Case Studies in Thermal Engineering 9 (2017) 72–78

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

Numerical study on turbulent forced convective heat transfer using nanofluids TiO_2 in an automotive cooling system

Adnan M. Hussein[a,b,*], H.K. Dawood[c,d,**], R.A. Bakara[a], K. Kadirgamaa[a]

[a] Faculty of Mechanical Engineering, University Malaysia Pahang, 26600 Pekan, Pahang, Malaysia
[b] Al-Haweeja Institute, Northern Technical University, Iraq
[c] Mechanical Engineering Department, College of Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia
[d] Department of Mechanical Engineering, College of Engineering, University of Anbar, Ramadi, Anbar, Iraq

ARTICLE INFO

Keywords:
Nanofluid
Friction factor
Nusselt number
Turbulent Convective Heat Transfer
Car radiator

ABSTRACT

The limited thermal properties of liquids have led to the addition of solid nanoparticles to liquids in many industrial applications. In this paper, the friction factor and forced convection heat transfer of TiO_2 nanoparticles dispersed in water in a car radiator was numerically determined. Four different nanofluid volume concentrations (1%, 2%, 3% and 4%) were used, and the resulting thermal properties were evaluated. The Reynolds number and inlet temperature ranged from 10000 to 100000 and from 60 to 90 °C, respectively. The results showed that the friction factor decreases as the Reynolds number increases and increases as the volume concentration increases. Additionally, the Nusselt number increases as the Reynolds number and volume concentration of the nanofluid increases. The TiO_2 nanofluid at low concentrations can enhance the heat transfer efficiency up to 20% compared with that of pure water. There was good agreement among the CFD analysis and experimental data available in the literature.

1. Introduction

Heat transfer performance of liquids is limited by their low thermo-physical properties compared with those of solids. The primary reason behind adding solid particles less type of fluid is called a nanofluid. Dispersing solid metallic or non-metallic materials in a base fluid (liquid), such as water, ethylene glycol or glycerol, has become an interesting topic recently [1–5]. Base fluids have been used as conventional coolants in automobile radiators for many years; however, these fluids have low thermal conductivities. The low thermal conductivities have thus prompted researchers to search for fluids with higher thermal conductivities than that of conventional coolants. Therefore, nanofluids have been used instead of the commonly used base fluids [6,7]. Peyghambarzadeh et al. [8] investigated forced convection heat transfer to reduce circulating water in an automobile radiator, where the effects of different amounts of Al_2O_3 nanoparticles on the heat transfer performance of an automobile radiator was determined experimentally. The range of flow rates was varied between 2 and 6 LPM with a changing fluid inlet temperature for all experiments. The results showed that the heat transfer was enhanced using nanofluids by 40% compared with pure water. A numerical study on laminar heat transfer using CuO- and Al_2O_3-ethylene glycol and water inside a flat tube of a car radiator was performed by Vajjha et al. [9]. The air flow was simulated using the commercial software ANSYS 12.1, where the geometry was created in the software

* Corresponding author at: Faculty of Mechanical Engineering, University Malaysia Pahang, 26600 Pekan, Pahang, Malaysia.
** Corresponding author at: Mechanical Engineering Department, College of Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia.
E-mail address: hathim_iraq@yahoo.com (H.K. Dawood).

http://dx.doi.org/10.1016/j.csite.2016.11.005
Received 13 October 2016; Received in revised form 26 November 2016; Accepted 30 November 2016
Available online 09 December 2016
2214-157X/

Nomenclature

C	specific heat capacity [J/kg °C]	u	Velocity [m/s]
D	diameter [m]	μ	Viscosity [N s/m^2]
E	energy [W]	ρ	Density [kg/m^3]
f	friction factor	τ	Shear stress [N/m^2]
h	convection heat transfer coefficient [W/m^2 °C]	ϕ	Volume concentration
k	thermal conductivity [W/m °C]	*Subscripts*	
Nu	Nusselt Number [$h\,D/k$]	f	liquid phases
P	Pressure [N/m^2]	p	solid particle
Pr	Prandtle Number [$C\,\mu/k$]	nf	nanofluid
Re	Renolds Number [$\rho Dh\,u/k$]	h	hydraulic

Solid works, followed by creating both the surface mesh and the volume mesh accordingly. The results were compared and verified according to a known physical situation and existing experimental data. The results serve as a good database for future investigations. New correlations for the viscosity and thermal conductivity of nanofluids as a function of volumetric particle concentration and temperature developed from the experiments were used in this paper. The convective heat transfer coefficient and shear stress of the nanofluid showed marked improvement over the base fluid, showing higher magnitudes in the flat regions of the tube. The results showed that increasing the nanofluid volume fraction increased the friction factor and convective heat transfer coefficient. A numerical study that analysed mixed convection flows in a U-shaped grooved tube in a radiator was conducted by Park and Pak [10]. A modified SIMPLE algorithm for the irregular geometry was developed to determine the flow and temperature field. The results have been used as fundamental data for tube design by suggesting optimal specifications for radiator tubes. Two liquids, water and an ethylene glycol/water mixture, used as the coolant fluid in a meso-channel heat exchanger were studied numerically by Dehghandokht et al. [11]. The predicted results (heat transfer rate, pressure and temperature drops in the coolants) from the numerical simulation were compared with the experimental data for the same geometrical and operating conditions and showed good agreement. Additionally, the results showed the heat exchanger was enhanced, with heat transfer rate approximately 20% greater than that of a straight slab of the same length; the enhanced heat exchanger has a good potential to be used as a car radiator with reasonably enhanced heat transfer characteristics using an ethylene glycol/water mixture as the coolant. The application of a copper-ethylene glycol nanofluid in a car cooling system was studied by Leong et al. [12].

As seen in these and/or similar works, heat transfer mechanisms in an automotive cooling system could be very complex and this geometry could be appeared in many industrial installation. In this paper, the heat transfer enhancement of turbulent flow through an automobile radiator is evaluated numerically using TiO_2-water nanofluid. The commercial available CFD software, FLUENT© 6.3.26 was used to solve the governing equations of continuity, momentum and energy. The Reynolds numbers based on the hydraulic diameter of the flat tube (Dh) ranged from 10000 to 100000. The nanofluid volume fraction and the inlet temperature are in the range of 1–4% and 60–90 °C respectively. The numerical results are compared with experimental data available in literature.

2. Theoretical analysis

2.1. Physical model

Fig. 1 shows the automobile radiator used in this study, which consists of a flat tube with a length (L=500 mm) and hydraulic diameter (Dh=4.5 mm).

The Reynolds number was calculated based on the hydraulic diameter (Dh):

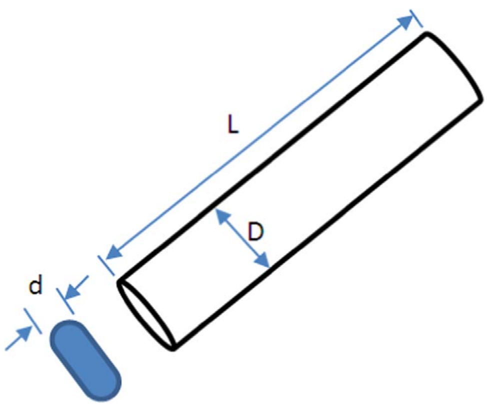

Fig. 1. Flat tube of radiator.

$$D_h = \frac{4 \times Area}{Perimeter} \tag{1a}$$

$$D_h = \frac{4 \times [\frac{\pi}{4}d^2 + (D - d) \times d]}{\pi \times d + 2 \times (D - d)} \tag{1b}$$

Reynolds number (Re) is determined as:

$$\mathrm{Re}_D = \frac{\rho \times D_h \times u}{\mu} \tag{2}$$

Several assumptions were made on the operating conditions of the automotive cooling system, [13,14]:

Steady-state, incompressible and Newtonian turbulent fluid flows with constant thermophysical properties of the nanofluid assumed. Additionally, heat conduction in the axial direction and wall thickness of the tubes was neglected.

2.2. Governing equations

Using infinitesimal (less than 100 nm) solid particles, the single-phase approach can be used, and thus, the single-phase approach was adopted for nanofluid modelling. The thermal properties of the nanofluid can be estimated by the equations below [15]:

$$\rho_{\mathrm{nf}} = \left(\frac{\phi}{100}\right)\rho_p + \left(1 - \frac{\phi}{100}\right)\rho_f \tag{3}$$

$$C_{nf} = \frac{\frac{\phi}{100}(\rho C)_p + (1 - \frac{\phi}{100})(\rho C)_f}{\rho_{nf}} \tag{4}$$

$$k_{nf} = (1 + 3\Phi)k_f \tag{5}$$

$$\mu_{nf} = (1 + 2.5\Phi)\mu_f \tag{6}$$

where ρ, *C*, *k* and μ are the density, specific heat capacity, thermal conductivity and viscosity, respectively, and the subscripts, *nf*, *f*, and *p*, represent the nanofluid, fluid and solid properties, respectively. The following are the thermal properties of the solid particles: kp=8.4 W/m °C, ρp=4175 kg/m^3, Cp=692 J/kg K [15]. For all assumptions, the dimensional governing equations at steady state are the continuity, momentum and energy equations [16]:

$$\nabla \cdot V = 0 \tag{7}$$

$$V_x\frac{\partial V_z}{\partial x} + V_y\frac{\partial V_z}{\partial y} + V_z\frac{\partial V_z}{\partial z} = -\frac{1}{\rho}\frac{\partial P}{\partial z} + \upsilon\frac{\partial^2 V_z}{\partial z^2} + g_z \tag{8}$$

$$V_x\frac{\partial T}{\partial x} + V_y\frac{\partial T}{\partial y} + V_z\frac{\partial T}{\partial z} = \alpha\frac{\partial^2 T}{\partial z^2} \tag{9}$$

2.3. Numerical parameters and procedures

The numerical simulations were carried out using the software FLUENT 6.3.26 with segregated solver strategy and convergence criteria of 1×10^{-06}. The SIMPLE algorithm was used for the pressure-velocity coupling, the PRESTO (pressure staggered option) scheme was adopted for the pressure discretisation, and the First Order Upwind algorithm was used for the momentum equations discretisation and for the turbulence model equations. The RANS turbulence model used in the CFD simulations was the *k*-ε standard with two additional transport equations. The default values (Fluent, 2006) were adopted for model's constants of turbulence model.

Although, a high Reynolds number was used as an input parameter, therefore the results of the simulation were compared with the equations for the friction factor (10) and Nusselt number (11) correlated by Blasius and Dittus-Boelter respectively [17]:

$$f = \frac{0.316}{\mathrm{Re}^{0.25}} \tag{10}$$

$$Nu = \frac{h}{k}D_h = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3} \tag{11}$$

A value of 0.3 was used as the power of Pr for the cooling system.

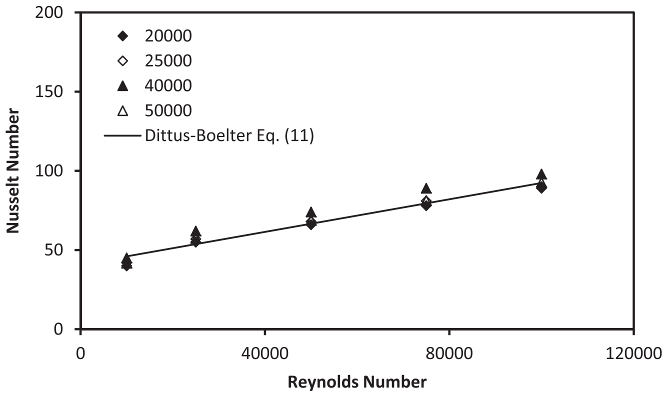

Fig. 2. Grid independent test.

2.4. Boundary conditions

TiO_2-water nanofluid volume concentrations of 1%, 2%, 3% and 4% at a base temperature of 25 °C were used as the input fluids. The inlet temperature to the radiator is from 60 to 90 °C. For comparison purposes, water was also used as the working fluid. CFD studies were performed with a uniform velocity profile at the inlet, and a pressure outlet condition was used at the outlet of the radiator. The walls of the radiator tubes were assumed to be perfectly smooth. The Reynolds number was varied from 10000 to 100000 at each iteration step as input data. The Nusselt number was the output data.

2.5. Grid independence test

Grids independence was determined using the GAMBIT software and was found for 50000 cells (1000×50), with subdivisions in the axial directions and the face of the flat area. To determine the most suitable size of the mesh faces, a grid independence test was performed for the physical model. In this study, rectangular cells were used to mesh the surfaces of the tube wall, and triangular cells were used to mesh the surfaces of the gap, as shown in Fig. 2. Grid independence was checked using different grid systems, and four mesh faces were considered, 50000 cells (1000×50), 25000 cells (1000×25), 40000 cells (800×50) and 20000 cells (800×25) for pure water. The Nusselt number was determined for all four mesh faces, and the results all agreed with each other. All four mesh faces could have been used, and in this study, the mesh face with 50000 cells was adopted because it was the best in terms of accuracy.

3. CFD simulation

CFD simulations were performed using FLUENT software with the solver strategy, and the Gambit software was used to analysis the problems. To numerically simulate the governing equations, single-phase conservation equations were solved by the control volume approach; the equations were then converted to a set of algebraic equations. The simulation results were compared with the predicted results of [5,8]. Using FLUENT software for CFD analysis has been done in the literature, and a detailed description of the mathematical model can be found in Fluent User's Guide, 2006 [17]. There are distinct steps to model a region using CFD: in the first step, the preprocess stage, the geometry of problem was constructed as a flat tube, and the computational mesh was generated in GAMBIT. The next step involves creating the physical model and choosing the boundary conditions and other parameters required to define the model setup and solving stage. All scalar values and velocity components of the problem were calculated at the centre of the control volume interfaces, where the grid schemes are used intensively. Throughout the iterative process, the residuals were continually monitored. When the residuals for all governing equations were less than 10^{-6}, all solutions were assumed to be converged. Finally, the results were obtained when the FLUENT iterations converged. The Nusselt number inside the flat tube could then be determined throughout the computational domain in the post-process stage.

4. Results and discussion

4.1. Friction factor

The effect of nanoparticle volume concentration on the friction factor is shown in Fig. 3 for TiO_2-water. The friction factor increases with increasing of volume concentration but decreases with increasing Reynolds number. Note that the Blasius Eq. (10) is indicated as the black solid line for pure water. It seems that the friction factor for 4% nanofluid volume concentration have the highest values than other volume concentrations and water. The maximum deviation is not more than 11%. This data agrees with the data available in the literature [9,10]. Fig. 4 shows the effect of the inlet temperature on friction factor of the TiO_2 nanofluid with

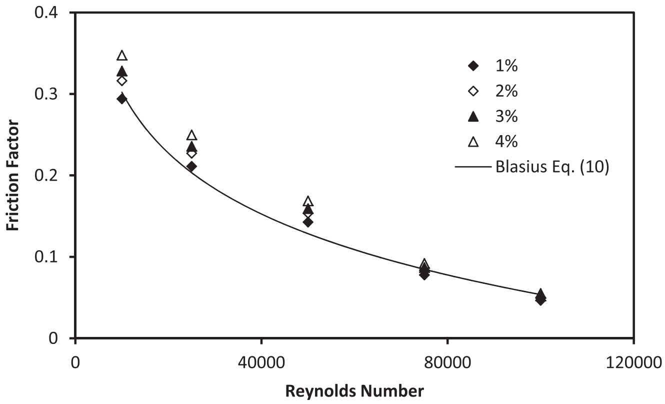

Fig. 3. The effect of nanofluid volume concentrations on the friction factor.

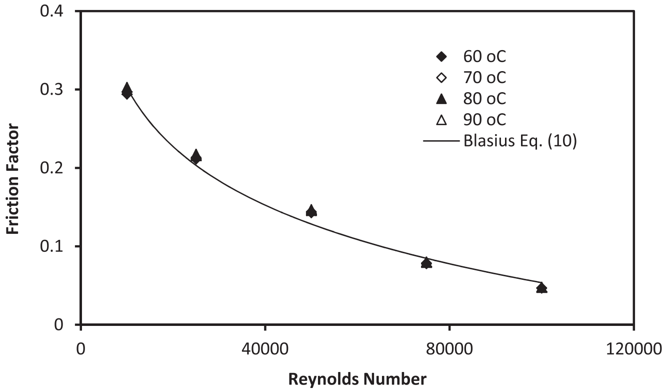

Fig. 4. The effect of inlet temperature on the friction factor.

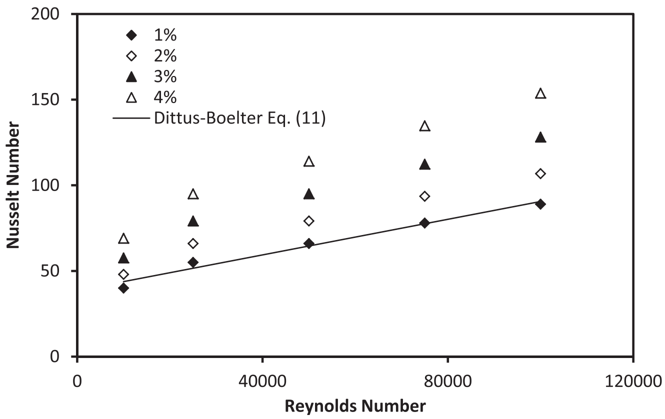

Fig. 5. The effect of nanofluid volume concentrations on the Nusselt number.

volume concentrations of 1%. The maximum deviations of friction factor values were not greater than 2%. It appeared that there is significant effect of the nanofluid volume concentrations on the friction factor whereas, insignificant influence of the inlet temperature on the friction factor.

4.2. Nusselt number

The effect of the nanoparticle concentration on the average Nusselt number is shown in Fig. 5. Similar behavior is observed for

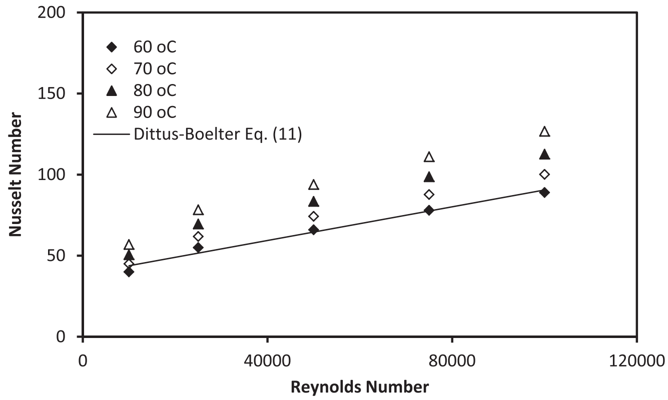

Fig. 6. The effect of inlet temperature on the Nusselt number.

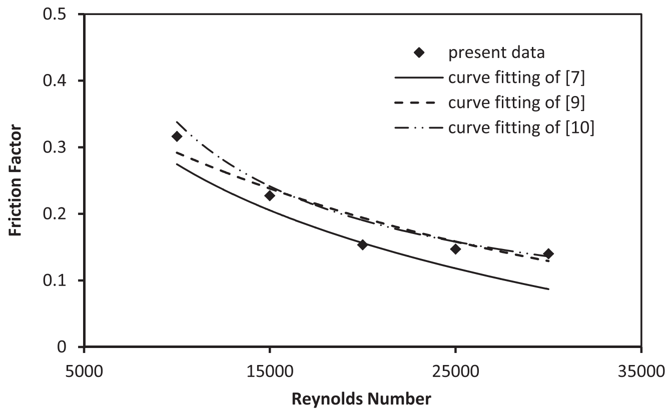

Fig. 7. Friction factor validation.

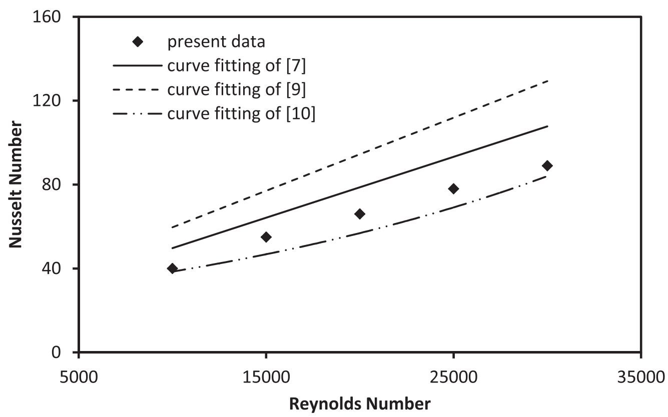

Fig. 8. Nusselt number validation.

the Nusselt number with increasing of volume concentrations and Reynolds numbers. Nusselt number increases with increasing of volume concentration and Reynolds number. The Dittus-Boelter Eq. (11) for pure water is indicated as the black solid line. It can be seen that the 4% nanofluid volume concentration has maximum Nusselt number value than other types and pure water, which agrees with [2,8]. Fig. 6 shows that the effect of the inlet temperature on friction factor of the TiO_2 nanofluid with volume concentrations of 1%. It seems that the increasing of the inlet temperature causes to increase of Nusselt number. The maximum deviations among the

Nusselt numbers were not greater than 10%. This behavior of Nusselt number is similar to [1–5]. It seems that there is significant effect of the nanofluid volume concentrations and the inlet temperature on Nusselt number.

4.3. Validation of CFD analysis

The CFD results were validated with experimental data of other investigators and the theoretical equations in Figs. 7 and 8. It can be observed that the maximum deviations of friction factor and Nusselt number are 7% and 8%, respectively. There is good agreement among CFD analysis and the experimental results of [7,9].

5. Conclusions

The friction factor and forced convection heat transfer enhancement of TiO_2 nanoparticles suspended in water were determined. Significant increases in friction factor and heat transfer enhancement were observed when nanoparticles at different volume concentrations were added to the base fluid. The maximum values of friction factor increased by 12% for TiO_2 nanoparticles dispersed in water at a 4% volume concentration. Likewise, the inlet temperature affected was studied on the friction factor. Insignificant influence observed of the inlet temperature from 60 to 90 °C to the friction factor. The highest Nusselt number obtained for TiO_2 nanoparticles in water was 18% better than that of pure water. The simulation results showed that the friction factor and Nusselt number behaviour of the nanofluids were highly dependent on the volume concentration, inlet temperature and Reynolds number. The results proved that TiO_2 nanofluids have a significant potential for hydrodynamic flow and heat transfer enhancement and are highly appropriate for industrial and practical applications. This solution provides promising ways for engineers to develop highly compact heat exchangers and automobile radiators. When adding nanoparticles to the base fluid, such as water, the potential enhancement of car engine cooling rates could entail more engine heat being removed or a reduction in size of the cooling system. Smaller cooling systems would lead to smaller and lighter radiators, which would benefit almost every aspect of car performance and increase fuel economy.

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