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Heat Transfer Analysis of Propylene Glycol and Water Mixture Based TiO_2 Nanofluids in a Shell and Tube Heat Exchanger

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Abstract- *In this experimental work, heat transfer in a shell and tube heat exchanger was investigated. Nanofluids were prepared taking 60% water and 40% propylene glycol with volume concentration of 0.1%, 0.2% and 0.3% TiO_2 nanoparticle. All the experiments were conducted varying the nanofluid flow rate at 6,8,10, and 12 Liters/min. The hot water flow rate was fixed at 12 Liters/min. Findings showed that increasing nanoparticle volume concentration and cold fluid flow rate could improve heat transfer rate, overall heat transfer coefficient, and convective heat transfer coefficient. It is found that the maximum enhancement of heat transfer rate and overall heat transfer coefficient of TiO_2/PGW nanofluid compared to the base fluid are 44.39%, and 48.13% respectively at 0.3% nanoparticle volume concentration and 12 liters/min flow rate of nanofluid. The average enhancement of convective heat transfer coefficient at 0.1%, 0.2%, and 0.3% nanoparticle volume concentration are 5.54%, 11.04%, and 14.55% respectively.*

Keywords: Heat Transfer, Shell and Tube Heat Exchanger, Nanofluid, TiO_2 nanoparticle, and Propylene Glycol

1. INTRODUCTION

A heat exchanger is a device that is used to transfer heat between one medium to another efficiently [1]. Heat exchangers can be classified based on their configuration such as tubular, plate and shell & tube heat exchangers. A shell and tube heat exchanger is the most common type of heat exchanger that is used in different industrial applications such as energy conversion, evaporators, condensers, power utility systems as well as heating, cooling, ventilating and air conditioning engineering [2]. Researchers have been trying to enhance the heat transfer rate of heat exchangers, reduce the heat transfer time, reduce the size, weight, and cost of heat exchangers, eliminate energy losses and increase energy and fuel efficiencies. There are several methods to improve the performance of heat exchanger such as the application of fins and usage of microchannels etc. Heat transfer ability can also be enhanced by increasing the thermal conductivity of working fluid [3]. The conventional heat transfer fluids are refrigerants, water, engine oil, vegetable oil, paraffin oil, propylene glycol, ethylene glycol, etc. have low thermal conductivities, when compared to the thermal conductivity of solids. By adding some solid particles of high thermal conductivity to a base fluid, the thermal conductivity of that fluid can be increased. But suspended micrometer or millimeter-sized particles may cause severe problems, such as clogging, abrasion, high-pressure drop, and sedimentation of particles. To remove these problems, nanoparticles (average size below 100 nm) can be used instead of suspended large particles [4]. Nanofluids are colloidal suspensions of nanoparticles in a base fluid which is used in a variety of engineering applications and is expected to replace conventional fluids soon [5]. Nanoparticles include chemically stable metal (e.g., copper, silver, gold), metal oxides (e.g. alumina, titania, zirconia, silica, bismuth oxide), several allotropes of carbon (e.g., diamond, single-walled and multi-walled carbon nanotubes) [6].

Water is the most common base fluid. However, water has some disadvantages as a coolant. Water has low boiling and freezing temperatures. If water is used as a coolant, it may cause some problems like corrosion. To solve these problems, ethylene glycol or propylene glycol is used as an antifreeze and water-antifreeze mixture is used as a coolant. Although EGW has more desirable physical properties than PGW, PGW is used in applications where toxicity might be a concern. PGW is generally recognized as safe for use in food or food processing applications [7].

Hamilton et *al* [8] in 1962 developed a thermal conductivity model for a two-phase mixture based on their theoretical study. Choi [9] first used the term "nanofluid" for fluids with suspended nanoparticles. Eastman et *al* [10] examined that a 5% volume fraction of water-based CuO nanoparticles results in a 60% improvement in thermal conductivity compared to water without nanoparticles. Masuda et *al*. [11] reported that the enhancement in the thermal conductivities of Al_2O_3 and TiO_2 nanofluids (4.3% volume concentration) was about 32% and 11% respectively. Cabaleiro et *al.* [12] studied thermal conductivity behavior for ethylene and

propylene glycol-based TiO_2 nanofluids up to nanoparticle volume concentrations of 8.5%. Sundar et *al.* [13] studied the thermal and rheological properties of propylene glycol and water mixture based Fe_3O_4 nanofluids. In that study, the enhancement in thermal conductivity was 20.53% for 20:80% PG/W nanofluid and 17.26% for 40:60% PG/W nanofluids at 0.5% particle concentration at a temperature of 60^0. Hussein et *al.* [14] studied experimentally heat transfer enhancement in car radiator by using water-based TiO_2 and SiO_2 nanoparticles of 1.0-2.5% volume fraction respectively. Results showed that the heat transfer increases with increasing of nanofluid volume fraction. Sandhya et *al*. [6] investigated the performance of ethylene glycol and water-based TiO_2 nanofluids as an automobile radiator coolant is determined experimentally. Nanofluids were prepared taking 40% ethylene glycol and 60% water with volume concentrations of 0.1%, 0.3%, and 0.5% of TiO_2 nanoparticles and maximum enhancement of heat transfer rate was 37% in comparison with base fluid. Aghayari et *al.* [4] investigated the enhancement of heat transfer coefficient and Nusselt number of a nanofluid containing nanoparticles (γ-AL_2O_3) of volume fraction of 0.1%–0.3% in a double pipe heat exchanger. Experimental results showed up to 19%–24% increase in heat transfer coefficient and Nusselt number respectively. Palanisamy et *al.* [15] investigated the heat transfer and the pressure drop of cone helically coiled tube heat exchanger using MWCNT/water nanofluids and experimental Nusselt number was 28%, 52%, and 68% higher than water for the nanofluids of 0.1%, 0.3%, and 0.5% volume concentration respectively. Jagadishwar et *al.* [16] investigated the performance of water and propylene glycol mixture based TiO_2 nanofluids (nanoparticle volume concentration of 0.1%, 0.2%, and 0.35%) on an automotive radiator at different flow rates. The experiment results showed that the heat transfer rate increases with increasing flow rate for a particular concentration of nanofluid and also with increasing nanoparticle concentration at a particular flow rate.
In this study, heat transfer of propylene glycol and water mixer based TiO_2 nanofluid is investigated in a shell and tube heat exchanger. Heat transfer rate, overall heat transfer coefficient, convective heat transfer co-efficient and energy effectiveness of the shell and tube heat exchanger is analyzed at different nanofluid (cold fluid) flow rates and nanoparticle volume concentrations.

2. PREPARATION OF TiO_2 NANOFLUID

In this study, the nanofluid was prepared by using 40% propylene glycol and 60% water with different volume concentrations of TiO_2 nanoparticle by using the two-step method. The number of nanoparticles required for the preparation of nanofluids was calculated using the law of mixture formula. The weight of nanoparticles required for preparation of the nanofluid of a particular volume fraction, using propylene glycol-water mixture (40:60) as base fluid was calculated by using the following relation:

$$\% \text{ vol. concentration, } \varphi = \frac{\frac{w_{nanoparticle}}{\rho_{nanoparticle}}}{\frac{w_{nanoparticle}}{\rho_{nanoparticle}}+\frac{w_{base\ fluid}}{\rho_{base\ fluid}}} \quad (1)$$

The required nanoparticles were added with the 500 ml base fluid and the solution was subjected to the mixing process using a magnetic stirrer for 10 hours and then underwent a sonication process using an ultrasonic bath for 1h. No surfactant was used. A total of 5Liters nanofluid of a particular volume concentration were prepared for the present investigation. In this study, 0.1%, 0.2% and 0.3% volume concentration of TiO_2 nanoparticles were used.
Pak and Cho [17] equations were used for the estimation of density, viscosity, specific heat and thermal conductivity and the equations are presented below:

$$\rho_{nf} = \varphi\rho_{np}+(1-\varphi)\,\rho_{bf} \quad (2)$$

$$C_{p,nf} = \frac{\varphi(\rho Cp)_{np}+(1-\varphi)(\rho Cp)_{bf}}{(1-\varphi)\rho_{bf}+\varphi\rho_{np}} \quad (3)$$

$$\mu_{nf} = \mu_{bf}\,(1+2.5\varphi) \quad (4)$$

$$K_{nf} = K_{bf}\,\frac{K_{np}+2\,K_{bf}-2\,\varphi(K_{bf}-K_{np})}{K_{np}+2\,K_{bf}+\varphi(K_{bf}-K_{np})} \quad (5)$$

The thermal properties of TiO_2 nanoparticle, water, and propylene glycol–water mixture (base fluid) are shown in Table 1.

Table 1: Thermal properties of nanoparticle, water, and base fluid[13][7]

Material	Density (kg/m^3)	Specific heat (J/Kg K)	Thermal conductivity (W/m K)
TiO_2	4175	692	8.4
Water	997	4186.8	0.6
PGW(40:60)	1033.70	3747.186	.388

3. EXPERIMENTAL SETUP AND PROCEDURE

In this study, a shell and tube heat exchanger was used. The heat exchanger had two tubes inside a cylindrical shell. The heat exchanger was made of stainless steel. Each tube was 0.48m long and had inside and outside diameter of 0.009m and 0.0095m respectively. The cylindrical shell had a 0.15m outer diameter and it was 0.3 m long. According to TEMA(Tubular Exchanger Manufacturers Association) nomenclature © 1988, the shell and tube heat exchanger (Figure 1.2) that was used in this study is NFU type. N denotes channel integral with tube sheet and removable cover. F denotes a two-pass shell with the longitudinal baffle. U denotes the U-tube bundle. According to the flow arrangement, the heat exchanger used in the experimental investigation was a parallel flow heat exchanger.

In this experimental investigation, an experimental setup was developed to analyze the heat transfer of a shell and tube heat exchanger. It consisted of a hot fluid tank, a cold fluid tank, two 0.5 hp centrifugal pump, two flow measuring devices (rotameter), two flow control valve, an electric heater, pipes, joints, etc. The experimental set up was well insulated by using insulation tape, glass wool, and aluminum foil to eliminate heat loss between test rig and surrounding. A schematic diagram and a photograph of the experimental set up is shown in fig. 1 and fig. 2 respectively.

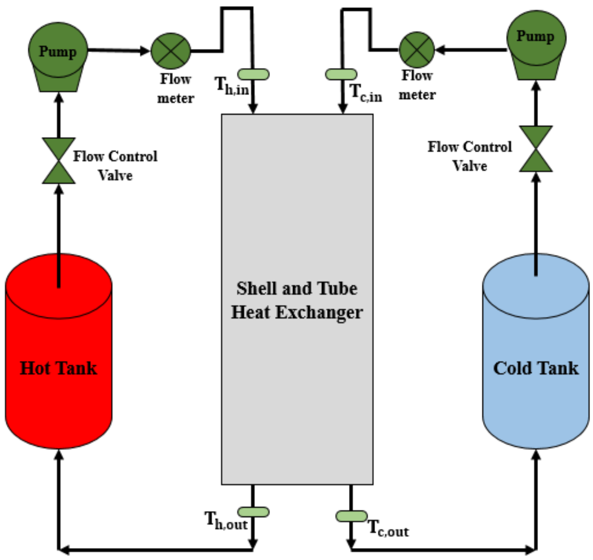

Fig.1: Schematic Diagram of Experimental Setup

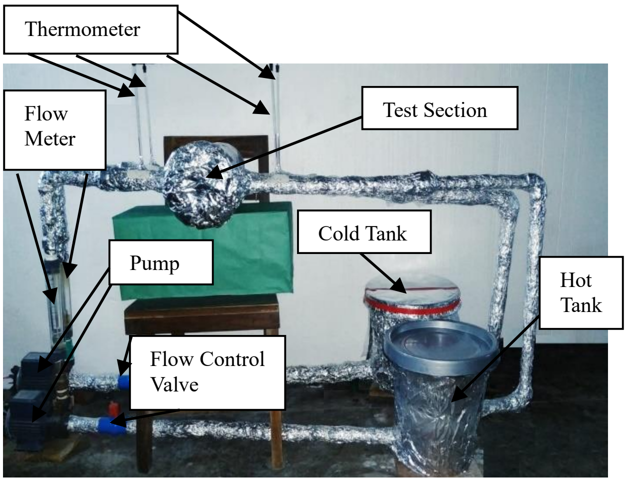

Fig.2: Image of the Experimental Setup

Two buckets were connected in closed-loop with the heat exchanger wherein one there was nanofluid (coolant) and in another, there was hot water that was heated by using an electric heater. Both the hot water and nanofluid were circulated by two different pumps through a pipe of 1-inch diameter. Hot water was circulated in the tube side and nanofluid was circulated in the shell side. The volume flow rate of the hot water and nanofluid was measured by using two flow meters (rotameter) which were connected to the loop. Gate valves were used for changing the flow rate. The hot fluid flow rate was kept constant at 12 Liters/min. The nanofluid flow rate was varied at 6,8,10 and 12 Liters/min. There were four red spirit-filled thermometers (0.5 ^{0}C division) inserted in the pipe at the inlet and outlet of the nanofluid and hot water to measure the required temperatures. The data were collected when the flows were in steady condition.

4. DATA DEDUCTION

The experimental data were used to calculate the heat transfer rate, overall heat transfer coefficient and convective heat transfer coefficient of nanofluid at different nanoparticle volume concentration and nanofluid flow rate.

The heat transfer rate of the cold fluid (nanofluid) can be expressed as

$$\dot{Q}_c = \dot{m}_c C_{pc} (T_{c,out} - T_{c,in}) \tag{6}$$

where $\dot{m}_c$ is the mass flow rate of nanofluid, C_{pc} is the specific heat of nanofluid, $T_{c,in}$ and $T_{c,out}$ are the inlet and outlet temperature of the nanofluid respectively.

The heat transfer rate of the hot fluid(water) can be expressed as

$$\dot{Q}_h = \dot{m}_h C_{ph} (T_{h,in} - T_{h,out}) \tag{7}$$

where $\dot{m}_h$ is the mass flow rate of hot fluid, C_{ph} is the specific heat of water, $T_{h,in}$ and $T_{h,out}$ are the inlet and outlet temperature of the hot fluid respectively.

Overall heat transfer coefficient of nanofluid can be expressed as

$$U_0 = \frac{\dot{Q}_c}{A_o\, F\, \Delta T_m} \tag{8}$$

Overall heat transfer coefficient of hot fluid can be expressed as

$$U_i = \frac{\dot{Q}_h}{A_i\, F\, \Delta T_m} \tag{9}$$

where ΔT_m is the log mean temperature difference and F is the LMTD correction factor.

$$\Delta T_m = \frac{(\Delta T_1 - \Delta T_2)}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{10}$$

$$\Delta T_1 = T_{h,in} - T_{c,in} \tag{11}$$

$$\Delta T_2 = T_{h,out} - T_{c,out} \tag{12}$$

$$A_0 = n\pi D_o L \tag{13}$$

$$A_i = n\pi D_i L \tag{14}$$

The correction factor can be obtained from J.P. Holman et al. [18] chart using two parameters P and R.

$$\text{Here, } P = \frac{t_2 - t_1}{T_1 - t_1} = \frac{T_{h,out} - T_{h,in}}{T_{c,in} - T_{h,in}} \tag{15}$$

and $R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{T_{c,out} - T_{c,in}}{T_{h,out} - T_{h,in}}$ (16)

The heat transfer coefficient of the nanofluid, h_o can be calculated as follows :

$$\frac{1}{U_i} = \frac{1}{h_i} + \frac{D_i \ln(\frac{D_i}{D_o})}{2K_w} + \frac{D_i}{D_o} + \frac{1}{h_i} \quad (17)$$

where D_i and D_o are the inner and outer diameters of tubes respectively, h_i and h_o are the individual convective heat transfer coefficients of the fluids inside and outside the tubes, respectively, and k_w is the thermal conductivity of the tube wall. Here, h_i can be estimated using equation (18) and (19).

Nusselt number of the tube side fluid can be estimated as:

$$Nu_i = \frac{h_i D_i}{K_i} \quad (18)$$

Gnielinski correlation for turbulent flow through a tube [4]:

$$Nu_i = 0.012\ (Re_i^{0.87} - 280)\ Pr_i^{0.4} \quad (19)$$

Here Re_i and Pr_i are the Reynolds number, and the Prandtl number for hot fluid (water) are defined, respectively as

$$Re_i = \frac{\rho_i V_i D_i}{\mu_i} \quad (20)$$

$$Pr_i = \frac{\mu_i\ C_{pi}}{k_i} = \frac{\mu_i\ C_{ph}}{k_i} \quad (21)$$

Effectiveness of a single pass 2 tube passes shell and tube heat exchanger can be expressed as:

$$\varepsilon = 2\{1 + c + \sqrt{1 + C^2}\, \frac{1+\exp[-NTU\sqrt{1+C^2}]}{1-\exp[-NTU\sqrt{1+C^2}]}\}^{-1} \quad (22)$$

$$\text{Here, } NTU = \frac{U_o A_o}{C_{min}} \quad (23)$$

$$\text{and } c = \frac{C_{min}}{C_{max}} = \frac{(\dot{m}C_p)_{min}}{(\dot{m}C_p)_{max}} \quad (24)$$

5. RESULTS AND DISCUSSION

5.1 Heat Transfer Rate

The effect of nanoparticle concentration on the heat transfer rate is demonstrated in fig. 3. It appears that there is the same behavior of heat transfer rate with volume concentration and volume flow rate of nanofluid. Heat transfer rate increases with an increase of both volume concentration and flow rate. The maximum value of the heat transfer rate is 503.17 W at 0.3% volume concentration and 12 liters/min flow rate of TiO_2/PGW nanofluid. The average enhancement of heat transfer rate at 0.1%, 0.2% and 0.3% nanoparticle volume concentration are 10.55%, 26.27% and 38.27% respectively compared to base fluid.

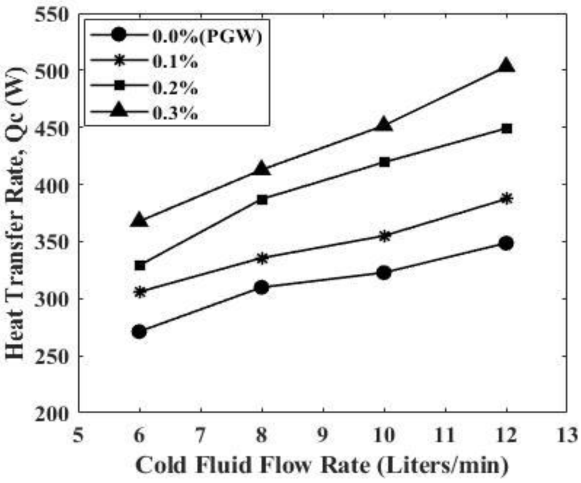

Fig. 3: Heat transfer rate of TiO_2/PGW nanofluid versus nanofluid (cold fluid) flow rate for different nanoparticle volume concentrations.

5.2 Overall Heat Transfer Coefficient

The effect of nanoparticle concentration on the overall heat transfer coefficient is presented in fig. 4. From fig. 4, we can see that the overall heat transfer coefficient increases with the increase of nanofluid (coolant) flow rate and nanoparticle volume concentration. The maximum value of the overall heat transfer coefficient is 1141.82 $W/m^2.K$ at 0.3% volume concentration and 12 Liters/min flow rate of nanofluid. The average enhancement of overall heat transfer coefficient at 0.1%, 0.2%, and 0.3% nanoparticle volume concentration are 10.59%, 29.35%, and 42.26% respectively.

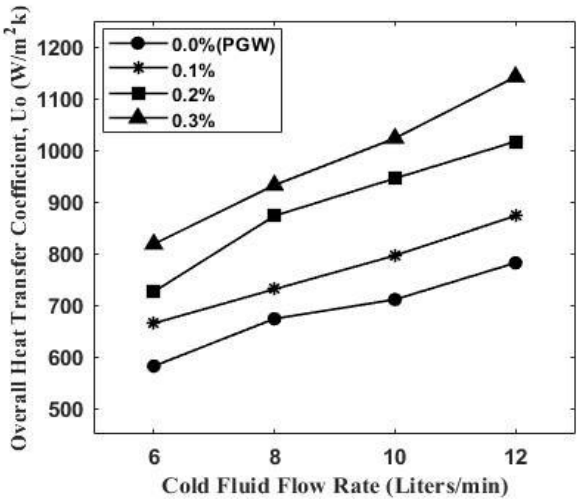

Fig. 4: Overall Heat transfer Coefficient of TiO_2/PGW nanofluid versus nanofluid (cold fluid) flow rate for different nanoparticle volume concentrations.

5.3 Convective Heat Transfer Coefficient

The effect of nanoparticle concentration on the convective heat transfer coefficient is shown in fig. 5. With the increase of nanofluid (coolant) flow rate and nanoparticle volume concentration, the convective heat transfer coefficient also increases. The maximum value of convective heat transfer coefficient is 1866.73 $W/m^2.K$

at 0.3% volume concentration and 12 Liters/min flow rate of nanofluid when the hot fluid flow rate was constant(12 liters/min). The average enhancement of convective heat transfer coefficient at 0.1%, 0.2% and 0.3% nanoparticle volume concentration are 5.54%, 11.04% and 14.55% respectively compared to base fluid (PGW).

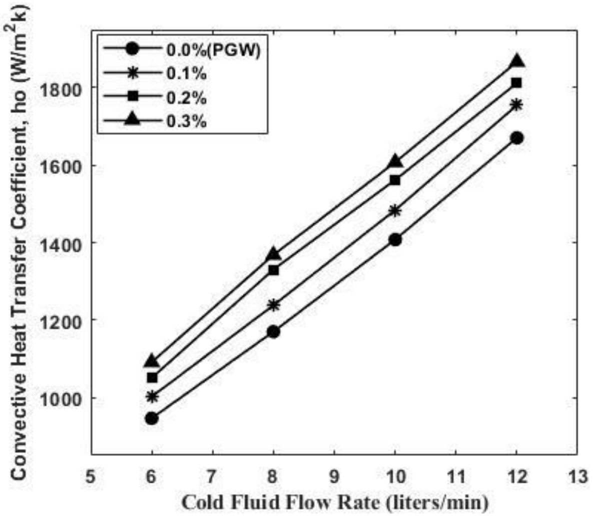

Fig. 5: Convective Heat transfer Coefficient of TiO_2/PGW nanofluid versus nanofluid (cold fluid) flow rate for different nanoparticle volume concentrations.

5.4 Effectiveness

The effect of nanofluid flow rate and nanoparticle volume concentration on the energy effectiveness of the shell and tube heat exchanger is presented in fig. 6. When the nanofluid flow rate is increased at a constant hot fluid flow rate, energy effectiveness is decreased. However, effectiveness increases with the increase of nanoparticle volume concentration. The average enhancement of heat transfer rate at 0.1%, 0.2% and 0.3% nanoparticle volume concentration are 11.8%, 23.5% and 33.8% respectively compared to base fluid.

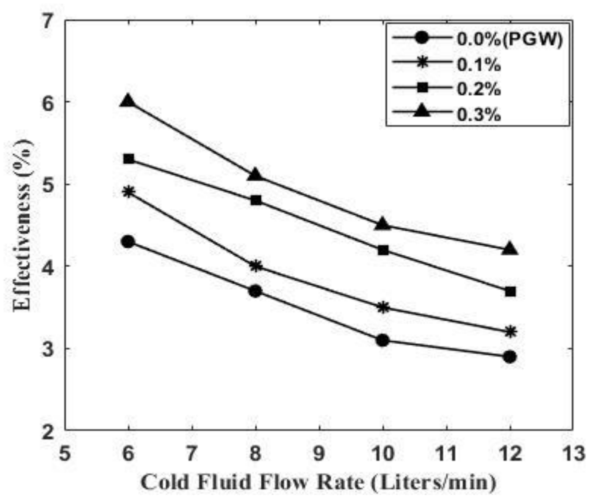

Fig. 6: Effectiveness of the heat exchanger versus nanofluid (cold fluid) flow rate for different nanoparticle volume concentrations.

6. CONCLUSION

In this work, heat transfer of 0.1%, 0.2% and 0.3% volume concentration of propylene glycol and water mixture based TiO_2 nanofluid in a shell and tube heat exchanger has been studied. Experiments indicate that the heat transfer rate, overall heat transfer coefficient, and convective heat transfer coefficients enhance with increasing nanoparticle volume concentration and nanofluid flow rate. Experimental results showed that the maximum enhancement of the heat transfer rate of TiO_2/PGW nanofluid was 44.39% compared to the base fluid at 0.3% nanoparticle volume concentration and 12 Liters/min flow rate of nanofluid. The maximum enhancement of the overall heat transfer coefficient was 48.13% when nanoparticle volume concentration and nanofluid flow rate were 0.3% and 12 Liters/min respectively. The average enhancement of convective heat transfer coefficient at 0.1%, 0.2% and 0.3% nanoparticle volume concentration are 5.54%, 11.04% and 14.55% respectively. The effectiveness of the heat exchanger is increased with nanoparticle volume concentration and decreased with nanofluid flow rate. So, the nanofluid (cold fluid) flow rate should be kept lower to get higher effectiveness of the heat exchanger. The heat transfer enhancement with nanoparticle volume concentration may be due to Brownian motion, intensification of turbulence due to the presence of nanoparticles, clustering of nanoparticles in the base fluid, etc. More research is required to find out the heat transfer characteristics of nanofluid. There are some limitations in this experimental investigation. Four thermometers were used to measure inlet and outlet temperature. However, there may have some parallax errors during taking the temperature reading. The stability of nanofluid is a major concern. In this study, the stability of nanofluid is not analyzed. Future work is needed for investigating the stability of TiO_2/PGW nanofluid.

7. ACKNOWLEDGEMENT

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8. NOMENCLATURE

Symbol	Meaning	Unit
A	Heat transfer area	(m^2)
C_p	Specific Heat	(J/kg k)
D	Tube diameter	(m)
h	Convective heat transfer coefficient	(W/m^2K)
k	Thermal conductivity	(W/mK)
L	Tube length	(m)
T	Temperature	(K)
$\dot{Q}$	Heat transfer rate	(W)
U	Overall heat transfer coefficient	(W/m^2K)
n	No. of tube	(Dimensionless)
$\dot{m}$	Mass flow rate	(Kg/s)
Re	Reynolds number	(Dimensionless)
Pr	Prandtl number	(Dimensionless)
Nu	Nusselt number	(Dimensionless)
V	Velocity	(m/s)
μ	Dynamic viscosity	(Pa.s)
ρ	Density	(Kg/m^3)
φ	Volume concentration	(Dimensionless)
Subscript		
h	Hot fluid	
c	Cold fluid	
np	Nanoparticle	
bf	Base fluid	
i	Inner side of tube	
o	Outer side of tube	