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Thermal Performance of Shell and Tube Heat Exchanger Using PG/Water and Al₂O₃ Nanofluid

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Additional information is available at the end of the chapter

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Abstract

This study investigates experimentally the thermal performance of propylene glycol/water with a concentration of (10/90) % and Al₂O₃/water nanofluid with a volume concentration of (0.1, 0.4, 0.8, 1.5, and 2.5) percentage under turbulent flow inside a horizontal shell and tube heat exchanger. The results indicate that the convective heat transfer coefficient of the nanofluid is higher than the base PG/water for the same inlet temperature and mass flow rates. The heat transfer of the nanofluid increases with the increase in mass flow rate as well as the Al₂O₃ nanofluid volume concentration. Results also indicate that the increase in the concentration of the particles causes an increase in the viscosity which leads to an increase in friction factor. The effect of Peclet number, Reynolds number, Nusselt number, and Stanton number has been investigated. Those dimensionless number values change with the change in the working fluid density, Prandtl number, and volume concentration of the suspended particles.

Keywords: heat exchanger, nanofluid, convection heat transfer

1. Introduction

With the rapid advancement in modern nanotechnology, nanofluids which are the working fluids with nanometer-sized particles (normally less than 100 nm) are used instead of micrometer size for dispersing in base fluids. The name was suggested for the first time by Choi [1]. The nanofluid can have significantly greater thermal conductivity with main disadvantage, which is increase in pressure drop. In this new age of energy awareness, reducing the size of the devices and increasing the efficiency are the main goal. Nanofluids have been demonstrated to be able to handle this role in some instances as a smart fluid. In electric power plants, the hot steam coming out from the turbine needs to be condensed, the unit that does this job

called a condenser. Since its large size, the process of maintenance is difficult, is expensive, and needs a space for occupation. To minimize the size of the condenser, but still gets the same or better efficiency, we need to use a better working fluid than the water, and here comes the need of the nanofluid. The chapter is organized as follows: experimental setup is presented in Section 2. An explanation of the device used is introduced in Section 3. Experimental results are shown in Section 4. Finally, conclusion is outlined in Section 3.

2. Experimental setup

The project has been designed in [2] and used here to transfer heat from hot water in a heat exchanger to nanofluid and/or propylene glycol/water with a concentration of (10/90) % stored in a separate tank and make temperature calibrations for the same by employing two thermocouples. Moreover, flow meters are installed in the pipes carrying nanofluid and PG/water to check the flowing rate. The complete system is very dynamic and easy to use. The mechanical structure design is shown in **Figure 1**.

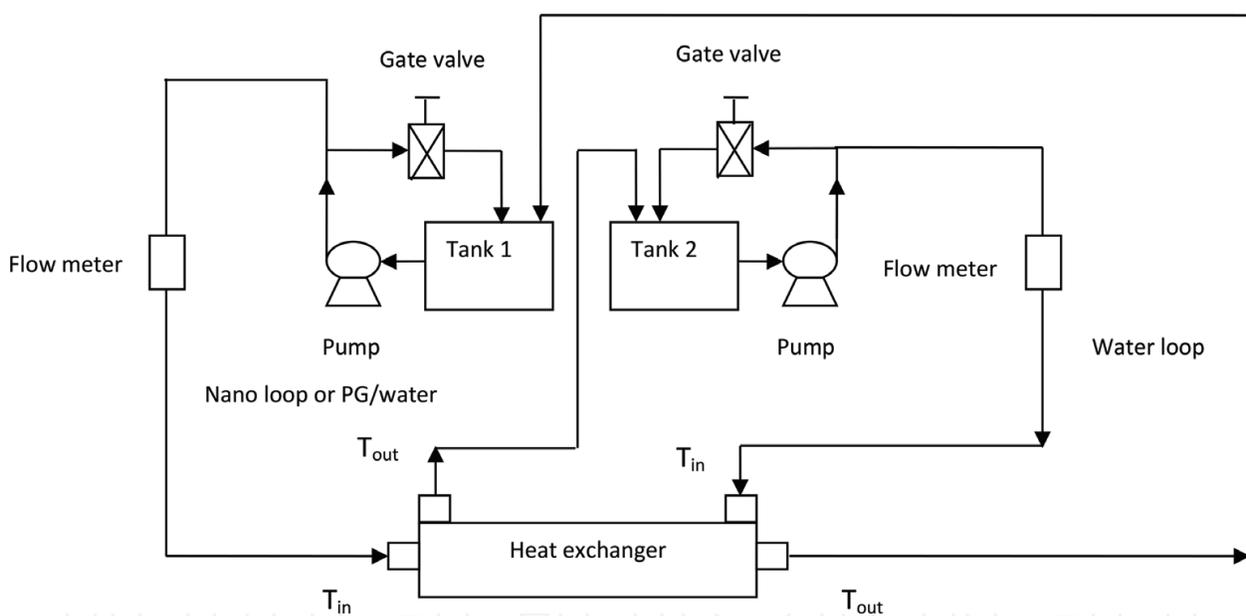


Figure 1. System diagram.

3. Basic working of the heat exchanger device

There are two loops in the system; the two flow loops carry heated nanofluid or PG/water and the other cooling water. Each flow loop contains a tank, a pump with a flow meter, and a bypass valve to choose the required flow rate for the study. The nanofluid tank (Tank 1) is filled with 4 liters, while the hot water tank (Tank 2) is filled with 12 liters. The 248-mm-long shell

and tube heat exchanger is made of stainless steel type 316 L, with 37 tubes inside the shell. Each tube diameter is 2.4 mm, a wall thickness of 0.25 mm, and a heat transfer area of 0.05 m². Both inlet and outlet points of the liquid streams have a J-type thermocouples with removable bulbs for measuring the bulk temperatures. The experimental device was kept working for 15 minutes time period in each case of the chosen mass flow rates.

The system operates in a way that when the nanofluid or PG/water flows inside the tubes in the heat exchanger, the temperature reading will be calibrated that would come out to be normal room temperature. On the other hand, there is also another inlet valve that is connected to the tank where hot water is stored. This hot water also flows inside the shell of the heat exchanger device, and according to the law of thermodynamics, heat is transferred from the hot water to the nanofluid or PG/water that again gets back to the Tank 1 where it was stored initially through an outlet valve. The temperature reading is calibrated at both the nanofluid or PG/water inlet and exit points and to calibrate the readings from time to time according to the requirements. This reading is calibrated with the help of thermocouples. Thermocouple is a device that generates electric voltage at output proportional to the temperature readings.

4. Experimental results

To evaluate the accuracy of measurements, experimental system has been tested first with propylene glycol/water (10/90) % concentration before measuring the heat transfer characteristics of different volume concentrations of Al₂O₃/water. From the experimental system, the values that have been measured are the hot water temperatures of the inlet and outlet as well as the inlet of the PG/water and the different concentrations of nanofluid at different mass flow rates. The nanofluid presented equations are calculated by using the Pak and Cho [3] correlations, which are defined as follows:

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_p$$

The specific heat is calculated from Xuan and Roetzel [4] as the following:

$$(\rho C_p)_{nf} = (1 - \phi)(\rho C_p)_f + \phi(\rho C_p)_p$$

Heat transfer rate can be defined:

$$Q = \dot{m} \cdot C_p \cdot \Delta T$$

The logarithmic mean temperature difference:

$$\Delta T_{lm} = \frac{(T_{wi} - T_{no}) - (T_{wo} - T_{ni})}{\ln \frac{(T_{wi} - T_{no})}{(T_{wo} - T_{ni})}}$$

The overall heat transfer coefficient:

$$Q = U \cdot A_s \cdot \Delta T_{lm}$$

An alternative formula for calculating the thermal conductivity was introduced by Yu and Choi [5], which is expressed in the following form:

$$K_{nf} = K_f \frac{K\rho + 2Kf - 2\phi(Kf - K\rho)}{K\rho + 2Kf + \phi(Kf + K\rho)}$$

Thermal diffusivity is given by

$$\alpha_{nf} = \frac{k_{nf}}{\rho_{nf} \cdot c_p}$$

Drew and Passman [6] suggested the well-known equation of Einstein for calculating viscosity, which is applicable to spherical particles in volume fractions less than 5.0 vol.% and is defined as follows:

$$\mu_{nf} = (1 + 2.5\phi)\mu_w$$

The kinematic viscosity can be calculated from

$$\nu = \frac{\mu}{\rho}$$

Calculating Reynolds [7], Peclet and Prandtl [8] and Stanton numbers [9] is defined as follows:

$$Re = \frac{V \cdot D}{\nu}$$

$$Pe = \frac{V \cdot D}{\alpha_{nf}}$$

$$Pr = \frac{\nu_{nf}}{\alpha_{nf}}$$

$$St = \frac{Nu}{Re \cdot Pr}$$

Friction factors and Nusselt numbers for single-phase flow have been calculated from the Gnielinski equation [10] that is suitable for turbulent flow. The Gnielinski equation is defined as

$$f = [1.58(\ln Re) - 3.82]^{-2}$$

Finding Nusselt number from the turbulent flow equation [10]:

$$Nu = \frac{(0.125f)(Re - 1000)Pr}{1 + 12.7(0.125f)^{0.5} (Pr^{2/3} - 1)}$$

Friction factor for each flow rate and nanoparticle concentration of the nanofluid can be found with the help of Duangthongsuk and Wongwises correlation [11] as Gnielinski equation [10] for single-phase flow cannot use for calculating friction factor as well as Nusselt number. Note that this equation is suitable for turbulent flow only and cannot be used for laminar flow:

$$f = 0.961 \cdot Re^{-0.375} \cdot \phi^{0.052}$$

Finding Nusselt number is calculated from Duangthongsuk and Wongwises correlation for turbulent flow [11]:

$$Nu = 0.074Re_{nf}^{0.707} \cdot Pr_{nf}^{0.385} \cdot \phi^{0.074}$$

4.1. Enhancement ratio of thermal conductivity

From the calculated result, we can examine the enhancement ratio of thermal conductivity for PG/water as well as for the chosen concentrations of the Al₂O₃/water nanofluid.

The results show that thermal conductivity is a function of particle volume concentration; it increases with the increase in volume concentration. **Figure 2** shows the increase of thermal conductivity with respect to volume concentration of the nanoparticles. The maximum amount of thermal conductivity has been measured at 2.5% volume concentration with a value of 0.61629 W/m.k. This gives the maximum enhancement ratio of 1.0626. **Table 1** shows thermal conductivity enhancement ratio.

In compliance with thermal conductivity measurement, results show that the viscosity of the nanofluid increases with the increase in particle volume concentration and with decrease in temperature. The ability of nanofluid to absorb heat increases with the increase in volume

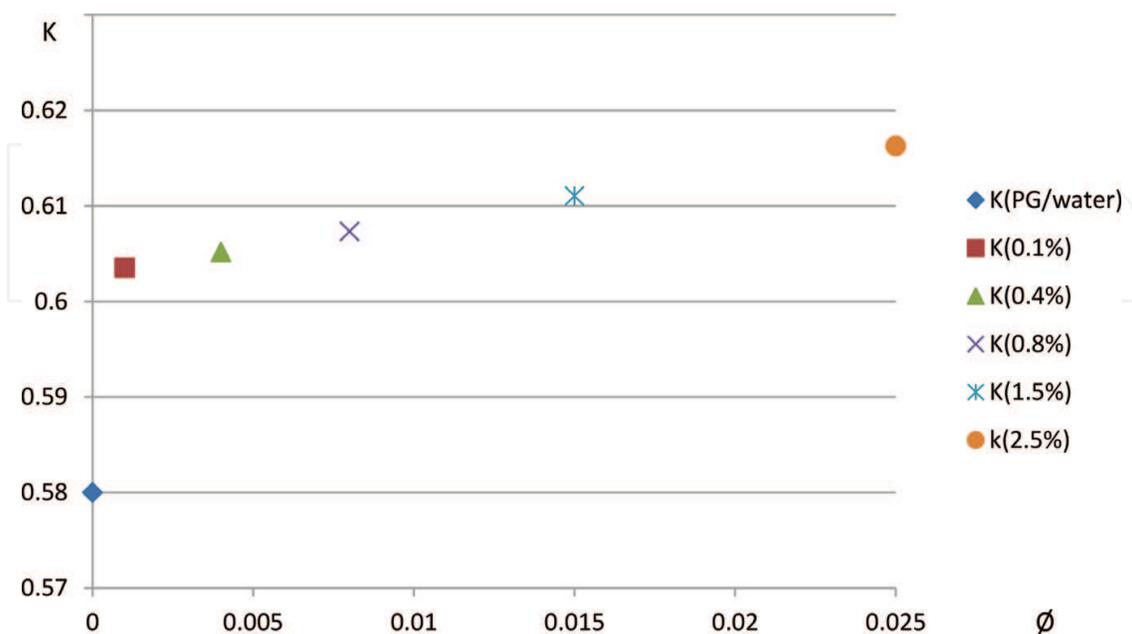


Figure 2. Thermal conductivity (K) versus volume concentration (φ).

Thermal conductivity	Amount of K (W/m.k)	Enhancement ratio
K (PG/water)	0.58	—
K (0.1%)	0.60354	1.0405
K (0.4%)	0.60517	1.0434
K (0.8%)	0.60732	1.0471
K (1.5%)	0.61105	1.0535
K (2.5%)	0.61629	1.0626

Table 1. Enhancement ratio of thermal conductivity.

concentration of the nanoparticles that is why the density of the nanofluid remarkably increases with the increase in particle volume concentration of the nanofluid. This leads to increase the outlet temperature of the nanofluid, leading to raise the temperature difference of the nanofluid. For the specific heat, the results show that C_p decreases with the increase in volume concentration of the nanofluid. However, the amount of decrease in C_p is less than the amount of increase in density, which leads to reduction in thermal diffusivity with the increase in volume concentration of the nanoparticles in the nanofluid. The relationship between the calculated values of thermal diffusivity and kinematic viscosity can be seen in **Figure 3**.

Therefore, to apply the nanofluid for practical application, it is important to investigate their flow features in parallel with the thermal performance. In this study, suspended nanoparticles with volume concentrations of 0.1, 0.4, 0.8, 1.5, and 2.5 are utilized to calculate the friction factor for each volume concentration and for all the mass flow rates. **Figure 4** illustrates the values of the calculated friction factor with every measured value of Reynolds number. The results show that the friction factor increases dramatically with the increase in nanoparticle volume concentration for a given mass flow rate and decreases with increase in Reynolds number.

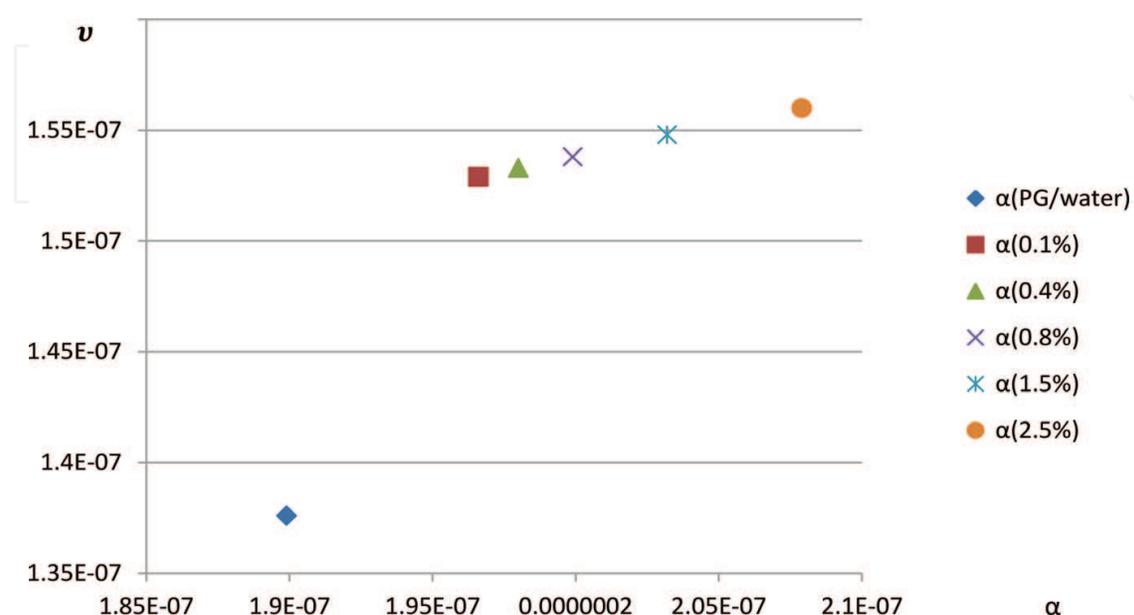


Figure 3. Thermal diffusivity (α) versus kinematic viscosity (ν).

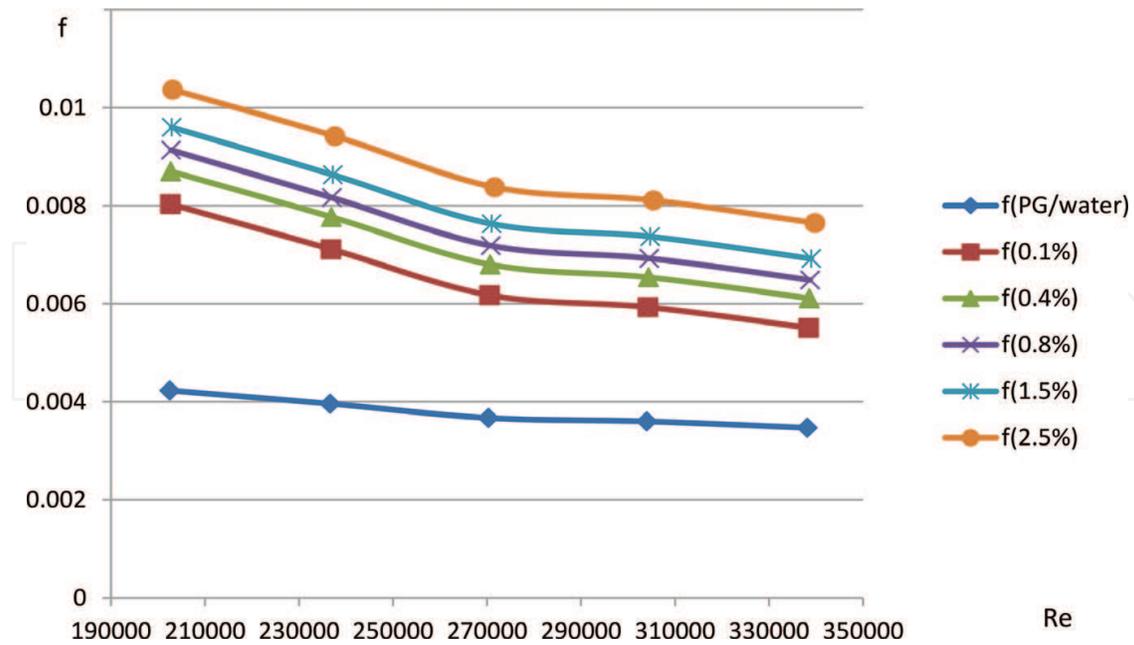


Figure 4. Friction factor (f) versus Reynolds number (re).

4.2. Enhancement ratio of heat rate

1. For $\dot{m} = 30$ L/min (Table 2)

Heat transfer rate	Amount of Q (W)	Enhancement ratio
Q (PG/water)	1514	—
Q (0.1%)	1519.5	1.0036
Q (0.4%)	1525	1.0006
Q (0.8%)	1540	1.0171
Q (1.5%)	1580	1.0435
Q (2.5%)	1624	1.0726

Table 2. Value of the enhancement ratio of heat rate at 30 L/min.

2. For $\dot{m} = 35$ L/min (Table 3)

Heat transfer rate	Amount of Q (W)	Enhancement ratio
Q (PG/water)	1843	—
Q (0.1%)	1848	1.0027
Q (0.4%)	1854	1.0059
Q (0.8%)	1875	1.0173
Q (1.5%)	1925	1.0444
Q (2.5%)	1950	1.058

Table 3. Value of the enhancement ratio of heat rate at 35 L/min.

3. For $\dot{m} = 40$ L/min (**Table 4**)

Heat transfer rate	Amount of Q (W)	Enhancement ratio
Q (PG/water)	2240	—
Q (0.1%)	2252	1.0053
Q (0.4%)	2264	1.0107
Q (0.8%)	2298	1.0258
Q (1.5%)	2320	1.0357
Q (2.5%)	2355	1.0513

Table 4. Value of the enhancement ratio of heat rate at 40 L/min.4. For $\dot{m} = 45$ L/min (**Table 5**)

Heat transfer rate	Amount of Q (W)	Enhancement ratio
Q (PG/water)	2341	—
Q (0.1%)	2372	1.0132
Q (0.4%)	2390	1.0209
Q (0.8%)	2405	1.0273
Q (1.5%)	2465	1.0529
Q (2.5%)	2485	1.0615

Table 5. Value of the enhancement ratio of heat rate at 45 L/min.5. For $\dot{m} = 50$ L/min (**Table 6**)

Heat transfer rate	Amount of Q (W)	Enhancement ratio
Q (PG/water)	3055	—
Q (0.1%)	3110	1.0180
Q (0.4%)	3155	1.0327
Q (0.8%)	3212	1.0513
Q (1.5%)	3222	1.0546
Q (2.5%)	3261	1.0674

Table 6. Value of the enhancement ratio of heat rate at 50 L/min.

The results show that the heat transfer rate of PG/water increases with the increase in mass flow rate till the amount of 45 L/min, and the heat rate starts to fall down at the mass flow rate of 50 L/min as the frictional forces became dominant. As for the nanofluid, the heat rate increases with the increase in mass flow rate and increases with the increase in volume concentration, a maximum enhancement ratio of 1.0674 is calculated at the maximum mass

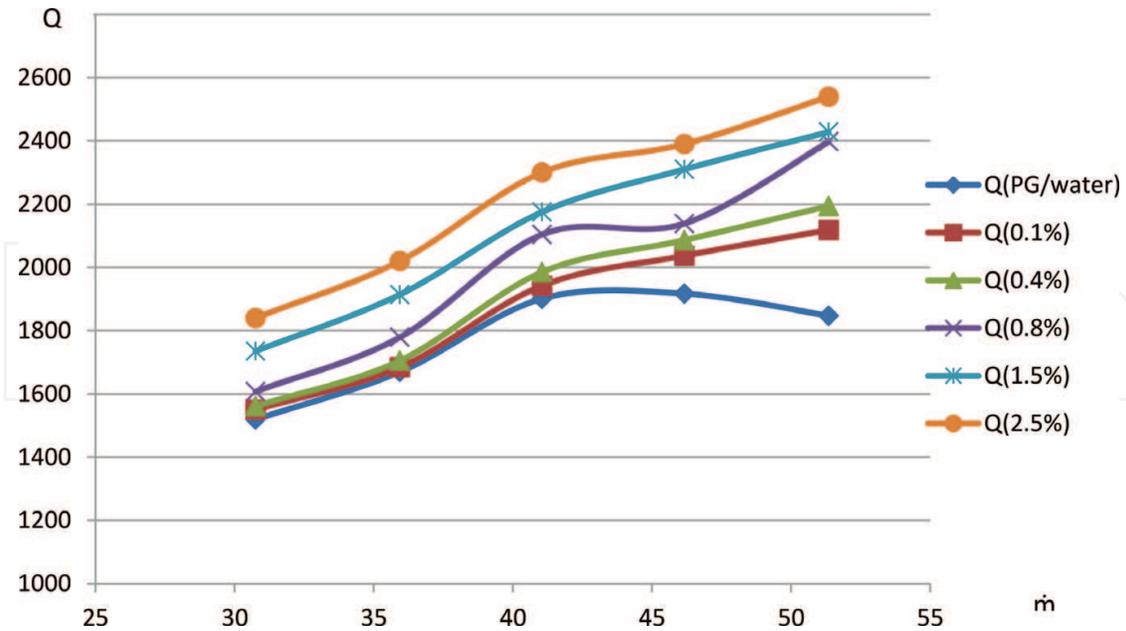


Figure 5. Heat rate (Q) versus mass flow rate (ṁ).

flow rate and at 2.5% volume concentration of nanofluid. Figure 5 shows the pattern of the heat rate procedure at a different mass flow rates.

4.3. Enhancement ratio of the overall heat transfer coefficient

From the heat rate formula, the heat transfer coefficient is increasing with the increase of the heat rate (illustrated in Figure 6). The effect of heat transfer coefficient is directly proportional to the heat transfer rate.

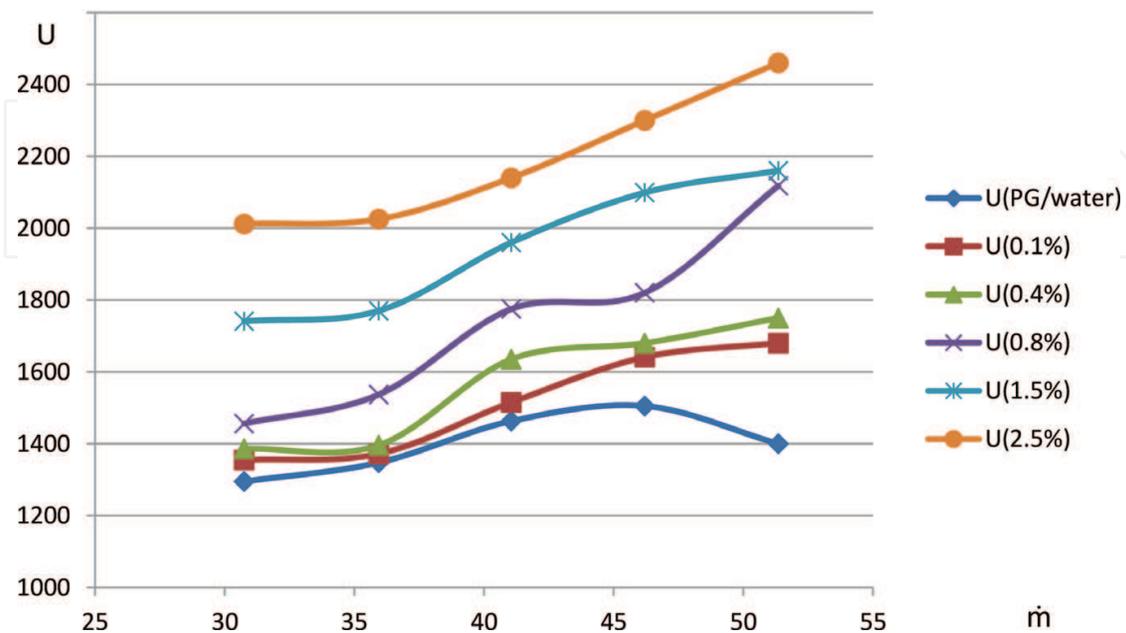


Figure 6. Overall heat transfer coefficient (U) versus mass flow rate (ṁ).

1. For $\dot{m} = 30$ L/min (Table 7)

Overall heat transfer coefficient	Amount of U (W/m ² k)	Enhancement ratio
U (PG/water)	1295	—
U (0.1%)	1355	1.0463
U (0.4%)	1386	1.0702
U (0.8%)	1456	1.1243
U (1.5%)	1741	1.3444
U (2.5%)	2012	1.5536

Table 7. Value of the enhancement ratio of overall heat transfer coefficient at 30 L/min.

2. For $\dot{m} = 35$ L/min (Table 8)

Overall heat transfer coefficient	Amount of U (W/m ² k)	Enhancement ratio
U (PG/water)	1347	—
U (0.1%)	1372	1.0185
U (0.4%)	1396	1.0363
U (0.8%)	1537	1.141
U (1.5%)	1770	1.314
U (2.5%)	2025	1.5033

Table 8. Value of the enhancement ratio of overall heat transfer coefficient at 35 L/min.

3. For $\dot{m} = 40$ L/min (Table 9)

Overall heat transfer coefficient	Amount of U (W/m ² k)	Enhancement ratio
U (PG/water)	1463	—
U (0.1%)	1515	1.0355
U (0.4%)	1635	1.1175
U (0.8%)	1775	1.2132
U (1.5%)	1960	1.3397
U (2.5%)	2140	1.4627

Table 9. Value of the enhancement ratio of overall heat transfer coefficient at 40 L/min.

4. For $\dot{m} = 45$ L/min (Table 10)

Overall heat transfer coefficient	Amount of U (W/m ² k)	Enhancement ratio
U (PG/water)	1505	—
U (0.1%)	1641	1.0903
U (0.4%)	1680	1.1162

Overall heat transfer coefficient	Amount of U (W/m ² k)	Enhancement ratio
U (0.8%)	1820	1.2093
U (1.5%)	2099	1.3946
U (2.5%)	2300	1.5282

Table 10. Value of the enhancement ratio of overall heat transfer coefficient at 45 L/min.

5. For $\dot{m} = 50$ L/min (**Table 11**)

Overall heat transfer coefficient	Amount of U (W/m ² k)	Enhancement ratio
U (PG/water)	1400	—
U (0.1%)	1680	1.2
U (0.4%)	1750	1.25
U (0.8%)	2118	1.5128
U (1.5%)	2160	1.5428
U (2.5%)	2460	1.7571

Table 11. Value of the enhancement ratio of overall heat transfer coefficient at 50 L/min.

Overall heat transfer coefficient and the heat rate shared the same thermal behavior. Initially, the overall heat transfer coefficient for propylene glycol/water increases as the increase in volumetric rate. However, the thermal energy starts reducing at a rate of 45 Ltr/min, as the frictional forces became dominant till it reaches the amount of 50 Ltr/min. The results indicate that when the mass flow rate as well as the nanoparticles volume concentration increases, the overall heat transfer coefficient of the nanofluid increases with a maximum value enhancement

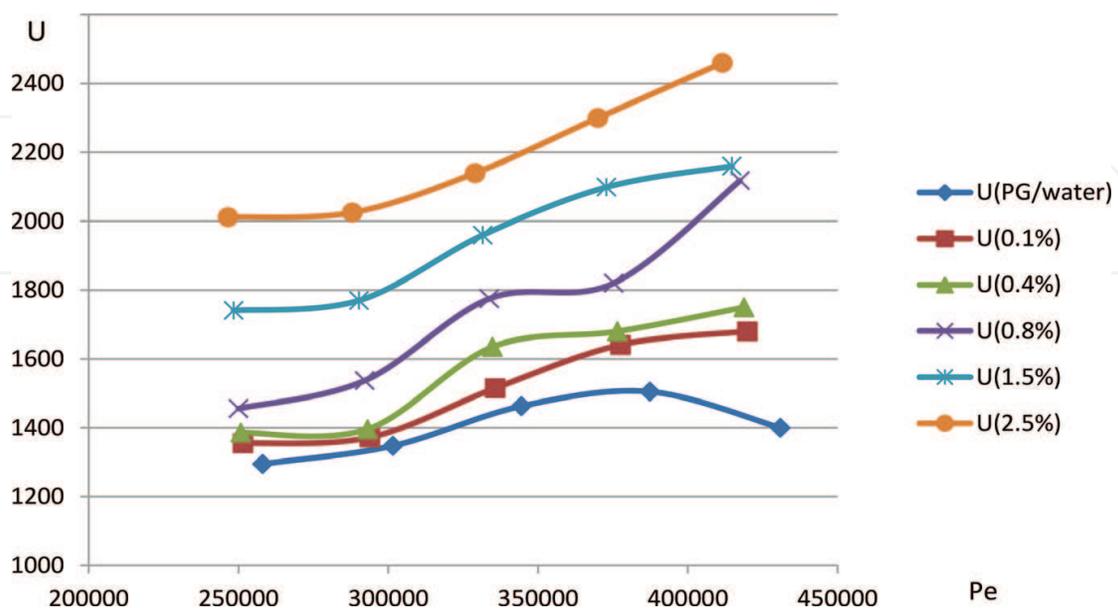


Figure 7. Overall heat transfer coefficient (U) versus Peclet number (Pe).

ratio of 1.7571 at a nanofluid with volume concentration of 2.5% and a volumetric rate of 50 L/min. The reason behind this increase in the thermal performance of the nanofluid is that the nanoparticles increase the thermal conductivity which leads to increase the heat transfer rate due to the chaotic movement of the nanoparticles. **Figures 6** and **7** show the process of the increase in heat transfer coefficient for a given mass flow rate and a given Peclet number.

4.4. Enhancement ratio of Nusselt number

1. For $\dot{m} = 30$ Ltr/min (**Table 12**)

Nusselt number	Amount of Nu	Enhancement ratio
Nu (PG/water)	412.58	—
Nu (0.1%)	521.34	1.2636
Nu (0.4%)	577.16	1.3989
Nu (0.8%)	606.374	1.4697
Nu (1.5%)	632.437	1.5328
Nu (2.5%)	647.135	1.5685

Table 12. Value of the enhancement ratio of Nusselt number at 30 Ltr/min.

2. For $\dot{m} = 35$ Ltr/min (**Table 13**)

Nusselt number	Amount of Nu	Enhancement ratio
Nu (PG/water)	458.03	—
Nu (0.1%)	582.08	1.2708
Nu (0.4%)	644.411	1.4069
Nu (0.8%)	677.47	1.479
Nu (1.5%)	706.315	1.542
Nu (2.5%)	723.1	1.5787

Table 13. Value of the enhancement ratio of Nusselt number at 35 Ltr/min.

3. For $\dot{m} = 40$ Ltr/min (**Table 14**)

Nusselt number	Amount of Nu	Enhancement ratio
Nu (PG/water)	492.96	—
Nu (0.1%)	639.54	1.2973
Nu (0.4%)	708.06	1.4363

Nusselt number	Amount of Nu	Enhancement ratio
Nu (0.8%)	744.442	1.51
Nu (1.5%)	776.05	1.574
Nu (2.5%)	794.808	1.6123

Table 14. Value of the enhancement ratio of Nusselt number at 40 Ltr/min.

4. For $\dot{m} = 45$ Ltr/min (**Table 15**)

Nusselt number	Amount of Nu	Enhancement ratio
Nu (PG/water)	546.162	—
Nu (0.1%)	694.87	1.2722
Nu (0.4%)	769.312	1.4085
Nu (0.8%)	808.805	1.4808
Nu (1.5%)	843.155	1.5437
Nu (2.5%)	863.484	1.581

Table 15. Value of the enhancement ratio of Nusselt number at 45 Ltr/min.

5. For $\dot{m} = 50$ Ltr/min (**Table 16**)

Nusselt number	Amount of Nu	Enhancement ratio
Nu (PG/water)	590.18	—
Nu (0.1%)	749.19	1.2694
Nu (0.4%)	829.465	1.4054
Nu (0.8%)	872.06	1.4776
Nu (1.5%)	909.1	1.5403
Nu (2.5%)	931.09	1.5776

Table 16. Value of the enhancement ratio of Nusselt number at 50 Ltr/min.

The results show that the values of Nusselt number increase with the increase in the fluid velocity. The results also indicate that the nanofluid values of Nusselt number are higher than the base fluid, and these values are increasing with the increase in the nanoparticle volume concentration and Reynolds number. **Figures 8** and **9** represent the calculated values of Nusselt number and Stanton number for PG/water as well as for different concentrations of the Al₂O₃/water nanofluid in relation to the calculated values of Peclet and Reynolds numbers.

This behavior of the nanofluid is expected and has been recorded in [2], and it is due to the presence of the nanoparticles in the base fluid which increase the advantages like thermal conductivity and the molecular interchange as the molecules flows faster and the drawbacks

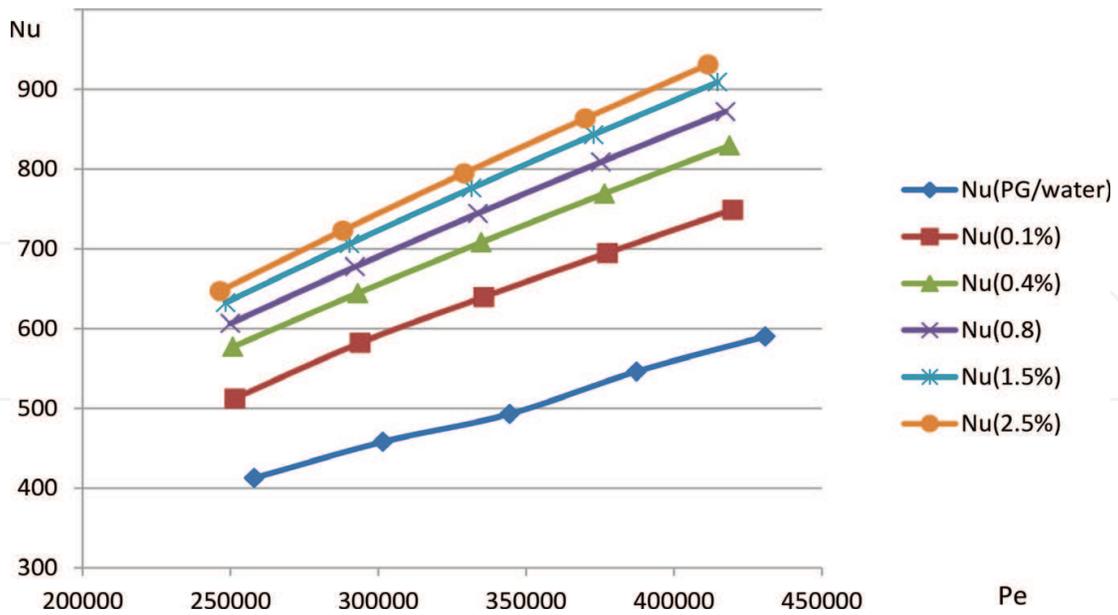


Figure 8. Nusselt number (nu) versus Peclet number (Pe).

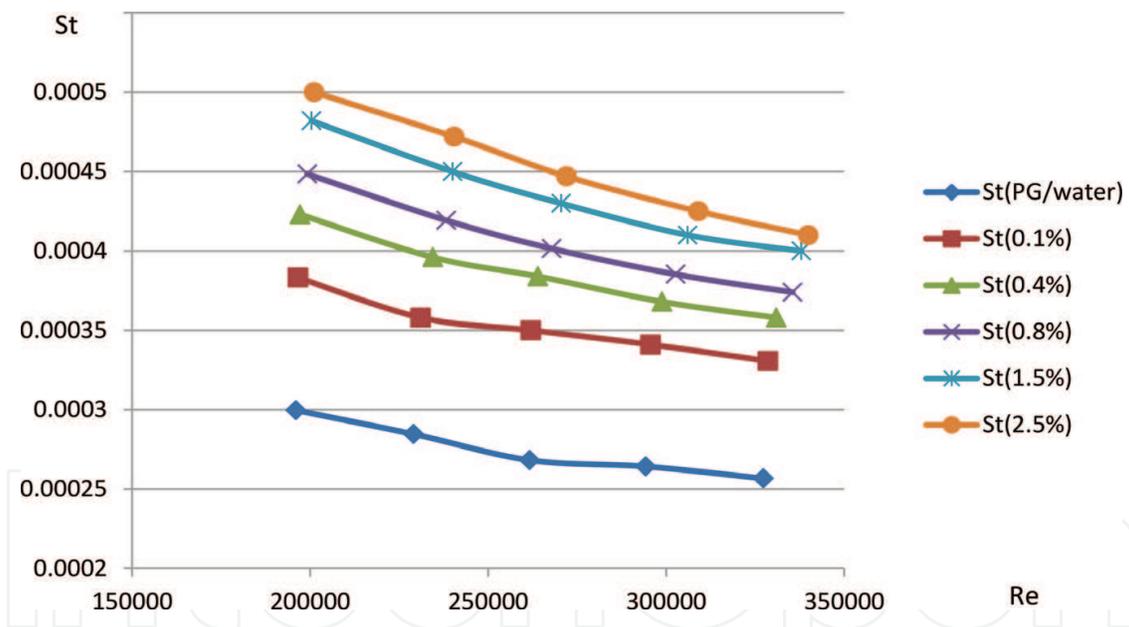


Figure 9. Stanton number (nu) versus Reynolds number (re).

mainly the viscosity at the same time. Heat transfer performance increases due to the increase in thermal conductivity, whereas the increase in viscosity leads to an increase in friction factor and increase in the boundary layer thickness. **Figure 10** illustrates the increase in the frictional forces versus the thermal energy enhancement (represented by Stanton number). It is worth mentioning that the temperature should be kept under the evaporation level to avoid the presence of vapor as the kinetic energy may exceed the binding energy causing the molecules to escape from the liquid.

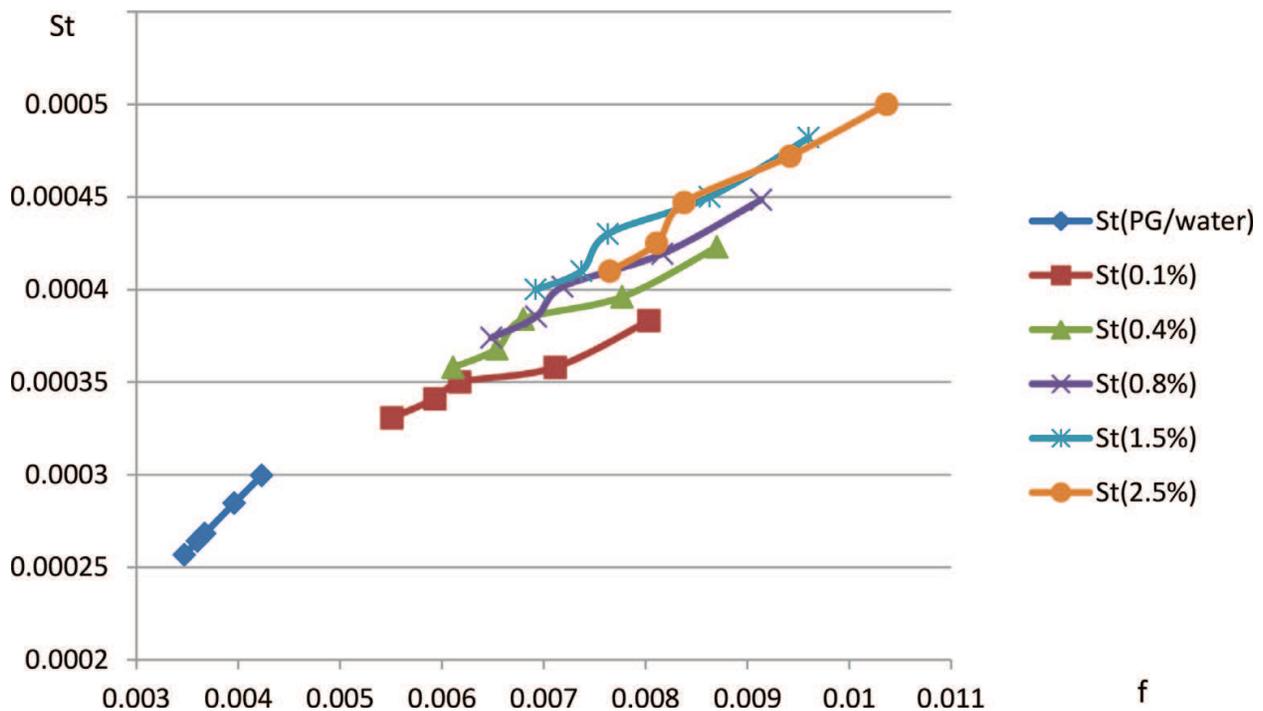


Figure 10. Stanton number (St) versus friction factor (f).

5. Conclusion

The convective heat transfer performance and flow characteristics of Al₂O₃ nanofluid flowing in a horizontal shell and tube heat exchanger have been experimentally investigated under turbulent flow. The effect of the Reynolds number and nanoparticle volume concentration on the flow behavior and heat transfer performance has been determined with different values of mass flow rates. Important conclusions have been achieved and are outlined as the following:

1. Thermal conductivity and viscosity increase due to the dispersion of the nanoparticles into the base liquid.
2. At a particle volume concentration of 2.5%, the use of Al₂O₃/water nanofluid gives significant higher heat transfer characteristics. For example, at the particle volume concentration of 2.5%, the greater enhancement ratio of heat transfer coefficient of the nanofluid at mass flow rate of 50 Ltr/min is 1.7571 which means that the amount of the heat transfer coefficient of the nanofluid is 57% greater than that of distilled water. As for Nusselt number, the maximum enhancement ratio at 50 Ltr/min is 1.5776. This means that Nusselt number of the nanofluid is 62.6% greater than that of distilled water.
3. Friction factor increases with the increase of a particle volume concentration. This is because of the increase in the viscosity of the nanofluid which means that the nanofluid incurs penalty in pressure drop which can lead to cavitation with higher volume concentrations.

Nomenclature

c_p	Specific heat (J/kg.k)
D	Tube diameter (m)
f	Friction factor
U	Overall heat transfer coefficient (W/m ² .k)
K	Thermal conductivity (W/m.k)
\dot{m}	Mass flow rate (Ltr/min)
Nu	Nusselt number
Pe	Peclet number
Pr	Prandtl number
Q	Heat transfer rate (W)
Re	Reynolds number
V	Mean velocity (m/s)
St	Stanton number

Greek symbols

\varnothing	Volume concentration (%)
ρ	Density (kg/m ³)
α	Thermal diffusivity (m ² /s)
μ	Viscosity (kg/m.s)
ΔT_{lm}	Logarithmic temperature difference (k)
ν	Kinematic viscosity (m ² /s)

Subscript

w_i	Water inlet
w_o	Water outlet
n_i	Nanofluid inlet
n_o	Nanofluid outlet
in	Inlet
out	Outlet
n	Nanofluid

f	Base fluid
p	Nanoparticles

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