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Experimental Investigation on Heat Transfer Performance of Titanium Oxide - Water and Ethylene Glycol Nanofluid in a Plate Heat Exchanger

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Abstract - Plate heat exchangers play vital roles in industrial applications, the use of nanofluids is essential in heat transfer due to its effective performance, the performance of nanofluids in mixture base fluids is yet to be explored. Hence, the nanofluids made of water and Ethylene glycol mixtures (60:40) as base fluid and 21 nm sized Titanium Oxide were investigated experimentally on thermophysical properties and heat transfer performance with different nanoparticle concentrations from 0.4% - 1.0% under flowrates from 0.2 - 0.6 l/min at nanofluid bulk temperature from 30 - 70°C. The results indicate that thermal conductivity, specific heat, viscosity, and density increase with the concentration of nanofluid, however, the viscosity change with concentration is not significant. The significant improvement of heat transfer rate by using the nanofluid is observed, the heat transfer rate increases with the concentration and bulk temperature of nanofluid. At 30°C when the concentration is changed from 0.4% to 1.0%, the heat transfer rate is improved by 42.9% - 69.7%, at the flowrate of 0.2 - 0.6 L/min; at 70°C when the concentration is changed from 0.4% to 1.0%, the heat transfer rate is improved by 11.9 - 24.0% at the flowrate of 0.2 - 0.6 L/min. The overall heat transfer coefficient increases as flowrate and nanoparticle concentration increase, the overall heat transfer coefficient increases by 8.7%, 6.9%, 7.0 %, and 6.7% when the concentration is increased from 0.4 to 1.0% at flowrate of 0.2, 0.3, 0.4, and 0.6L/min, respectively. Nanofluid can improve the effectiveness of plate heat exchanger significantly, the improvement of effectiveness of heat exchanger by using nanofluid at the flow rate of 0.2L/min is between 21.7-36.2%, 36.7-53.3%, 44.6-64.3%, 47.8-66.1%, and 52.9-76.5% at 30, 40, 50, 60 and 70 °C, respectively.

***Keywords*:** Plate heat exchanger, nanofluid, Titanium Oxide, Water-ethylene glycol mixture, heat transfer rate, overall heat transfer coefficient, effectiveness.

1. Introduction

Nanofluid is defined as the dispersion of nano-sized particles in a base fluid. Since the need for fluids that can enhance the performance of heat transfer equipment, nanofluid was introduced by Masuda et al. [1] where the experimental investigation was conducted on thermal properties of the nanofluid. Compared to the ordinary heat transfer fluid such as water and oil, nanofluids prove to exhibit superior heat transfer performance. With the studies conducted during past three decades, the nanofluid field has expanded with investigations on many aspects related to the performance of the nanofluids.

The performance of heat exchangers using nanofluids are dependent of many factors, such as type of heat exchangers, base fluid, nanoparticle (single or hybrid), concentration, and working conditions (flowrate and temperature, etc.).

The most common nanofluids investigated are water-based fluids with different type of nanoparticles at different sizes and concentrations, the performance exhibits considerably different. The most commonly used nanoparticles are Titanium Oxide, Copper Oxide, Aluminium Oxide with sizes from 10-50 nm and volume concentration of 0.05-5% , when the flow rate ranges from around 1-7.5 L/min with the Reynolds Number of 1000 to 30000 at temperature of 15-80 °C, the typical heat transfer rate improved is from 5% to 30% for double-tube heat exchangers, plate heat exchangers and shell and tube heat exchangers [2-11].

Water and Ethylene glycol mixtures at different compositions with the typical values of 60-40% and sometimes 50-50% are also commonly used as base fluids. When 13-50 nm sized Titanium Oxide, Aluminium Oxide nanoparticles were mixed with water and Ethylene glycol at the ratio of 60%/40%. Observing flow rates from 2 L/Min to 20 L/Min yielded Reynolds number between 3000 to 24 000 under range of temperatures of 30 to 70 °C, the choice of nanoparticle concentration was 0.5% - 1.5% by volume, the outcome of the experiment showed that the performance of the nanofluid was 1.3 - 44% more than that of the base fluid [12-14].

For specific applications, some uncommon base fluids with nano particles were also investigated on thermophysical properties. Wang et al. [15] selected 20 nm sized Titanium Oxide nanoparticles to be mixed with paraffin wax at temperatures from 15 °C to 65 °C and nanoparticle concentrations of 0.1% to 0.7% by weight. Increase in latent heat was observed at 0.7% nanoparticle concentration. Wei, Zou and Li [16] using 10 nm anatase Titanium Oxide nanoparticles mixed with diathermic oil, at temperature range from 20°C to 50°C saw an enhancement of thermal conductivity of 0.136 W/m.K at the highest temperature tested at 50°C and 1.0% nanoparticle concentration. The nanoparticle concentrations selected were of 0.1% to 1.0% by volume. Javadi et al. [17] used a plate fin heat exchanger in the experimental setup, with three types of Nanofluids observed, Silicon Dioxide with liquid nitrogen, Titanium Oxide with liquid nitrogen, and Aluminium Oxide with liquid nitrogen, the overall heat transfer coefficient was seen at the highest in the Aluminium Oxide Nanofluid at 308.69 $W/m^2.K$ for 2.0% nanoparticle concentration.

With the advancement of research, hybrid nanofluids were drawn attention. For example, Bhattad, Sarkar and Ghosh [18] considered hybrid nanofluids for milk chilling applications in corrugated plate heat exchanger using counterflow arrangement. The hybrid nanofluids considered were Alumina/Silver-Ethylene Glycol (20%)/Water (80%) and Magnesia/Silver-Ethylene Glycol (20%)/Water (80%) tested with various nanoparticle concentrations. The theoretical study focused on the energetic and exegetic performance of the counterflow plate heat exchanger, with increase observed for pumping power, pressure drop, convective and overall heat transfer coefficients, milk flowrate, heat transfer rate, irreversibility, second law efficiency and entropy generation rate. A decrease of hybrid nanofluid was observed with performance index, non-dimensional exergy destruction, and irreversibility distribution ratio. Comparing the hybrid nanofluid to the base fluid, a 1.6% and 9.4% increase was observed for heat transfer rate and convective overall heat transfer coefficient., with Alumina-Silver hybrid nanofluid yielding better results as compared to the Magnesia/Silver Hybrid nanofluid.

In this paper, the nanofluids made of water and Ethylene glycol mixtures (60:40%) as base fluid and 21 nm sized Titanium Oxide were investigated experimentally on thermophysical properties and heat transfer performance.

2. Experimental setup and Methods

2.1. Preparation of nanofluids

Titanium Oxide nanoparticles with the size of 21 nm and water-Ethylene Glycol (60:40%) were mixed at different concentrations for investigation of heat transfer performance at different operation conditions.

The nanofluid was prepared by using the two-step method with Hexadecyltrimethylammonium bromide (CTAB) used as surfactant for reducing the nanoparticle settling. Nanoparticles were firstly weighed on a scale with 100 ng accuracy, after the nanoparticles were added to the base fluid, the magnetic stirring at 300 rpm for the mixing of the nanoparticles and the base fluid was lasted for 8 hours to ensure homogeneity with no visible nanoparticle settling. Stability of the nanofluids has been tested by leaving the nanofluid in mixing container without any disturbance. It is observed that there has not been any settling of nanoparticles at the bottom of the container even after twelve hours. This observation ascertained that the nanofluid has been stable and the nanoparticles have been in a colloidal state. Nanoparticle concentrations of 0.4 %, 0.6 %, 0.8%, and 1.0% by volume were prepared for investigation of heat transfer performance.

The plate heat exchanger testing setup rig has a hot nanofluid storage tank with a pump for circulation, a heating equipment for control of nanofluid temperature, temperature sensors, flow meters, and power supply and included instruments for control and monitoring. The test rig is equipped with a control panel through which the inlet temperature of the nanofluid can be pre-selected to any desired temperature. The inlet temperature of the cold fluid (water) is recorded in-situ by a temperature sensor fixed in the pipeline. The eight-plate plate heat exchanger with the correction factor being at 0.93 is made of stainless steel with heat transfer area of 0.1036 m^2. The parallel flow arrangement for heat exchanger is selected for investigation. The experiments were taken under constant nanofluid flowrates of 0.2 l/min, 0.3 l/min, 0.4 l/min, 0.5 l/min, and 0.6 l/min and temperature of 30-70 °C.

Calibration of the test rig was conducted. Using a stopwatch to record the time it takes (in minutes) to pass litres of the nanofluid and comparing the results with the selected flow rates of 0.2l/min, 0.3l/min, 0.4l/min, 0.5l/min and 0.6l/min. The percentage (%) error found was at 3%. Heat balance test was conducted using equation (1) and the error was found at 4%.

$$(\dot{m}C_p(T_{co} - T_{ci}))_{water} = (\dot{m}C_p(T_{hi} - T_{ho}))_{nanofluid} \tag{1}$$

Where $\dot{m}$ is the mass flow rate, C_p is the specific heat, and T_{hi}, T_{ho}, T_{ci}, T_{co} are hot and cold fluids temperatures at inlet and outlet, respectively.

The heat transfer rate, overall heat transfer coefficient, Reynolds number, Nusselt number, pumping Power, pressure drop, and the effectiveness of the plate heat exchanger are determined using experimental data.

2.2. Thermophysical Properties

The thermophysical properties of the nanofluids were determined using equations (2)-(5) [19-20].

Thermal Conductivity:

$$k_{nf} = \frac{k_p + 2k_{bf} + 2\emptyset(k_p - k_{bf})}{k_p + 2k_{bf} - \emptyset(k_p - k_{bf})} \times k_{bf} \tag{2}$$

Density:

$$\rho_{nf} = (1 - \emptyset)\rho_{bf} + \emptyset\rho_p \tag{3}$$

Specific Heat:

$$C_{p,nf} = \frac{(1-\emptyset)\rho_{bf}C_{p,bf}}{\rho_{nf}} + \frac{\emptyset\rho_p C_{p,p}}{\rho_{nf}} \tag{4}$$

Viscosity:

$$\mu_{nf} = \mu_{bf}(1 + 2.5\emptyset) \tag{5}$$

Where $p, bf, and\ nf$ are abbreviations of particle, base fluid and nanofluid, $\emptyset$ is the mass percentage of nano particles in nano fluid.

2.3. Heat Transfer Analysis

Heat transfer rate is calculated by:

$$\dot{Q} = \dot{m}C_p\Delta T \tag{6}$$

Where $\dot{Q}$, $\dot{m}$, C_p, ΔT represents the heat transfer rate, mass flow rate, specific heat and change in temperature, respectively.

Overall heat transfer coefficient:

$$\frac{1}{U} = \frac{1}{h_{nf}} + \frac{\Delta x}{k} + \frac{1}{h_w} \tag{7}$$

Where $\dot{U}$, $\dot{h}_{nf}$, h_w, k, Δx represents the overall heat transfer coefficient, nano fluid side convection heat transfer coefficient, water side convective heat transfer coefficient, thermal conductivity, and thickness of plate, respectively.

Reynolds Number:

$$Re = \frac{4\dot{m}}{\pi \mu D_h} \tag{8}$$

Where $\dot{m}$ is the mass flow rate, μ is the viscosity, and D_h is the hydraulic diameter.

Nusselt Number:

$$Nu = \frac{hD_h}{k} \tag{9}$$

Where h is the heat transfer coefficient, D_h is the hydraulic diameter, and k is the thermal conductivity.

Effectiveness of the heat exchanger:

$$\varepsilon = \frac{\dot{Q}_h}{(\dot{m}C_p)_{min}(T_{hi}-T_{ci})} \tag{10}$$

Where ε, $\dot{Q}_h$, $(\dot{m}C_p)_{min}$, T_{hi}, T_{ci} are the effectiveness of the plate heat exchanger, the heat transfer rate of the nanofluid, minimum capacity, the inlet temperature of the hot fluid, and the inlet temperature of the cold fluid, respectively.

3. Results and Analysis

3.1. Thermophysical properties

Figures 1-4 indicate that thermal conductivity, specific heat, viscosity, and density increase with the concentration of nanofluid, however, the viscosity changes with concentration is not significant, the impact of temperature on thermophysical properties of nanofluid is same as of the base fluid.

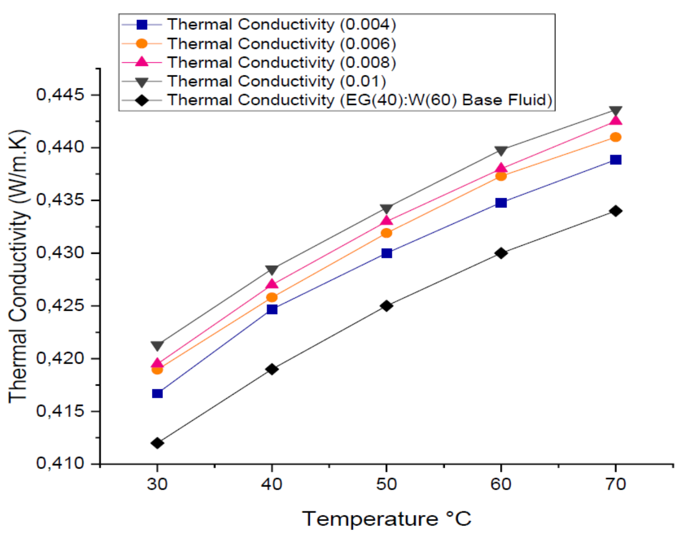

Fig. 1: Effects of temperature and concentration on thermal Conductivity

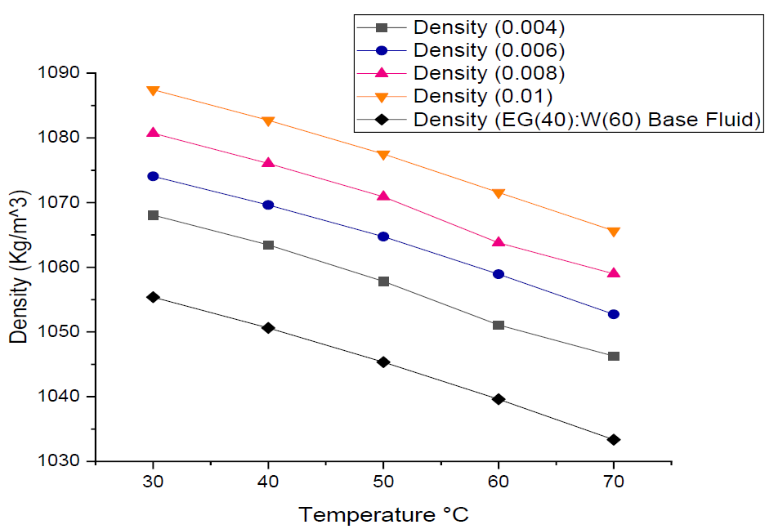

Fig. 2: Effects of temperature and concentration on density

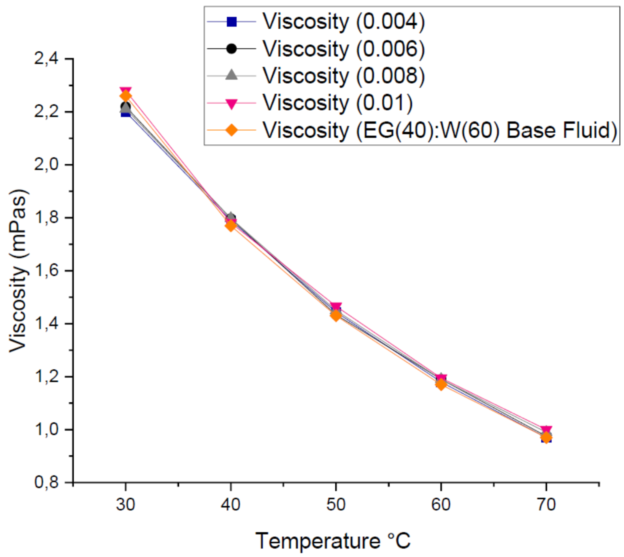

Fig. 3: Effects of temperature and concentration on viscosity

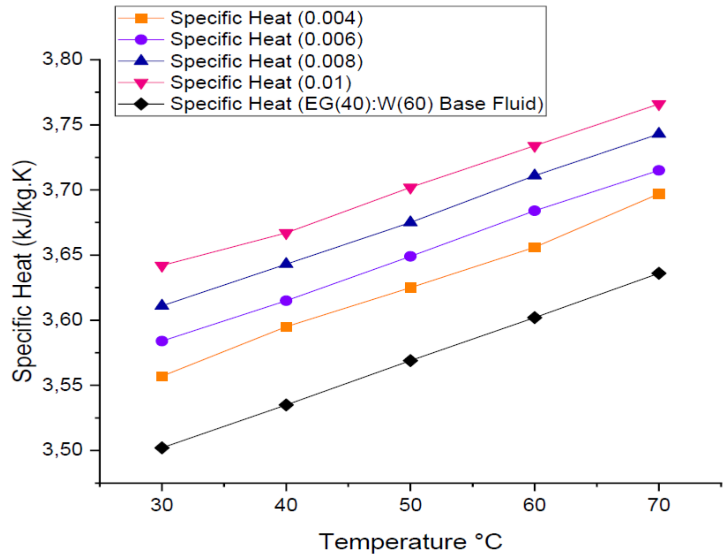

Fig. 4: Effects of temperature and concentration on specific Heat

3.2. Heat Transfer Rate

Impacts of concentration from 0.4% to 1.0%, bulk temperature from 30 to 70°C and flow rate from 0.2 to 0.6 l/min of Titanium Oxide - Ethylene Glycol:Water(40:60) nanofluid on heat transfer rate were investigated, the typical results are presented in Figures 5 and 6. The overall observation is that the heat transfer rate increase with the concentration and bulk temperature of nanofluid. At 30°C when the concentration is changed from 0.4% to 1.0%, the heat transfer rate is improved by 69.7%, 53.8%, 48.1% and 42.9% at the flowrate of 0.2, 0.3, 0.4, and 0.6 L/min, respectively; and at 70°C when the concentration is changed from 0.4% to 1.0%, the heat transfer rate is improved by 24.0%, 16.9%, 22.0, 11.9% and 16.7% at the flowrate of 0.2, 0.3, 0.4, 0.5 and 0.6 L/min, respectively. Therefore, the significant improvement of heat transfer rate by using the nanofluid is observed.

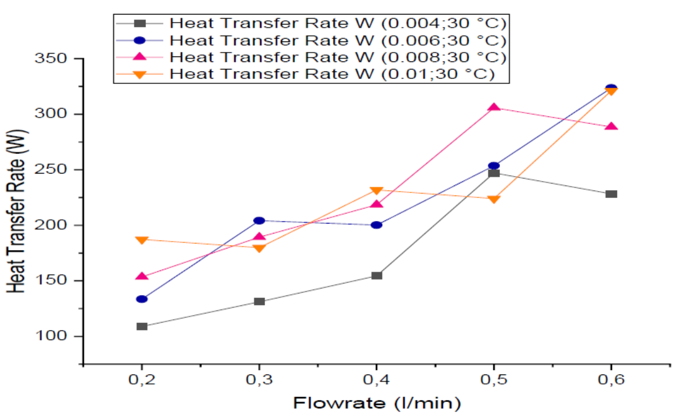

Fig. 5: Heat Transfer Rate at 30 °C

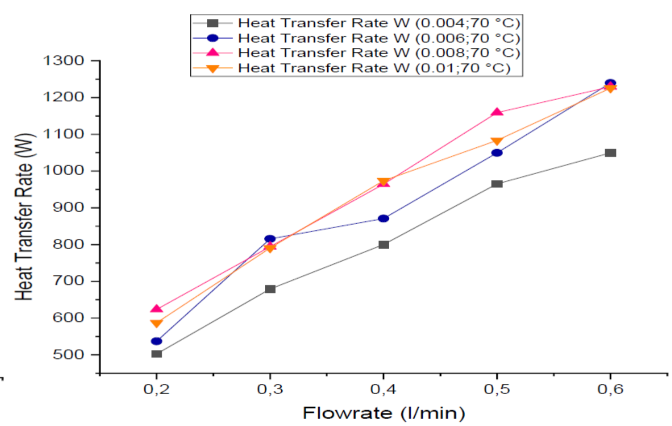

Fig. 6: Heat Transfer Rate at 70 °C

3.3. Overall Heat Transfer Coefficient

The results shown in Figure 7 displays the representative behaviour of the overall heat transfer coefficient at the different nanoparticle concentrations and flowrates, at temperature 70°C. The overall heat transfer coefficient increases as flowrate and nanoparticle concentration increase. The overall heat transfer coefficient increases by 8.7%, 6.9%, 7.0 %, and 6.7% when the concentration is increased from 0.4 to 1.0% at flowrate of 0.2, 0.3, 0.4, and 0.6L/min, respectively. The highest overall heat transfer coefficient occurs at flowrate 0.6 l/min as 1914 $\mathrm{W/m^2}$. K at 0.6% nanoparticle concentration, the lowest overall heat transfer coefficient occurs at flowrate 0.2 l/min and 0.4% nanoparticle concentration as 690.4 $\mathrm{W/m^2}$. K.

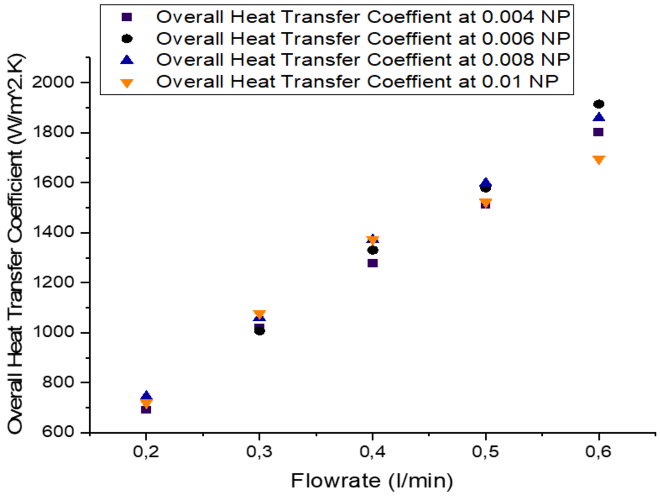

Fig. 7: Overall Heat Transfer Coefficient at 70°C

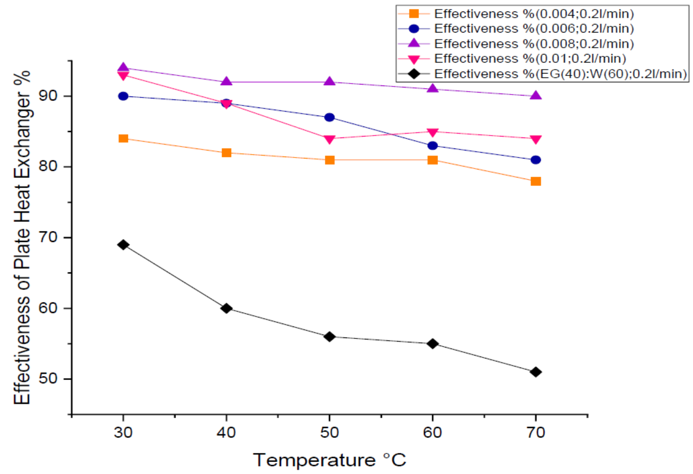

Fig. 8: Effectiveness of The Plate Heat Exchanger

3.4. Effectiveness

Fig.8 display results for the effectiveness of the plate heat exchanger in parallel flow arrangement. The results of the effectiveness of the plate heat exchanger using the base fluid is from 51% to 69% when the bulk temperature decrease from 70 to 30°C, which is far lower than the effectiveness of the Titanium Oxide-Ethylene Glycol(40%)/Water(60%) Nanofluids. The improvement of effectiveness of heat exchanger by using nanofluid at the flow rate of 0.2L/min is between 21.7-36.2%, 36.7-53.3%, 44.6-64.3%, 47.8-66.1%, and 52.9-76.5% at 30, 40, 50, 60 and 70 °C, respectively.

3.5. Uncertainty Analysis

The uncertainty analysis was carried out for the experimental investigation by the Kline and McClintock method [21]. Table 1 and Table 2 display the results.

Table 1: Measurements for Uncertainty

Measurement	Uncertainty
u_{R_e}- Reynolds Number	± 0.0371
$u_{\dot{m}}$ -Mass Flowrate	± 0.0309
$u_{\dot{Q}}$- Heat Transfer Rate	± 0.0404
u_{ε}- Effectiveness	± 0.0527
u_{μ} - Viscosity	± 0.0159

Table 2: Uncertainties on measuring devices

Equipment	Accuracy
Pressure	±0.1%
Weighing Scale	±100ng
Temperature	±0.5℃
Magnetic Stirrer Liquid Temperature Control	±1℃
Magnetic Stirrer Plate Temperature Control	±2℃

4. Conclusion

In this study an experimental investigation was conducted using Titanium Oxide-Ethylene Glycol (40): Water (60) Nanofluid with different nanoparticle concentrations of 0.4%, 0.6%, 0.8%, and 1.0% under different nanofluid flowrates 0.2 l/min, 0.3 l/min, 0.4 l/min, 0.5 l/min, and 0.6 l/min at nanofluid bulk temperature from 30 - 70°C.

Thermal conductivity, specific heat, viscosity, and density increase with the concentration of nanofluid, however, the viscosity changes with concentration is not significant.

The significant improvement of heat transfer rate by using the nanofluid is observed. The heat transfer rate increases with the concentration and bulk temperature of nanofluid. At 30°C when the concentration is changed from 0.4% to 1.0%, the heat transfer rate is improved by 69.7%, 53.8%, 48.1% and 42.9% at the flowrate of 0.2, 0.3, 0.4, and 0.6 L/min, respectively; and at 70°C when the concentration is changed from 0.4% to 1.0%, the heat transfer rate is improved by 24.0%, 16.9%, 22.0, 11.9% and 16.7% at the flowrate of 0.2, 0.3, 0.4, 0.5 and 0.6 L/min, respectively.

The overall heat transfer coefficient increases as flowrate and nanoparticle concentration increase. The overall heat transfer coefficient increases by 8.7%, 6.9%, 7.0 %, and 6.7% when the concentration is increased from 0.4 to 1.0% at flowrate of 0.2, 0.3, 0.4, and 0.6L/min, respectively.

Nanofluid can improve the effectiveness of plate heat exchanger significantly. The improvement of effectiveness of heat exchanger by using nanofluid at the flow rate of 0.2L/min is between 21.7-36.2%, 36.7-53.3%, 44.6-64.3%, 47.8-66.1%, and 52.9-76.5% at 30, 40, 50, 60 and 70 °C, respectively.

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