for $2300 \le Re \le 10{,}000$, a fully turbulent condition in many practical applications can be achieved when $Re > 4000$.

We know that internal flow behaves like a laminar flow when flow pattern of fluids forms a parallel layer inside the domain with no disturbance between the layers. But, imposing external disturbance can make the flow unstable sometimes. This can be seen from the flow fields where small fluctuation occurs in the parallel layer. Such behaviour is known as transitional behaviour and we simply say that transition flow is a state between the laminar and turbulent flow. It is important to note that the flow in a smooth pipe is said to be transitional when $2300 \le Re \le 10{,}000$. Very few researches have been done on pipe under transition flow region and most of them were experimental and details are discussed in the following section:

Tang *et al.* [5] experimentally investigated the hydrodynamic behaviour of Al_2O_3–water nanofluid flowing through a horizontal tube. Their results indicated that transition flow had been monitored at $Re \sim 1500$ comparing with $Re \sim 2300$ given in Cengel [2] for the transition regime. It suggested, the transition regime could start from $Re \sim 1500$ although many researchers monitored it to be $2000 < Re < 4000$. However, few works have been done on horizontal tube with twisted tape or wire coil inserts in order to see the effect on the heat transfer performance under transition flow condition. Sharma *et al.* [6] and Chandrasekar *et al.* [7] observed the heat transfer behaviour experimentally using Al_2O_3–water nanofluid flowing through a circular tube with twisted tape or wire coil inserted under the transitional flow regime. The maximum heat transfer enhancement of 20% and 23.07% had been achieved for $\chi = 0.1\%$ at $Re = 5000$ and $Re = 9000$ respectively. A similar experimental investigation was done by Naik *et al.* [8] for water–propylene glycol based CuO nanofluid and the maximum enhancement of 76.06% had been attained at $Re = 10000$ and for $\chi = 0.5\%$. Analysing their findings, it is concluded that maximum enhancement of heat transfer can be observed for the high Reynolds number. Meyer *et al.* [9], first time in the recent years, has experimentally investigated the heat transfer behaviour influenced by multi-walled carbon nanotubes inside the smooth horizontal tube

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Nomenclature

A	Acceleration (m/s^2)
β_1, β_2, α^*, α_1	Model constants
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)
E_{gen}	Entropy generation (W/K)
F_1, F_2	Blending functions
F	Darcy friction factor
f_{drag}	Drag function
G_κ	Generation of turbulent kinetic energy
G_ω	Production of ω
H	Enthalpy (J/kg)
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	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
SPM	Single phase model
T	Time average temperature (K)
u_B	Nanoparticle particle mean Brownian velocity (m/s)
u_τ	Friction velocity (m/s)
$\vec{V}$	Time average velocity vector(m/s)
x_c	Critical distance(m)

Greek symbols

P	Density (kg/m^3)
μ	Dynamic viscosity (kg/ms)
Λ	Thermal conductivity ($W/m\,K$)
K	Turbulent kinetic energy (m^2/s^2)
Ω	Specific rate of turbulent dissipation (m^2/s^3)
ν	Kinematic viscosity (m^2/s)
σ_t	Constant of turbulent Prandtl number
μ_t	Turbulent molecular viscosity
σ_κ	Effective Prandtl number for turbulent kinetic energy
σ_ω	Effective Prandtl number for specific rate of dissipation
X	Nanoparticles concentration
τ_D	Time (s)
$\bar{\tau}_\tau$	Ratio of average shear stresses

Subscripts

Avg	Average
Eff	Effective
F	Base fluid
Fr	Freezing
In	Inlet
M	Mixture
Mean	Mean
nf	Nanofluid
Out	Outlet
P	Nanoparticles
S	Secondary phase
W	Wall

under transitional flow regime. In their investigation, transition flow behaviour is observed in between $2900 \leq Re \leq 3600$. They have mentioned, the heat transfer rate decreases while using multi-walled carbon nanotubes.

Recently, effect of concentrations, size diameters and Brownian motion of nanoparticles on the convective heat transfer and entropy generation of Al_2O_3 and TiO_2–water nanofluids have been investigated by Saha and Paul [10, 11] using both single and multi-phase models. However, no research has been found to understand the heat transfer and entropy generation behaviour of Al_2O_3 and TiO_2–water nanofluids flowing through a horizontal pipe using smooth pipe wall under the transitional to turbulent flow regimes. Hence, the main objective of this research is to analyse the effects of different nanoparticles size and concentrations with the Brownian motion of nanoparticles on heat transfer under transition to turbulent flow condition. Finally, results have been presented in terms of local and average Nusselt number, average wall shear stress coefficient ratio, thermal performance factor and entropy generation.

2. Mathematical modelling

In this research, numerical investigations have been carried out using single phase model. Here, two-dimensional axi-symmetric model of a horizontal pipe with the length L of 1.0 m and internal diameter, D_h of 0.019 m has been considered to analysis the heat transfer performance of Al_2O_3 and TiO_2–water nanofluids through it. The geometry is shown in Fig. 1. Also, the dimensional steady-state governing equations of fluid flow and heat transfer for the single phase model is presented under the following assumptions:

- Fluid flow is incompressible, Newtonian and transitional,
- The Boussinesq approximation is negligible as the pipe is placed horizontally,
- Fluid phase and nanoparticle phase are in thermal equilibrium with no-slip between them,
- Nanoparticles are spherical and uniform in size and shape,
- Radiation effects and viscous dissipation are negligible.

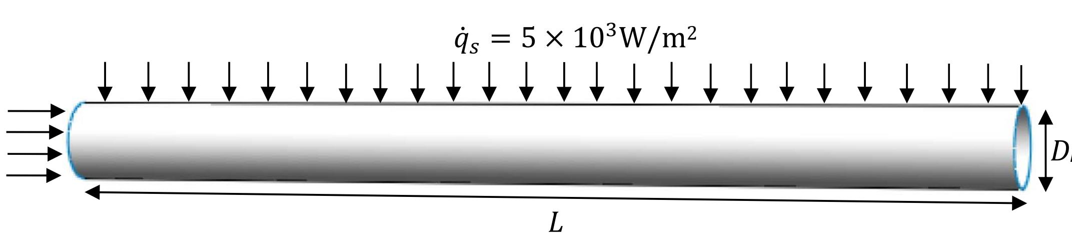

Fig. 1. Schematic diagram of the geometry under consideration.