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CFD Analysis of Heat Transfer Performance in a Car Radiator with Nanofluids as Coolants

Rajashekhar Pendyala*, Jia Ling Chong, Suhaib Umer Ilyas

Chemical Engineering Department, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia
rajashekhar_p@petronas.com.my

Nanofluids are the new developed thermal fluids with enhanced thermophysical properties which can improve heat transfer performance of various applications. By introducing nanoparticles with high thermal conductivity in the car radiator coolant can enhance the effective thermal conductivity of coolant which improves the performance of cooling system. Alumina, silica and copper oxide nanoparticles with ethylene glycol-water mixture (60:40) have been used in 3-dimentional car radiator simulations to study fluid flow patterns and heat transfer performance. Heat transfer performance for ethylene glycol-water mixture based nanofluids at different nanoparticle concentrations has been studied. Heat transfer coefficients are determined by numerical simulations with varying coolant velocities. Overall heat transfer performance is found to be improved using nanofluids with high effective thermal conductivity. Results display significant increase in heat transfer performance of coolant in car radiator with an increase in the particle loading.

1. Introduction

Nanofluids have great potential for heat transfer applications due to their enhanced thermal properties (Peyghambarzadeh et al., 2013). A significant improvement in heat transfer characteristics has been observed in many studies with the usage of nanofluids (Wang and Mujumdar, 2007) due to improved thermophysical properties of heating media (Ilyas et al., 2014a). The nanofluids can be used in various heat transfer applications such as car radiator, industrial cooling, nuclear reactors and variety of other situations (Ilyas et al., 2014b). Studies are available on the stability of such smart fluids for heat transfer applications (Ilyas et al., 2013). Researchers have overcome the settling issues of nanoparticles in the fluid by applying different mechanical and chemical techniques (Ilyas et al., 2014c). Cooling in car radiator is one of the key factors for engine efficiency and performance. Coolants with nanoparticles of high effective thermal conductivity in car radiator can enhance the heat transfer performance (Bubbico et al., 2015). The radiator can be designed in smaller size at high heat transfer performance, which can improve the fuel consumption of the vehicle.

Water is a conventional heat transfer fluid which is extensively used in many cooling applications. Mixture of water with ethylene glycol has shown enhanced heat transfer capabilities due to anti-freezing behaviour of ethylene glycol (Peyghambarzadeh et al., 2011). Vajjha et al. (2010) in their study investigated the heat transfer performance of copper oxide and alumina based nanofluids in ethylene glycol/water mixtures as coolants in a flat tube radiator system. Significant improvement in the convective heat transfer coefficient was found using nanofluid coolants over base fluid alone. In another study by Leong et al. (2010), heat transfer properties were investigated using copper nanoparticles in ethylene glycol/water nanofluid system. It was found that the higher concentrations of nanoparticles are more effective for cooling applications.

The objective of this paper is to study the heat transfer performance of coolant using metallic oxide nanoparticles. The CFD simulations of heat transfer characteristics in a car radiator with different nanofluids in laminar and turbulent flow models are discussed. The study has significant importance towards the estimation of heat transfer coefficient and percentage enhancement in thermal efficiency of a

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car radiator using nanofluid coolants. The novelty of this study is to compare the heat transfer performance by the three nano particles in the same car radiator geometry.

2. Methodology

Heat transfer characteristics have been studied numerically in 3-dimensional car radiator. The geometry consists of a duct in which coolant flows and fins are attached outside of the duct wall, shown in Figure 1. Cooling process of the fluid inside the duct is driven by forced convection heat transfer of air which passes through the fins mounted on the outer duct wall (Frass, 1989). The simulations are carried out in ANSYS Fluent 15.0 to study the numerical heat transfer behaviour of nanofluid coolants. Nanofluids coolant containing copper oxide 29 nm (CuO), alumina 45 nm (Al_2O_3) and silicon dioxide 20 nm (SiO_2) in ethylene glycol- water mixture (60:40 wt%) at various concentrations (1 vol%, 3 vol% and 5 vol%) have been taken under consideration. Thermophysical data has been used from Vajjha et al., (2012). Fine meshing with air flow domain has been done to predict accurate results. The boundary conditions for the duct wall are set to be non-slip and stationary. The viscous dissipation and the compression work are considered to be negligible. Nanofluids are studied at different flow conditions (laminar and turbulent), $100 \leq Re \leq 10{,}000$. Semi-Implicit Method for Pressure Linked Equations-Consistent (SIMPLEC) scheme for laminar and Coupled scheme for turbulent flow. Standard κ-ε turbulent model is used with enhanced wall treatment for turbulent modelling. Navier-stokes equations, non-linear fluid flow equations and continuity equations are considered. The inlet temperatures for coolant and air are set to be 363 K and 303 K. The axial air velocity is set to be constant (4.4 m/s) and considered to be flow over bodies. A total number of 25 fins are mounted on the duct having fin thickness of 0.0001 m. The hydraulic diameter for coolant side is calculated to be 0.0404 m.

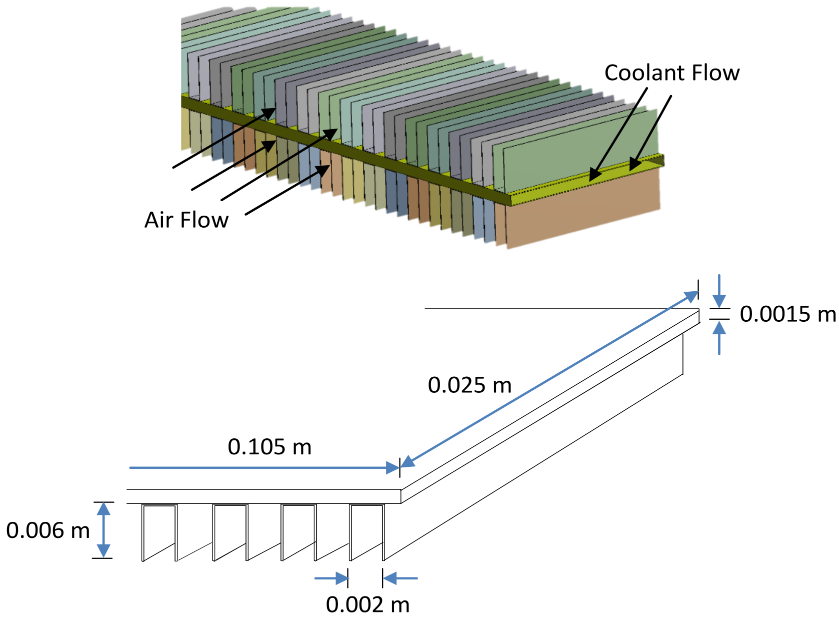

Figure 1: Car radiator model under consideration with dimensions

3. Results and discussion

3.1 Convective heat transfer of nanofluids

Simulations are performed in car radiator model to study the forced convective heat transfer behavior of coolant with and without nanoparticles. Heat transfer coefficient for coolant is determined at different particle loading and Reynolds number. Local heat transfer coefficient along the duct length for various nanofluids at different concentrations in laminar flow for Re = 100 is shown in Figure 2 (a), (b) and (c). The difference between coolant inlet and outlet temperature decreases with the increase in coolant flow rate. This is due to the lesser residence time for coolant to transfer heat to the fins and air. Similar situation can be found in the work by Kulasekharan et al., (2012). As the wall temperature and outside condition are same, the amount of heat loss by coolant is nearly constant for different flow rates, hence the moving average graphs of local heat transfer coefficient along the duct length is plotted. The first few points are not considered due to variation of temperature at the entry region. At constant laminar flow the local heat transfer coefficient is found to be higher at the inlet (Z = 0 m) due to developing flow. It is observed that heat transfer coefficient decreases gradually along the duct until the fully developed region is reached. Similar graphical trends have been found in previous literature by Vajjha et al., (2010) and Gunnasegaran et al. (2012). Local heat transfer coefficient has been studied at turbulent flow at different Reynolds numbers i.e. 5,000, 7,500 and 10,000 for different nanofluids. The variation of heat transfer coefficient along the duct length for various nanofluid coolants with turbulent flow for Re = 7,500 is shown in Figure 3.

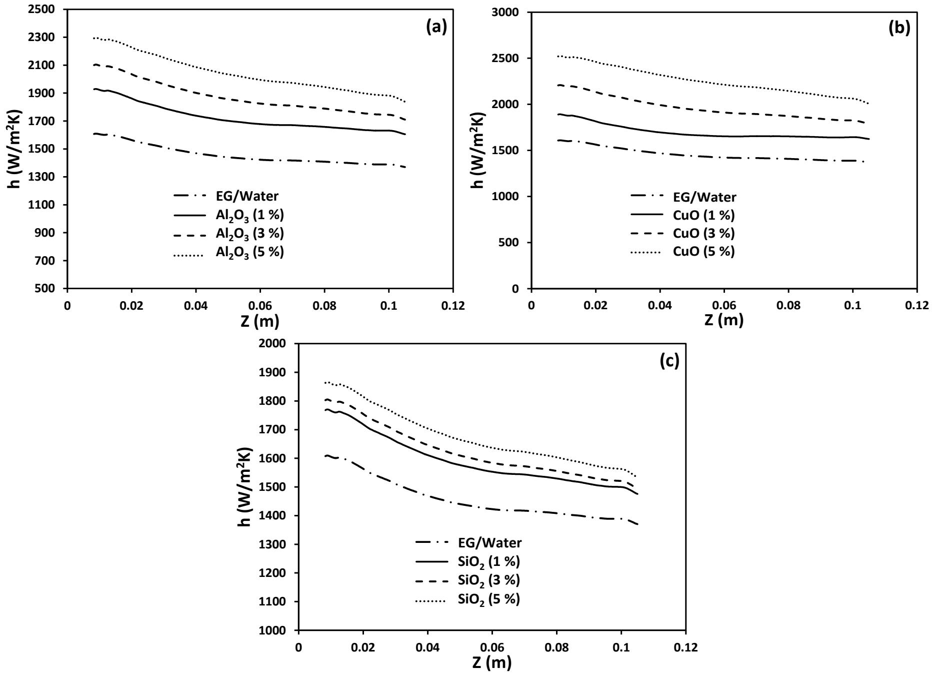

Figure 2: Effect of heat transfer coefficient along the duct length for different nanofluids (a) Al_2O_3 (b) CuO and (c) SiO_2 in laminar flow for Re = 100

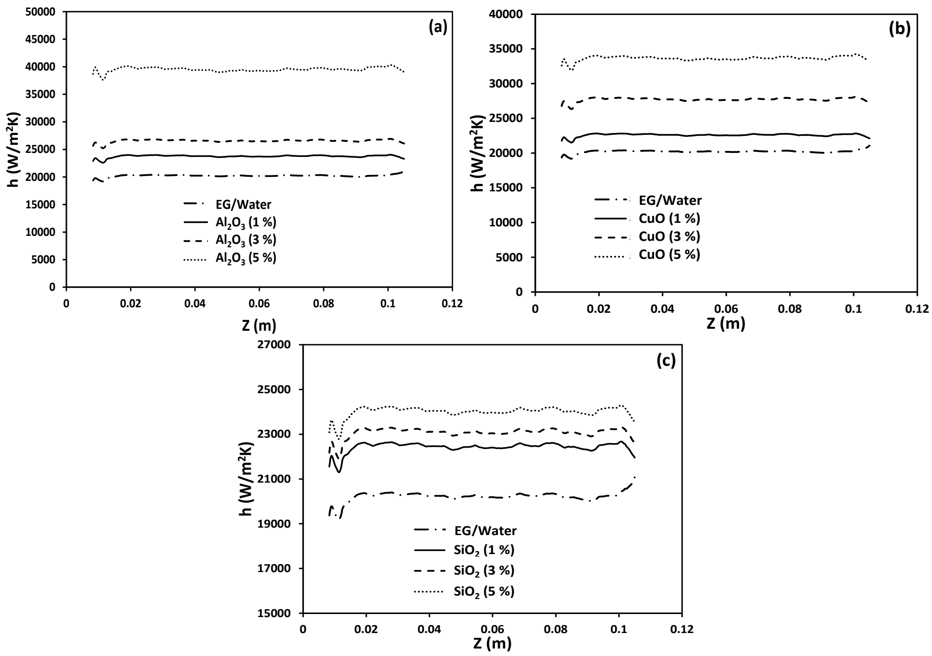

Figure 3: Effect of heat transfer coefficient along the duct length for different nanofluids (a) Al_2O_3 (b) CuO and (c) SiO_2 in turbulent flow for Re = 7,500

It is observed that local heat transfer coefficient in the coolant side is higher near the fins due to enhancement in the heat transfer by fins. However, high local heat transfer coefficient is predicted at turbulent flow conditions than laminar flow conditions. Addition of nanoparticles with different particle loading in coolant has significant importance towards efficient heat transfer. It is observed that all types of nanoparticles with high thermal conductivity increases heat transfer coefficient. The results demonstrate that replacing ordinary coolant with nanofluid gives high heat transfer rate along the duct. Heat transfer coefficient is found to be increased by the increase in nanoparticle concentration in ethylene glycol-water mixture at fixed Reynolds number. It can be seen in Figure 2 and Figure 3 that concentration of alumina, copper oxide and silica at 5 vol% shows higher heat transfer coefficient than the base-fluid alone.

3.2 Influence of coolant Reynolds number

The thermal performance of radiator is significantly influenced by the coolant Reynolds number. Reynolds number of coolant is one of the considerable factors towards controlling the temperature of engine to avoid overcooling or overheating. The coolant Reynolds number and air Reynolds number is controlled to ensure that the radiator is operating at optimum temperature. The flow rate of coolant is controlled by thermostat and coolant pump (Leong et al., 2010). Average heat transfer coefficients and Nusselt number of coolant are estimated at different nanoparticles concentration. The change in average coolant heat transfer coefficient with the coolant Reynolds number for alumina, copper oxide and silica based nanofluids in ethylene glycol-water mixture are shown in Figure 4. It is observed that at constant air velocity of 4.4 m/s thermal performance of radiator is significantly improved at high Reynolds number. The average heat transfer coefficient is found to be increased with the increase in Reynolds number.

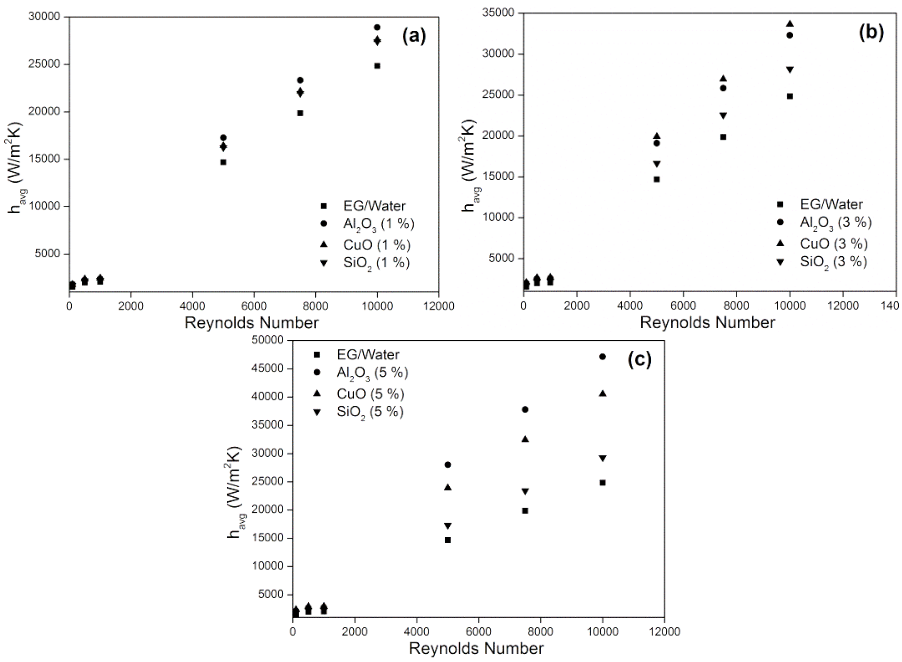

Figure 4: Effect of average coolant heat transfer coefficient with the coolant Reynolds number at different particle concentrations in ethylene glycol-water mixture i.e. (a) 1 vol% (b) 3 vol% and (c) 5 vol%

The improvement for the average heat transfer coefficient during laminar flow conditions (100 – 1,000) for 3 vol% alumina, copper oxide and silica based nanofluids are estimated to be about 27.28 %, 32.97 % and 10.23 %. When coolant Reynolds number is increased from 5,000 to 10,000, the percentage increase in average heat transfer coefficient in EG/Water mixture with 3 vol% of alumina, copper oxide and silica are found to be about 30.07 %, 35.55 % and 13.50 %. Copper oxide based nanofluids exhibits high thermal performance than alumina and silica during laminar and turbulent flow conditions due to high thermal conductivity. However, under certain conditions of turbulent flow, alumina based nanofluids showed better average heat transfer coefficient than copper oxide based nanofluids (Almohammadi et al., 2012). Similar trends are found in few studies for CuO (Heris et al., 2006) and alumina (Heris et al. 2007) based nanofluids.

3.3 Correlation development for Nusselt number

The Nusselt number for the nanofluid as a function of Reynolds number and volume concentration of nanoparticles are investigated. The Nusselt number is found to be increased uniformly with Reynolds number and concentration of nanoparticles. The Nusselt number and Prandtl number are significantly influenced by the thermophysical properties of the coolant nanofluid i.e. density, viscosity, thermal conductivity and specific heat capacity. Correlations are developed for Nusselt number (Nu) in terms of Reynolds number (Re) and particle concentration (φ_p) for laminar and turbulent flow conditions. It is found that Prandtl number has negligible effect on the Nusselt number in case of laminar and turbulent flow conditions due to low temperature difference. The correlations at laminar flow and turbulent flow conditions are given in Eq(1) and Eq(2).

For laminar flow

$$\begin{aligned} &Nu = 1.53 + \mathrm{Re}(0.0178 - 5\times10^{-7}\,\mathrm{Re} + 1.112\varphi_p) \\ &100 \le \mathrm{Re} \le 1000 \\ &0.01 \le \varphi_p (Vol\ \ fr.) \le 0.05 \end{aligned} \tag{1}$$

For turbulent flow

$$\begin{aligned} &Nu = 8.65 + \mathrm{Re}(0.0119 - 8\times10^{-6}\,\mathrm{Re} + 0.0107\varphi_p) \\ &5000 \le \mathrm{Re} \le 10000 \\ &0.01 \le \varphi_p (Vol\ \ fr.) \le 0.05 \end{aligned} \tag{2}$$

Performance of correlation for Nusselt number is shown in Figure 5 for laminar and turbulent flow conditions. The presented correlation for laminar flow exhibits 1.79 % average absolute deviation (AAD) and the sum of squared errors (SSE) is found to be 2.58. The correlation shows ±7.5 % mean absolute error. The AAD of the Nusselt number correlation for turbulent flow is found to be 6.81 % and all the data points are in agreement within ±20 of mean absolute error.

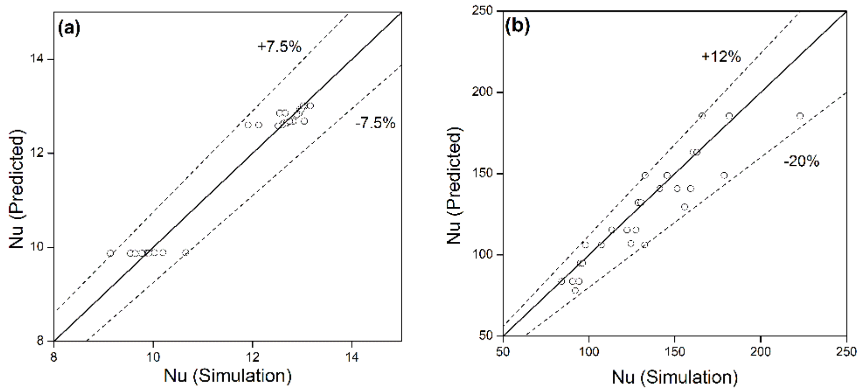

Figure 5: Performance of correlation for predicting Nusselt number at (a) laminar flow conditions and (b) turbulent flow conditions

4. Conclusions

In order to ensure improvement in heat transfer in nanofluid, the Brownian motion of the nanoparticles plays a vital role. The nanoparticles move randomly in the fluid and resulting in the decrease of the boundary layer thickness and thus enhancing the heat transfer from wall to the bulk fluid. The forced convection heat transfer characteristics of ethylene glycol/water based nanofluids are presented. SiO_2, Al_2O_3 and CuO nanofluids are numerically investigated in laminar and turbulent flow regimes in a 3D car radiator model. It is found that local heat transfer coefficient decreases gradually with distance along the duct until the fully developed region is reached in laminar flow conditions. It is observed that nanoparticle concentration plays an important role towards heat transfer enhancement. It is found that heat transfer coefficient increases significantly with the increase of particle loading. Copper oxide and alumina based nanofluids showed higher thermal efficiency than silica based nanofluids in laminar and turbulent flow conditions. The correlations are developed for Nusselt number as a function of Reynolds number and particle concentration. Different combinations of nanofluids can be prepared using different nanoparticles with varying particle loading to study thermal performance in different heat transfer applications.

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