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Thermal hydraulic performance for hybrid composition ratio of TiO_2–SiO_2 nanofluids in a tube with wire coil inserts

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ABSTRACT

Hybrid nanofluids flows with wire coils are proven to be beneficial in improving the performance of heat transfer. The thermal-hydraulic performance with different hybrid composition ratio for two or more suspended nanoparticles in the hybrid nanofluids with wire coils is unknown. Therefore, the research work was carried out to evaluate the effect of hybrid composition ratio on the overall system performance for flow with wire coils. The TiO_2–SiO_2 nanofluids was prepared at constant 1.0% of volume concentration and hybrid composition ratio, R of TiO_2 to SiO_2 nanoparticles at variation of 0.2, 0.4, 0.5, 0.6, and 0.8. The wire coils were studied for various pitch ratio up to 4.17. The TiO_2–SiO_2 nanofluids heat transfer was improved up to 211.75% for flow with wire coils. The best thermal performance factor (TPF) was exceeded 1.72 and performed with $R = 0.2$ composition ratio and pitch ratio of 0.83. The present TPF for hybrid nanofluids is higher than TPF for existing single nanofluids hence confirmed the applicability of TiO_2–SiO_2 nanofluids at $R = 0.2$ composition ratio flow with wire coils.

1. Introduction

The convection heat transfer rate can be increased effectively by using passive, active and combination of heat transfer techniques. The active approach requires external energy with complex design and limited for specific application only. Meanwhile the passive technique was implemented without existence of external power. The passive method was increased the fluid turbulence and consequently improved the heat transfer with utilizing of inserts namely twisted tape, wire coils, helical wires and vortex generators [1,2]. Wire coils are utilized widely in heat transfer equipments. The application of wire coils come with several advantages as stated in the literatures [3,4]. (i) Low cost and simple design. (ii) Simple installation and easy to remove. (iii) Strengthen the mechanical strength of the plain tube. (iv) Possible to install in various heat exchanger system (retrofit). (v) Mitigation of fouling formation especially in chemical, refineries, and marine applications.

Researcher investigated the numerical heat transfer with employment of wire coils [5]. Hamid et al. [5] developed numerical

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model to estimate the heat transfer performance and friction factor of hybrid nanofluids with wire coil. They proposed new variables in eddy diffusivity of momentum and heat by using the coefficient, K and Prandtl index, ζ, respectively into van Driest eddy diffusivity equation. However, the model is only applicable for the hybrid nanofluids with composition ratio $R = 0.2$ at different volume concentrations and temperatures. Several experimental studies were undertaken by using single nanofluids with wire coils [6–9]. Saeedinia et al. [6] studied the performance of CuO/oil nanofluids in horizontal tube with wire coils. The study was conducted under laminar flow condition. The best performance evaluation factor was reported with the pitch and diameter of 30 mm and 1.5 mm, respectively. In another paper, Naik et al. [7] also considered CuO nanoparticle in their study however they used water as the base fluids. Two types of inserts were employed in their investigation namely wire coils and twisted tapes. They used the inserts in their evaluation of nanofluids performance under turbulent flow condition. They found that the performance for CuO nanofluids with wire coils is higher than the CuO nanofluids with twisted tapes.

Another study by Akbaridoust et al. [8] also used the similar type of CuO nanofluids. The study was carried out under laminar flow Reynolds number of 200 to 1000 at different wire coils pitch ratios and constant wall temperature. The wire coil pitch ratio of 0.11–0.35 was employed in their experimental investigation. The results concluded the performance index in the range of 0.973–1.162. In addition, the maximum performance index attained at 0.1% concentration and 0.25 pitch ratio. Later, Bahremand et al. [9] undertaken an experimental investigation of Ag/water nanofluids under turbulent flow and up to 40,000 Reynolds number. Four wire coils with pitch ratio of 0.200–0.355 were used in their study. They concluded that the helical pipe with greater curvature ratio at higher concentration of nanofluids resulted with significant increment of heat transfer coefficient.

Behabadi et al. [10] investigated the performance of MWCNT/water nanofluids with the employment of wire coils in a horizontal tube. They analysed the nanofluids flow of 10,000 to 20,000 Reynolds number. Five wire coils were used with pitch ratio and e/D (thickness over diameter) ratio in a range of 1.70–2.83 and 0.113 to 0.170, respectively. The results demonstrated the maximum enhancement in heat transfer up to 85% whereas the friction factor was increased 4.75 times higher than water in a tube. Sundar et al. [11] evaluated the performance of low concentration Fe_3O_4/water nanofluids with return bend and wire coils. The maximum enhancement in Nusselt number was increased up to 32.03% and accompanied by increasing in friction factor of 1.162 times at 0.06% concentration. Goudarzi and Jamali [12] utilized Al_2O_3/EG nanofluids in radiator with two types of wire coils. The wire coils were located at the right and left channel of the radiator. The use of nanofluids and wire coils in radiator was showed a significant improvement in heat transfer performance. The thermal performance factor also was improved in the range of 1.019–1.087.

Single nanofluids was widely used in various research [13–17] and applications [17–20]. Until recently, hybrid nanofluids have been implemented in many studies [21]. The characteristics and thermal properties of the hybrid nanofluids improved the heat transfer performance and observed better than the single nanofluids [22,23]. The reviews on hybrid nanofluids performance can be found in various literatures [24–27]. Yarmand et al. [28] studied the convective heat transfer of GNP-Pt hybrid nanofluids. They reported a significant increment heat transfer performance and proportional with Reynold number and weight concentration of the hybrid nanofluids. The heat transfer enhancement was increased for up to 28.48%. Hussien et al. [29] carried out an experimental investigation of single MWCNTs and MWCNTs-GNPs hybrid nanofluids in a mini channel. The MWCNTs-GNPs hybrid nanofluids was found to provide higher heat transfer enhancement compared to MWCNTs nanofluids. Yang et al. [30] was considered nanoparticles migration by using a mathematical model. They used Al_2O_3–TiO_2 and Al_2O_3–ZrO_2 hybrid nanofluids. The results indicated that Al_2O_3–TiO_2 nanofluids exhibits higher Nusselt number and better Performance Evaluation Criteria (PEC) with lower friction factor than Al_2O_3–ZrO_2 nanofluids. Huminic and Huminic [31] conducted a numerical study on MWCNT-Fe_3O_4 and ND-Fe_3O_4 hybrid nanofluids and they tested in a flattened tube. They concluded that the MWCNT-Fe_3O_4 hybrid nanofluids exhibited more reduction in entropy generation in comparison to ND-Fe_3O_4 hybrid nanofluids.

In the literature, several studies were investigated the thermo-physical properties and heat transfer performance of TiO_2–SiO_2 nanofluids. The thermal conductivity [32] and dynamic viscosity of TiO_2–SiO_2 nanofluids were presented for various volume concentrations [33,34] and different hybrid composition ratios [35]. Further, the heat transfer performance investigations for turbulent flow in a tube were undertaken for TiO_2–SiO_2 nanofluids at different volume concentrations [36–39] and various hybrid composition ratios [21]. From the authors' knowledge, limited study in literature conducted for convection heat transfer with hybrid nanofluids by utilizing wire coils in a tube. In the previous work, only one paper presented the TiO_2–SiO_2 nanofluids performance with wire coil [40]. Abdul Hamid et al. [40] studied the heat transfer performance with wire coils and limited for TiO_2–SiO_2 nanofluids at different volume concentrations. However, the present work focused on the additional parameter namely hybrid composition ratios, R with the use of wire coils. The present work is undertaken to explore the significant contribution of hybrid nanoparticles composition ratio of TiO_2–SiO_2 nanofluids on thermal-hydraulic performance for flow with wire coils. Five composition ratios, R of TiO_2 to SiO_2 nanoparticles are prepared for 0.2, 0.4, 0.5, 0.6, and 0.8 by volume percent. The experiment is conducted with TiO_2–SiO_2 nanofluids at 1.0% volume concentration and wire coil pitch ratios of 0.83–4.17.

2. Methodology

The present section explains the procedures of hybrid nanofluids preparation. In addition, the section describes the measurement technique for thermo-physical properties of hybrid nanofluids. Further, the experimental approach for forced convection is explained comprehensively by covering the related heat transfer analysis, thermal-hydraulic performance and uncertainty analysis. The friction factor analysis is also considered in the present work. Lastly, the effectiveness of hybrid nanofluids flow with wire coils is analysed by using the thermal performance factor (TPF). The TPF is defined by a ratio of the heat transfer rate difference to the variation in the friction factor [41]. The materials of TiO_2 and SiO_2 nanoparticles are used in the present study. TiO_2 nanoparticles have been used widely in water treatments and cosmetic applications hence a safe material for commercialization. SiO_2 nanoparticles performed with high strength and stiffness. In addition, the nanoparticles behaved with outstanding mechanical properties and excellent thermal stability [42,43]. The dispersion of both SiO_2 and TiO_2 nanoparticles in base fluids mixture was improved the thermal properties [33,35] and heat transfer performance [36].

2.1. TiO_2–SiO_2 nanofluids preparation

The hybrid nanofluids was formulated by mixing the single TiO_2 and SiO_2 nanofluids into the mixture of the base fluids in 60:40 vol ratio for water and EG, respectively. The TiO_2 and SiO_2 nanofluids in the suspended form was produced from US Research Nanomaterials, Inc. With original concentration of 40% and 25%, respectively in weight percent. Table 1 describes the related properties in the present study for water, EG, single TiO_2 and SiO_2 nanofluids. Eq. (1) was used in the present analysis to convert the original weight concentration into volume concentration. Further, the dilution process of single nanofluids from original concentration to 1.0% volume concentration was undertaken by using Eq. (2).

$$\phi = \frac{\omega \rho_{bf}}{\left(1 - \frac{\omega}{100}\right)\rho_p + \frac{\omega}{100}\rho_{bf}} \tag{1}$$

$$\Delta V = (V_2 - V_1) = V_1\left(\frac{\phi_1}{\phi_2} - 1\right) \tag{2}$$

The single TiO_2 and SiO_2 nanofluids at 1.0% volume concentration were mixed together at the composition ratio, R of 0.2, 0.4, 0.5, 0.6, and 0.8 by volume percent. The samples were subjected to ultrasonic bath for sonication stage. The sonication process is important in preparing the nanofluids to ensure a uniform dispersion of nanoparticles and production of stable nanofluids [44,45]. The sonication was undergone for 2 h by referring to the previous literatures [46,47]. The presence of single nanoparticles elements in the hybrid nanofluids were confirmed by using TEM images in Fig. 1. The details evaluation for stability condition of TiO_2–SiO_2 nanofluids were presented in Hamid et al. [35].

2.2. Thermo-physical properties of TiO_2–SiO_2 nanofluids

The regression equations of Eq. (3) and Eq. (4) were used in the estimation of thermal conductivity and dynamic viscosity, respectively for TiO_2–SiO_2 nanofluids at different hybrid composition ratios. The equations were established by Hamid et al. [35]. The equations are applicable for the estimation of TiO_2–SiO_2 nanofluids at 1.0% volume concentration. Meanwhile, the estimation of density and specific heat of TiO_2–SiO_2 nanofluids is determined from the conventional mixture relation as presented by Eq. (5) and Eq. (6), respectively.

$$k_{eff} = \frac{k_{nf}}{k_{bf}} = 1.17(1+R)^{-0.1151}\left(\frac{T}{80}\right)^{0.0437} \tag{3}$$

$$\mu_r = \frac{\mu_{nf}}{\mu_{bf}} = 1.42(1+R)^{-0.1063}\left(\frac{T}{80}\right)^{0.2321} \tag{4}$$

$$\rho_{nf} = (1-\varphi)\rho_{bf} + \varphi(R\rho)_{TiO_2} + \varphi(R\rho)_{SiO_2} \tag{5}$$

$$C_{nf} = \frac{(1-\varphi)\rho_{bf}C_{bf} + \varphi(R\rho C)_{TiO_2} + \varphi(R\rho C)_{SiO_2}}{\rho_{nf}} \tag{6}$$

Table 1
Description of materials and solution used in preparation of TiO_2–SiO_2 nanofluids [58–60].

Descriptions	TiO_2		SiO_2		Water	EG
Phase	Solid	Liquid	Solid	Liquid	Liquid	Liquid
Size [nm]	50	–	22	–	–	–
Thermal conductivity k [W/m.K]	8.4	–	1.4	–	0.619	0.253
Dynamic viscosity, μ x10^{-3} [kg/m.s]	–	–	–	–	1.41	0.777
Density, ρ [kg/m^3]	4230	–	2220	–	995	1110
Specific heat, C_p [J/kg.K]	692	–	745	–	4070	2430
Weight concentration, ω [%]		40		25	–	–
Volume concentration, φ [%]		13.61[a]		13.05[a]	–	–

[a] Conversion from Eq. (1).

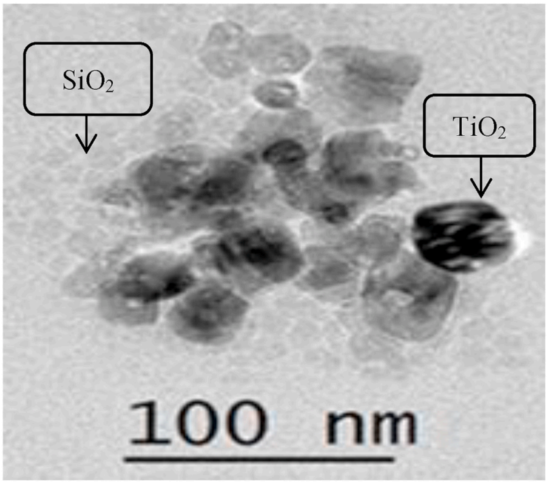


Fig. 1. TEM images for TiO_2–SiO_2 nanofluids.

2.3. Forced convection heat transfer experiment

The forced convection experiment was undertaken under constant heat flux condition and bulk temperature of 7955 W/m^2 and 30 °C, respectively. The main test section was fabricated by using a tube of diameters 16 mm for inner side and 19 mm for outer side with nichrome heater of 12 kW ratings. Ceramic fibre was used to insulate the test unit. Two thermocouples (K-type) are used to measure inlet and outlet of the test section. While, five more thermocouples are measured the surfaces of the tube wall. The five thermocouples were located at 0.25, 0.5, 0.75, 1.0 and 1.25 m from the inlet to measure the surface temperature of the tube whereas another two thermocouples were mounted on the inlet and outlet of the test section to measure the fluid temperature. In the present study, the heat transfer analysis was performed using the surface temperature of the outer surface. By assuming no heat loss, the effect of copper tube thickness (1.5 mm) was calculated to evaluate the difference between inner and outer surface temperature. The difference between the inside surface temperature (T_i) and outside surface temperature (T_o) was calculated to be 0.089%. The difference between the outside and inside surface temperature is considerably small, hence the temperatures taken at the outside surface of the tube as the surface temperature are considered reliable for the present heat transfer analysis.

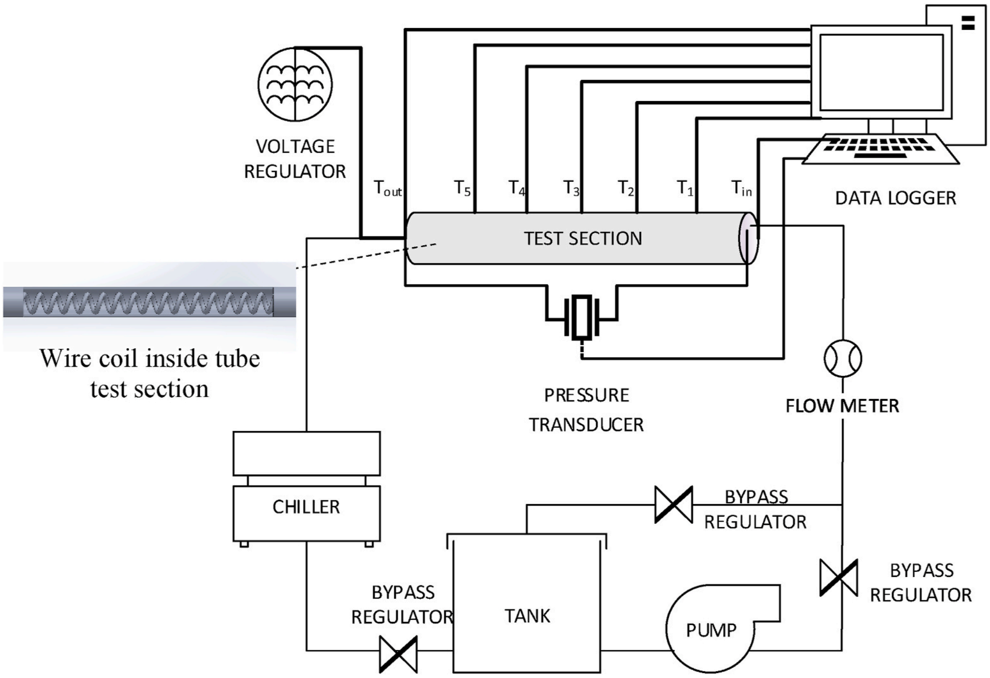


Fig. 2. Schematic diagram of forced convection heat transfer test setup.

The sample of hybrid nanofluids with minimum quantity of 20 L was used in the present study. The nanofluids were circulated by using 1.0 hp pump. The fluids were heated and later the heat was extracted from the fluids with the use of chiller at the outlet of the test section. The flow rate was controlled in the range of 4–20 LPM. The pressure drop within the test unit was measured from a calibrated differential transducer of 5.0 psi. A data logger was used to record the experimental data of temperatures and pressure drop. Fig. 2 illustrated the test setup diagram. The experimental setup was validated by experimental data water/EG (60:40) mixture. The validation stage is important to confirm the capability of the setup to evaluate the heat transfer performance of hybrid nanofluids. The setup was idled for 30–60 min to achieve steady state condition. The temperatures, pressures and flow rates were recorded at steady state condition. Under steady state condition, the temperature will remain constant with time. The data logger was set to record the temperature and pressure for 1 min with every 2 s interval. The bulk temperature, by using the average value of the inlet and outlet temperature, was controlled and monitored at a constant temperature of 30 °C with variation of ±1 °C. For the new flow rate, the previous procedure was repeated continuously with flow rate increment of 2 lpm until the maximum flow rate of 18 lpm was reached. The experiment was repeated for three times and average data was considered in the final analysis. Previously, the similar test setup was used by Abdul Hamid et al. [40], Mohamad et al. [37] and Nabil et al. [36] for various types of nanofluids.

The wire coils were designed for five pitch-to-diameter ratios, P/D or known as pitch ratio. Constant diameter, d and thickness, e are considered in the design with varying the pitch, P of the coils. The geometries and characteristics of the wire coils were shown in Fig. 3 and Table 2, respectively. Teflon layers was used to insulate the mild steel of wire coils to avoid the direct conduction from the tube wall [40,48,49]. Hydraulic diameter, D_h was calculated from Eq. (7) as suggested by previous studies for wire coils [10,11] where D_c is coil diameter. In the present paper, the notation for pitch ratio is given by P/D instead of P/D_c. The effective hydraulic diameter was decreased because the presence of wire coils in the tube.

$$D_h = \frac{D^2 - \pi e^2 D_c/P}{D + \pi e D_c/P} \tag{7}$$

The heat transfer analysis is based on Newton's law of cooling. Eq. (8) represents the heat transfer rate, $\dot{Q}$ to fluids. Noted that the heat supplied to the test section is given by $\dot{Q} = VI$. The heat loss to the surrounding was neglected with 2.0% difference between heat supplied and heat absorbed. Eq. (9) estimated the heat transfer coefficient of the nanofluids. Finally, Darcy friction factor in Eq. (10) was used to estimate the friction factor of the present system.

$$\dot{Q} = hA(T_s - T_b) = \dot{m}C_p\Delta T \tag{8}$$

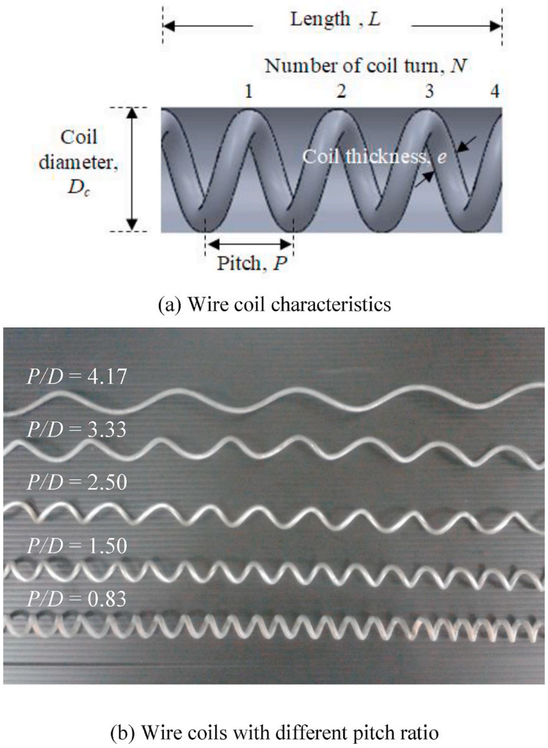


Fig. 3. Wire coil with various pitch ratio, P/D.

Table 2
Characteristic dimensions of the wire coils.

Wire coil number	Diameter, D_c (mm)	Hydraulic diameter, D_h (mm)	Pitch, P (mm)	Thickness, e (mm)	P/D (mm/mm)	e/D (mm/mm)
WC1	12	8.13	10	3	0.83	0.25
WC2		10.64	18		1.50	
WC3		12.38	30		2.50	
WC4		13.15	40		3.33	
WC5		13.65	50		4.17	

$$h_{exp} = \frac{\dot{Q}}{A(T_s - T_b)} \tag{9}$$

$$f_{exp} = \frac{\Delta P_{exp}}{\left(\frac{L}{D}\right)\left(\frac{\rho \nu^2}{2}\right)} \tag{10}$$

Eqs. (11)–(13) are determined the parameter for Prandtl number, Reynolds number, and Nusselt number. The experimental Nusselt number and friction factor of water/EG mixture were validated with the Dittus and Boelter [50] and Blasius [51] equations as given in Eqs. (14) and (15), respectively.

$$\mathrm{Pr} = \frac{\mu C_p}{k} \tag{11}$$

$$\mathrm{Re} = \frac{\rho \nu D}{\mu} \tag{12}$$

$$\mathrm{Nu} = \frac{hD}{k} \tag{13}$$

$$\mathrm{Nu}_{DB} = 0.023\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} \tag{14}$$

$$f_{Bl} = \frac{0.3164}{\mathrm{Re}^{0.25}} \tag{15}$$

2.4. Thermal-hydraulic performance

The wire coils is known with capability to enhance the performance of heat transfer. However, the heat transfer enhancement was accompanied with high pressure drop hence disadvantage to the overall performance. Therefore, the thermal performance factor (TPF) is determined to assess the overall effectiveness of the wire coils. Thermal-hydraulic performance of hybrid nanofluids for flow with wire coils is evaluated by a parameter of the thermal performance factor, η. TPF is the Nusselt number ratio to friction factor ratio to the power of 1/3 and presented by Eq. (16). The index of 1/3 is used and consistent with the previous studies [7,8,30,52] to compare under identical pumping power. TPF with more than one (1) indicates more enhancements in heat transfer compared to the enhancement in friction factor with the use of wire coils. The high values of the TPF are recommended to represent the best condition for engineering applications. TPF of a device is said to be effective when its achieved significant improvement in heat transfer however with minimum increment of friction factor [53].

$$\eta = \frac{\frac{Nu_{nf,WC}}{Nu_{PT}}}{\left(\frac{f_{nf,WC}}{f_{PT}}\right)^{\frac{1}{3}}} \tag{16}$$

Table 3
Summary of uncertainties analysis.

No.	Parameter	Uncertainty error (%)
1	Reynolds number, *Re*	0.15–0.29
2	Heat flux, *q*	0.18
3	Heat transfer coefficient, *h*	0.75–0.91
4	Nusselt number, *Nu*	0.76–0.91
5	Friction factor, *f*	0.13–0.78

2.5. Uncertainty evaluation

The uncertainty analysis was undertaken for the instrumentations and relevant quantities in the present study. The quantities namely Nusselt number, friction factor, Reynolds number, heat transfer coefficient and heat flux were analysed accordingly. The present uncertainty evaluation was followed the similar procedures from literatures [54,55]. Table 3 was summarized the experimental uncertainty of the present experimental work.

3. Results and discussion

3.1. Experimental validation of wire coils

The details explanation on the TiO_2–SiO_2 nanofluids properties with composition ratio was presented in Hamid et al. [35]. The experiment with wire coils were undertaken under similar working conditions in the previous section. The water/EG mixture was considered in present analysis to confirm the reliability and accuracy of the setup with wire coils. The experiment was undertaken with five wire coils for dimensionless pitch ratio (P/D) of 0.83, 1.50, 2.50, 3.33 and 4.17 at various Reynolds numbers. The equations of Sundar et al. [11], Behabadi et al. [10] and García et al. [48] were compared with the experimental Nusselt numbers and friction factor of water/EG mixture with wire coils. These equations are applicable within the range of present experimental pitch ratio. The results for validation of Nusselt number and friction factor are presented in Fig. 4(a) and (b), respectively. Fig. 4(a) shows the comparison of present experimental data for wire coils with the equation of Sundar et al. [11]. The water/EG mixture Nusselt number was increased with decreasing pitch ratio. At the lowest pitch ratio of $P/D = 0.83$, the present data is found in agreement with estimated values from equation with average deviation of 3.1%. However, the equation by Sundar et al. [11] over predicts the Nusselt number at higher P/D value due to out-of-range pitch ratio.

The satisfactory agreement of the present data for friction factor of water/EG mixture in comparison to the equations by García

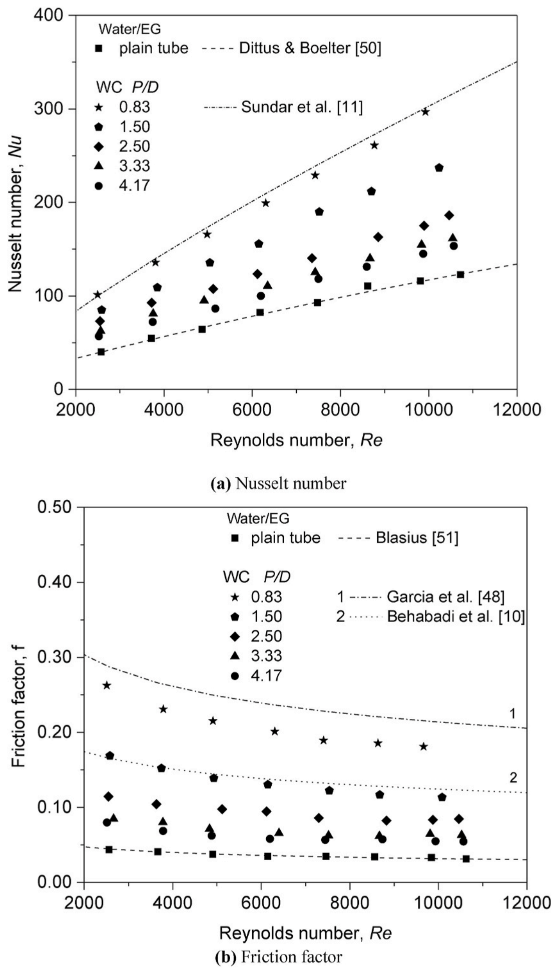


Fig. 4. Nusselt number and friction factor validation for water/EG mixture with wire coils.

et al. [48] and Behabadi et al. [10] is shown in Fig. 4(b). The present friction factor of water/EG mixture was decreased with pitch ratio. The average deviation of measured water/EG mixture with García et al. [48] at pitch ratio 0.83 is 14.2%. Meanwhile, 3.9% average deviation was recorded with Behabadi et al. [10] for 1.50 pitch ratio. The present data for both friction factor and Nusselt number is observed in agreement with the equations of Sundar et al. [11], Behabadi et al. [10] and García et al. [48] at low pitch ratios. However, significant deviation occurred for the wire coils at high pitch ratio. The deviation is due to the factors such as different acceptable range of pitch ratio, variation with wire coil geometries or materials and different working fluids. Sundar et al. [11], Behabadi et al. [10] and García et al. [48] used pitch ratios of less than 2.83 with water as the working fluids.

3.2. *Wire coils with different composition ratios*

The variation of Nusselt number and the increment of friction factor at all composition ratios of hybrid nanofluids with wire coils are illustrated in Fig. 5 and **6**, respectively. The Nusselt number for TiO2–SiO2 nanofluids are found better than mixture of water/EG at all pitch ratios. In addition, the highest heat transfer augmentation was obtained at $R = 0.2$ for all composition ratio. Meanwhile, the maximum heat transfer enhancement was occurred at pitch ratio of 0.83 for all composition ratios. Inversely, the pitch ratio of 4.17 showed the lowest heat transfer enhancement for each composition ratio.

With the decrease in pitch ratio from 1.50 to 0.83, the enhancement in heat transfer performance becomes more significant and increased for more than 100% when comparing to mixture of water/EG without wire coil. For example, the heat transfer enhancement is 211.75% at pitch ratio of 0.83 compared to water/EG mixture in a plain tube. Meanwhile, the lowest heat transfer augmentation occurred at composition ratio of $R = 0.5$ or $R = 0.8$ for all pitch ratios of wire coils. The use of wire coils contributes to the remarkable heat transfer improvement due to some reasons. The swirl flow inside the tube generated by the wire coil will cause the mixing fluid condition. At this state, the heat energy can be transferred efficiently [56]. Furthermore, mixing flow flattens the distribution of temperature. Therefore, the temperature gradient of the fluids and wall become steeper [57].

The effect of composition ratio on friction factor of hybrid nanofluids is shown in Fig. 6 for different pitch ratio. The friction factor of TiO_2–SiO_2 nanofluids was increased with reducing of pitch ratio. The friction factor was increased up to 1.8, 2.0 and 2.7 times greater than mixture of water/EG in a plain tube for 4.17, 3.33 and 2.50 pitch ratios, respectively. Furthermore, the friction factor was drastically enlarged for 1.50 and 0.83 pitch ratios with increments of more than 3.8 and 6.0 times, respectively. Meanwhile, the TiO_2–SiO_2 nanofluids friction factor was recorded with slightly higher than water/EG mixture for the condition of similar pitch ratio and different composition ratios. No significant variation of friction factor for different composition ratios of TiO_2–SiO_2 nanofluids and was applicable for all pitch ratios. In addition, the distribution of friction factor at all composition ratios showed to be almost equivalent to each other. The wire coil produced a substantial fluid friction and due to the dissipation of the fluids dynamic pressure. Moreover, the small pitch ratio value provides higher surface area with increasing of coil number at small pitch ratio. Consequently, the blockage of the flow by wire coil is also increased through the flow path, therefore contribute to significant increment in friction

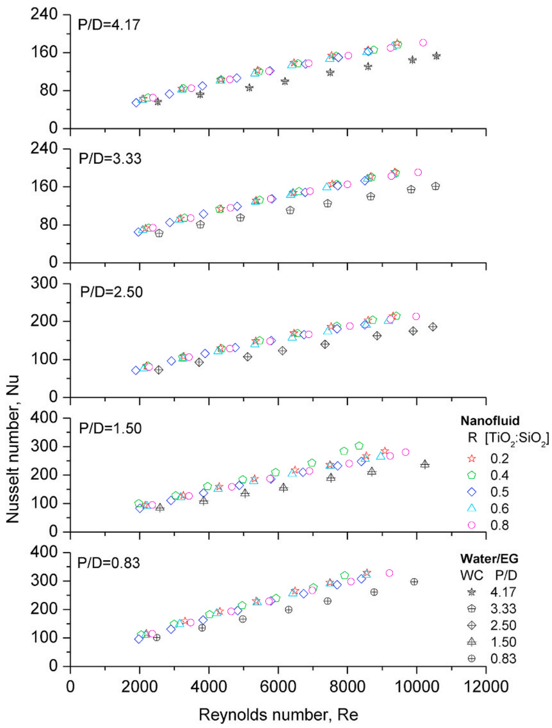


Fig. 5. Nusselt number of TiO_2–SiO_2 nanofluids for flow in a tube with wire coils.

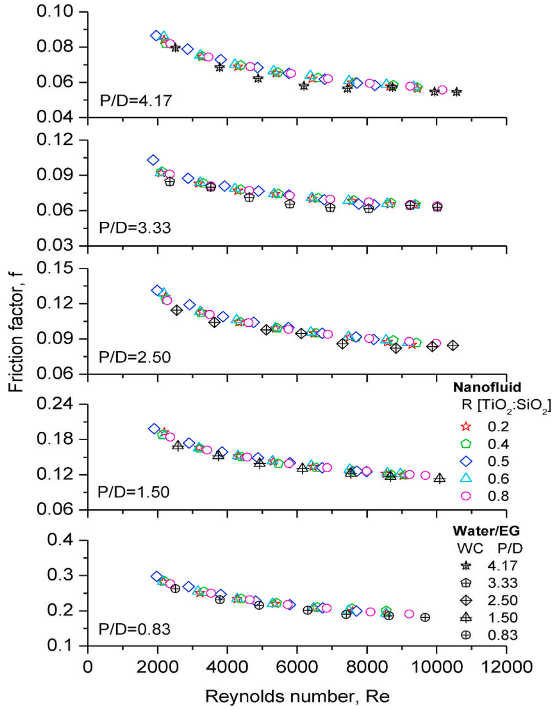


Fig. 6. Friction factor of TiO_2–SiO_2 nanofluids for flow in a tube with wire coils.

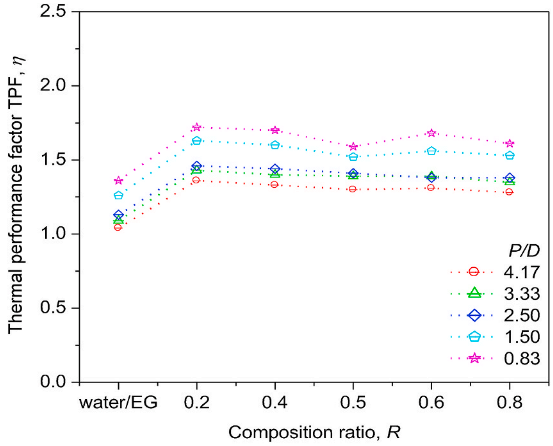
factor [10].

3.3. Thermal performance factor

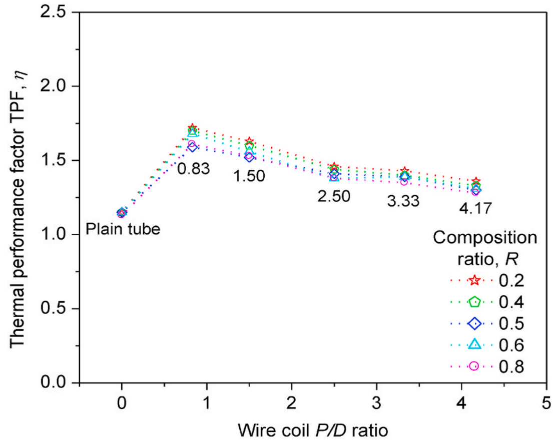
The TPF for various composition ratios and different pitch ratios is shown in Fig. 7. Fig. 7(a) illustrates the TPF against composition ratio at various pitch ratios. The TPF of hybrid nanofluids for all composition ratios and pitch ratios were shown to be greater than mixture of water/EG. The TPF also increased with decreasing wire coil pitch ratio and applicable for all TiO_2–SiO_2 nanofluids composition ratios. Furthermore, all composition ratios at pitch ratios of 4.17, 3.33 and 2.50 resulted with almost similar TPF. However, lower TPF than other composition ratios were found at $R = 0.5$ for wire coil pitch ratios of 1.50 and 0.83. The TPF variation with pitch ratio is provided by Fig. 7(b). The TPF of present nanofluids in a plain tube is approximately 1.15 for all composition ratios. Later, the TPF was increased significantly with the utilization of wire coils. The TPF of hybrid nanofluids with wire coils were recorded in the range of 1.28–1.72 for various pitch ratios at different composition ratios. The maximum TPF up to 1.72 was achieved at $R = 0.2$ with 0.83 pitch ratio. Meanwhile, the minimum TPF of 1.28 was observed at $R = 0.8$ with 4.17 pitch ratio. The TPF of hybrid nanofluids are strongly influenced by the variation of pitch ratio; however, it is insignificant with composition ratio. The heat transfer enhancement is more dominant than the raise of friction factor with the use of hybrid nanofluids and wire coils. Hence, this condition yields TPF greater than one or even better.

The TPF of the present study is compared with the existing TPF in the literature and presented in Fig. 8. Naik et al. [7], Akbaridoust et al. [8], Goudarzi and Jamali [12], and Keklikcioglu and Ozceyhan [49] were used air and single nanofluids as working fluids in their investigation. The comparison was considered the previous experimental studies with pitch ratios of less than 2.0. From the figure, the present data is comparable to the data of Keklikcioglu and Ozceyhan [49] even though they used air as the working fluid. This observation can confirm that the present hybrid nanofluids flow with wire coils in a tube feasible for heat exchanger applications. However, the best parameters condition specifically volume concentration and pitch ratio are needed for the optimum performance of TiO_2–SiO_2 nanofluids operating with wire coils.

Yang et al. [30] stated that by dispersing two or more nanoparticles into a based fluids can improve the heat transfer of hybrid nanofluids with the trade-off between the advantages and disadvantages of each nanoparticles. In the present work, the high percentage of SiO_2 in the solution provides more benefits to the performance of TiO_2–SiO_2 nanofluids. The results from the present heat transfer analysis and TPF evaluation showed good agreement by indicating $R = 0.2$ and $R = 0.4$ as the most recommended composition ratio for TiO_2–SiO_2 nanofluids. However, after considering from the factor of effective thermal conductivity, TPF performance and costing of each composition ratio, the composition ratio at $R = 0.2$ was selected as the optimum composition ratio. The composition ratio at $R = 0.2$ provides high heat transfer (comparable performance with $R = 0.4$), highest effective thermal conductivity, lowest relative viscosity and good PER performance with lowest production cost for composition of 80% SiO_2 and 20% TiO_2 nanoparticles. This finding was supported by previous published work in literature [35,36].



(a) Variation of *P/D* ratio



(b) Variation of composition ratio

Fig. 7. Thermal performance factor of TiO_2–SiO_2 nanofluids.

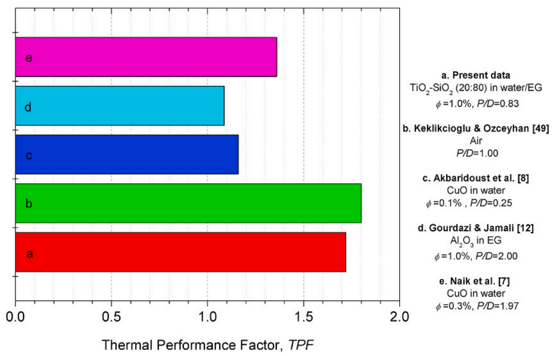


Fig. 8. Comparison of thermal performance factor with available literatures.

3.4. Experimental regression correlations

The regression correlations for the Nusselt number and friction factor are given by Eqs. (17) and (18), respectively for flow of hybrid nanofluids with wire coils. The regression models were considered 233 experimental data. The average deviation, standard deviation and maximum deviation are given in Fig. 9. A good agreement between the experimental data and the data estimation from Eqs. (13) and (14), was confirmed in Fig. 9. Eqs. (17) and (18) are applicable for are applicable for range of Reynolds number of 2300 $\leq Re \leq$ 12,000, volume concentration range of $0 \leq \varphi \leq 1.0\%$., composition ratio of $0.2 \leq R \leq 0.8$, and pitch ratio range of $0.83 \leq P/D \leq$

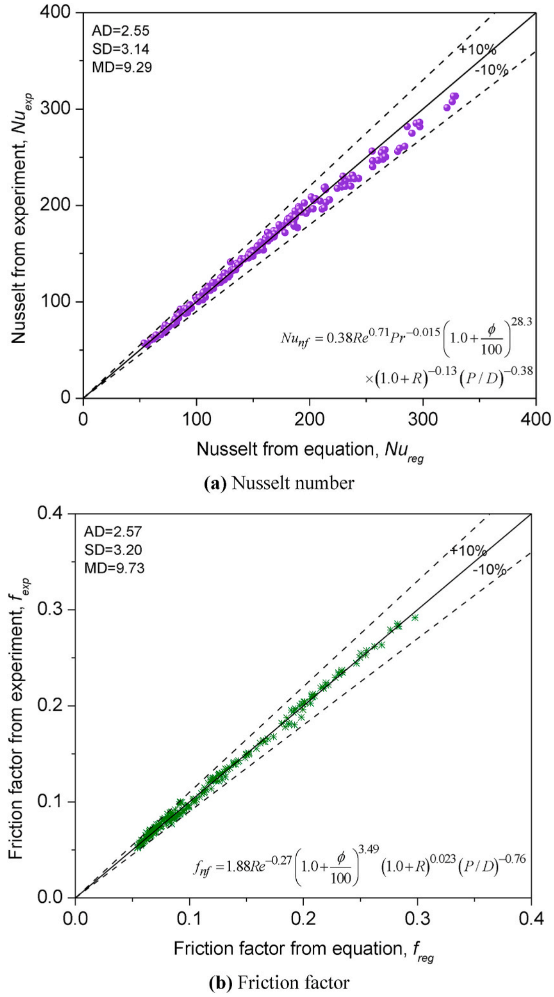


Fig. 9. Comparison of experimental TiO_2–SiO_2 nanofluids for wire coils with the proposed regression equations.

4.17. Fig. 9 presents the distributions of data from the experiment in comparison to the regression correlations.

$$\mathrm{Nu_{nf}} = 0.38\mathrm{Re}^{0.71}\mathrm{Pr}^{-0.015}\left(1.0+\frac{\varphi}{100}\right)^{28.3}(1.0+\mathrm{R})^{-0.13}(P/D)^{-0.38} \tag{17}$$

$$\mathrm{f_{nf}} = 1.88\mathrm{Re}^{-0.27}\left(1.0+\frac{\varphi}{100}\right)^{3.49}(1.0+\mathrm{R})^{0.023}(P/D)^{-0.76} \tag{18}$$

4. Conclusions

The present study emphasizes the characterization of TiO_2–SiO_2 nanofluids at different composition ratios. Furthermore, the thermal-hydraulic performance analysis was undertaken for flow of hybrid nanofluids with wire coils by evaluating the performance of heat transfer, the friction factor condition and TPF. The different composition ratio of single TiO_2 and SiO_2 nanofluids influence the properties of hybrid nanofluids. From the present experimental work, conclusions for are given as follows:

i. The thermal conductivity of composition ratio $R = 0.2$ and 0.4 have better improvements compared to other composition ratios. Meanwhile, for dynamic viscosity, the composition ratio $R = 0.5$ is the most disadvantageous among others due to the greater increment in viscosity, which is considered one of the drawbacks in heat transfer application.
ii. The significant enhancement in heat transfer was obtained at smaller wire coil pitch ratio for all composition ratios of hybrid nanofluids. The best condition of heat transfer was reached up to 211.75% higher than based fluids at condition of composition ratio $R = 0.2$, 1.0% concentration and 0.83 pitch ratio.
iii. The friction factor insignificantly increased with hybrid composition ratio for flow with and without wire coils.

iv The use of wire coils with hybrid nanofluids is feasible for heat exchanger applications with the TPF of more than 1.0 at all working conditions. The variation of TPF was recorded in the range of 1.28–1.72 for nanofluids at different composition ratios.

CRediT authorship contribution statement

W.H. Azmi: Project administration, Supervision, Methodology. **K. Abdul Hamid:** Data curation, Investigation, Writing – original draft. **A.I. Ramadhan:** Conceptualization. **A.I.M. Shaiful:** Resources, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

D	diameter
EG	ethylene glycol
f	friction factor
h	heat transfer coefficient
k	thermal conductivity
L	length
$\dot{m}$	mass flow rate
Nu	Nusselt number
ΔP	pressure drop
Pr	Prandtl number
P/D	pitch ratio, ratio of pitch to diameter of wire coil
$\dot{Q}$	power
R	volume fraction of single TiO_2 or SiO_2 nanofluids in mixture TiO_2–SiO_2
Re	Reynolds number
T	temperature
TEM	transmission electron microscopy
V	voltage
v	velocity

Greek symbols

φ	volume concentration, %
μ	dynamic viscosity, kg/m.s
ϕ	volume fraction
ρ	density, kg/m^3
ω	weight concentration, %

Subscript

b	bulk
bf	base fluid
Bl	Blasius
DB	Dittus-Boelter
nf	nanofluids
exp	experimental
p	nanoparticle
s	surface

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