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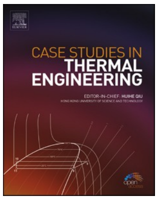

Heat transfer analysis of a shell and tube heat exchanger operated with graphene nanofluids

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ABSTRACT

Nanofluids have attracted huge attention because of their effective physical and thermal properties. One of many applications of nanofluids is the enhancement of the thermal performance of heat exchangers. In the current study, an experimental investigation has been conducted for studying the effects of graphene nanofluids on the convective heat transfer in a vertical shell and tube heat exchanger. Graphene flakes were prepared using graphite foam that is derived from sugar as a raw material. The prepared Graphene flakes have been characterized using scanning electron microscopy, X-ray diffraction, atomic force microscopy, and Raman spectroscopy. The graphene nanofluid has been used in the tube side of the heat exchanger to enhance its heat transfer performance. Different parameters such as nanofluids' concentration, flow rate and inlet temperature were studied and their effects on heat transfer coefficient and thermal efficiencies are discussed. The results show that using of graphene/water nanofluids enhances the thermal performance of the vertical shell and tube heat exchanger. A maximum increase in the heat transfer coefficient of 29% was achieved using 0.2% graphene/water nanofluids. Furthermore, the mean thermal efficiency of the heat exchanger was enhanced by 13.7% by using graphene/water nanofluid.

1. Introduction

Heat exchangers are widely used by various types of industries to exchange heat between different fluids for waste heat recovery and utilities cost reduction. The thermal and physical properties of the heat transfer fluids are crucial factors that dedicate the efficiency of heat exchangers. During the last two decades, nanofluids have attracted a huge attention of researchers due to its enhanced thermal properties and flow characteristics [1]. These advantages make nanofluids promising heat transfer fluids to be used for heat transfer enhancement. Many experimental studies have been conducted for the evaluation of heat transfer characteristics of nanofluids in different types of heat exchangers [2–7]. These types of heat exchangers include plate heat exchangers [2], double pipe heat exchangers [3], and micro heat exchangers [6]. However, in open literature, similar studies on shell and tube heat exchangers are scarce.

Thermal performance of a shell and tube heat exchanger was analytically investigated by Shahrul et al. using nanofluids of four different types of nanoparticles, Fe_3O_4, ZnO, TiO_2, CuO, and Al_2O_3 [8]. The results showed that a maximum heat transfer coefficient

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Fig. 1. The H101C heat exchanger [16].

was belonging to Al_2O_3/water nanofluids. Shell and tube heat exchanger was used to compare turbulent heat transfer performance of two types of nanofluids, Al_2O_3 and TiO_2 with water as base fluids [9]. The study indicated that TiO_2 nanofluids have better heat transfer characteristics than Al_2O_3 nanofluids. Lotfi et al. [10]. experimentally investigated the heat transfer performance of multi-walled carbon nanotube (MWNT)/water nanofluid in a shell and tube heat exchanger with a horizontal configuration. Compared to water, the results show that (MWNT)/water nanofluid enhances the overall heat transfer coefficient. Albadr et al. [11]. studied convective heat transfer characteristics for different concentrations of Al_2O_3/water nanofluid used in a horizontal type of the shell and tube heat exchanger. The results showed a slight improvement in the heat transfer coefficient. Shell and tube heat exchanger was also used by Ghozatloo et al. [12]. to investigate the convective heat transfer coefficients of graphene/water nanofluids under laminar flow. The study claimed that using graphene nanofluids at a concentration of 0.1 wt% can enhance the convective heat transfer coefficient up to 35.6% compared to the base fluid. Milad and Ehsan [13] used exergy analysis to study effects of different parameters on the thermal efficiency of graphene oxide nanofluids in a shell and tube heat exchanger. The results showed that using graphene oxide nanofluids enhances heat transfer in both laminar and turbulent flow conditions.

In the present study, heat transfer characteristics of graphene/water nanofluids were evaluated in a vertical shell and tube heat exchanger. Different parameters were studied at different nanofluids' concentrations.

2. Experimental investigation

2.1. Preparation and characterization of graphene flakes

Graphite foam was first produced by dehydration of sugar. Then, the graphite foam produced was used for preparation of graphene flakes (GF) with a size range of 50–140 nm. The prepared Graphene flakes have been identified and characterized using scanning electron microscopy, X-ray diffraction, Atomic Force Microscopy and Raman spectroscopy. The structural and morphological characteristics of the graphene flakes were good with acceptable amount of defects. The shape and position of the 2D band of Raman spectra revealed the formation of few layers graphene. The characterization results were presented in a previous work [14].

2.2. Preparation of graphene/water nanofluids (GNF)

Nanofluids are stable suspensions of nanoparticles in a base fluid. Two main methods can be used for the preparation of nanofluids, single-step and two-step methods [15]. In the single-step method, the nanoparticles and nanofluids are prepared simultaneously. In contrast, the nanoparticles in the two-step method are prepared first, and then nanofluids are formed by adding nanoparticles into the base fluid [15].

In the current work, the two-step method was used for the preparation of graphene/water nanofluids (GNF). The graphene powder was used for the preparation of graphene/water nanofluid by dispersing it into deionized water (DW). A magnetic agitation was used for 15 min for better dispersion enhancement. In order to increase the stability of GF suspension in the water, Gum Arabic (GA), was added as a surfactant agent into the DW prior to the addition of GF [14]. Four concentrations of GNF were prepared, 0.01, 0.05, 0.1 and 0.2 wt%.

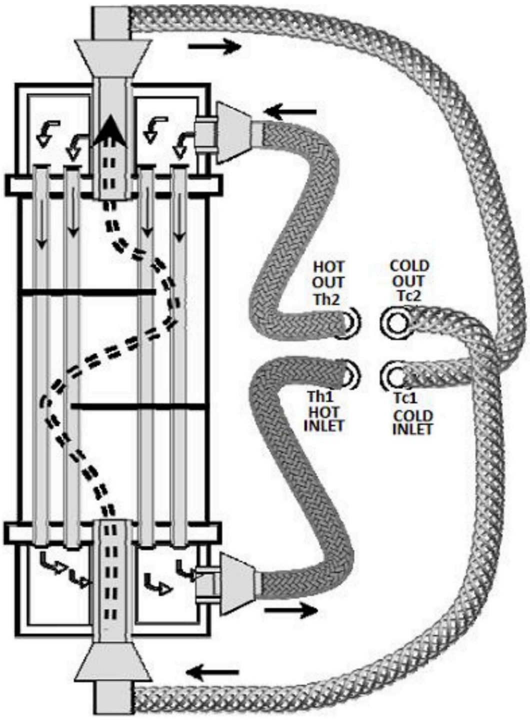

Fig. 2. Schematic diagram of the experimental setup [16].

Table 1
Physical properties of materials.

Material	Thermal Conductivity, k (W/m.K)	Density, **ρ** (kg/m^3)	Specific Heat, Cp(kJ/kg.K)
Water at 25 °C [17]	0.607	995	4.183
Graphene nanoparticles [18]	*3000*	*2200*	0.643

2.3. Experimental setup

H101C shell and tube exchanger model is used in the experimental investigation [16], Fig. 1.

The experimental setup of a vertical single-pass shell and tube heat exchanger consists of, a cylindrical glass shell of 7.5 cm inside diameter with 1 cm wall thickness, seven stainless steel tubes of 20.5 cm length with an outer diameter of 4.76 mm and tube wall thickness of 0.6 mm. Two baffles inside the shell are used to ensure efficient velocity and turbulence of the shell side-fluid. An electrical heating system is used for heating the tube side fluid (hot side) into different temperatures. Furthermore, a pump, two flow meters and four thermocouples are used. The schematic diagram of the experimental setup is sown in Fig. 2 [16].

3. Procedure and Calculations

This section presents the basic equations used in the current work to calculate physical properties of fluids used in both sides of shell and tube heat exchanger. Correlations used for the analysis of energy performance of heat exchanger are also provided.

3.1. Physical properties

Calculations are conducted with the assumption that cold fluid (water) pumped through the shell side, whereas the hot fluid (GFN) flowed through the tube side. Physical properties of GFN are calculated based on the fraction of graphene nanoparticles and water. The influence of GA on the physical properties of GFN is neglected due to its very low concentration. Table 1 presents the physical properties of graphene nanoparticles and deionized water.

3.1.1. Density

The density of GFN, ρ_{nf}, is calculated based on nanoparticle density, ρ_{np}, and base fluid density, ρ_{bf}, using the mixture rule as follows [19]:

$$\rho_{nf} = \phi\rho_{np} + (1-\phi)\rho_{bf} \tag{1}$$

where, ϕ is the fraction of nanoparticles in the base fluid.

The density of graphene nanoparticles is considered as temperature independence on the range of operating temperature. On the other hand, the water density is taken as a function of temperature [17]. The variation in water density, at constant volumetric flow rate, affects the calculated amount of heat transfer between hot and cold sides of the heat exchanger.

3.1.2. Specific heat

In the same way of estimation of nanofluid density, specific heat is calculated based on graphene, water volume fraction [19],

$$(\rho Cp)_{nf} = \phi(\rho Cp)_{np} + (1-\phi)(\rho Cp)_{bf} \tag{2}$$

3.1.3. Thermal conductivity

Numerous corrections are available in the literature to predict the thermal conductivity of nanofluids [20]. These correlations based on many parameters such as, thermal conductivities of nanoparticles and base fluids, geometry and surface area and fractions of nanoparticles, and temperature. In the current work, the Maxwell model is used to estimate thermal conductivity of GFN [21];

$$k_{nf} = k_{bf}\,\frac{k_{np} + 2k_{bf} + 2\phi\left(k_{np} - k_{bf}\right)}{k_{np} + 2k_{bf} - \phi\left(k_{np} - k_{bf}\right)} \tag{3}$$

where, k_{nf}, k_{np}, and k_{bf} are thermal conductivities of nanofluids, nanoparticles and base fluid respectively.

3.2. Thermal performance

For the thermal performance measurements, overall convective heat transfer coefficient, thermal effectiveness, thermal efficiency of tube side and shell side are used as evaluation parameters. Below are correlations used for estimation of important parameters of the performance.

3.2.1. Overall convective heat transfer coefficient

The convective heat transfer coefficient of the shell and tube heat exchanger is calculated based on the following correlation:

$$U = \frac{Q}{A \times LMTD} \tag{4}$$

where, A is total heat transfer area, m^2, Q is heat transfer from hot stream into cold stream, W, LMTD is logarithmic mean temperature difference, K.

$$Q = V\,(\rho Cp)_{nf}\;(T_{h1} - T_{h2}) \tag{5}$$

where, V is volumetric flow rate, m^3/hr, T_{h1}, T_{h2} are inlet and outlet temperatures of hot stream (tube side), ^oC.

The LMTD can be calculated as follows [2],

$$LMTD = \frac{(T_{h1} - T_{C2}) - (T_{h2} - T_{C1})}{\ln\frac{(T_{h1}-T_{C2})}{(T_{h2}-T_{C1})}} \tag{6}$$

where, T_{C1}, T_{C2} are inlet and outlet temperatures of cold stream (shell side) respectively.

3.2.2. Thermal efficiency

The thermal efficiency of the hot side η_{hot} is the ration of the temperature difference of the hot side to the maximum temperature difference between the hot and cold sides in a perfect heat exchanger.

$$\eta_{hot} = \frac{(T_{h1} - T_{h2})}{(T_{h1} - T_{C1})} \tag{7}$$

Similarly, the thermal efficiency of the cold side η_{cold} is the ration of the temperature difference of the cold side to the maximum temperature difference between the hot and cold sides in a perfect heat exchanger.

$$\eta_{cold} = \frac{(T_{C2} - T_{C1})}{(T_{h1} - T_{C1})} \tag{8}$$

The mean thermal efficiency, η_{mean}.

$$\eta_{mean} = \frac{\eta_{hot} + \eta_{cold}}{2} \tag{9}$$

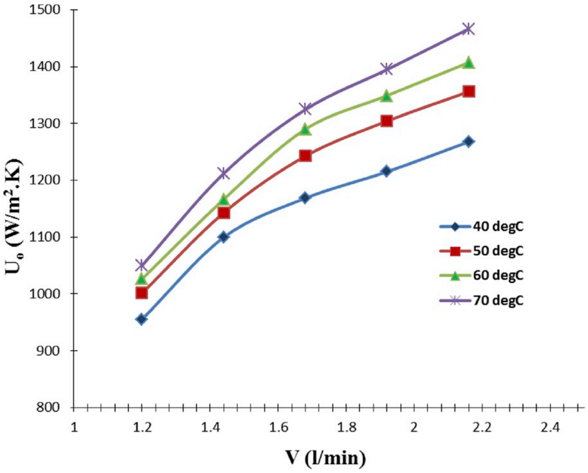

Fig. 3. Variation of tube side flow rate.

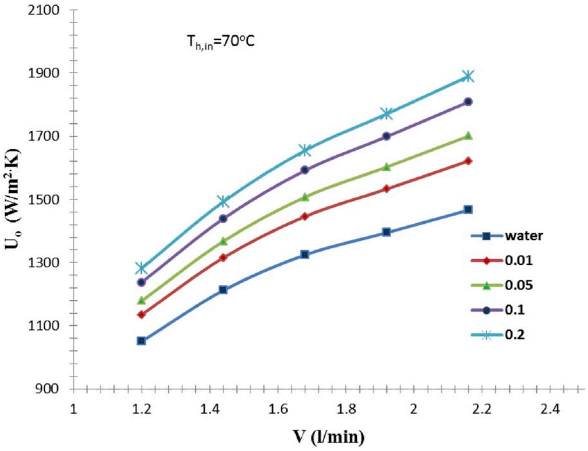

Fig. 4. Variation of graphene nanofluid concentration.

4. Results and discussion

4.1. Effect of change in mass flow rate of tube side fluid on the overall convection heat transfer coefficient

The convective heat transfer coefficient was investigated for various experiments in the case of a counter-current flow in a vertical shell and tube heat exchanger. Firstly, the convective heat transfer coefficient, U_o, was investigated for water/water heat exchange. Water flowing in the tube-side was heated by the heating system into five different temperatures, 30, 40, 50, 60 and 70 °C. The convective heat transfer coefficient is calculated at various flow rate of tube side fluid. Five different values of hot water flow rates were studied, 1.20, 1.44, 1.48, 1.92 and 2.16 l/min.

Fig. 3 shows effect of tube side flow rate on the heat transfer coefficient. The figure shows that when the hot side flow rate increases, the convective heat transfer also increases. Furthermore, the results show that at higher tube side flow rate, the influence of hot fluid inlet temperature was higher. The highest value of U_o was 1466 W/m^2.K at flow rate of 2.16 l/min and inlet temperature of 70 °C by an increase of 15.6% compared to its value at 40 °C, see Fig. 3.

4.2. Effect of nanofluids concentration on the overall convective heat transfer coefficient

The overall convective heat transfer coefficient was also investigated for water/graphene nanofluids heat exchange. The prepared graphene/water nanofluid is used as a hot fluid which is pumped through the tubes side. The inlet temperature of the tube side is kept constant at 70 °C. Fig. 4 shows the effect of variation in flow rate of graphene/water nanofluids on the overall heat transfer coefficient for different percentages of GFN (0.01, 0.05, 0.1, and 0.2).

The results show that if nanofluid flow rate increases, the overall heat transfer coefficient also increases. Fig. 4 shows that the

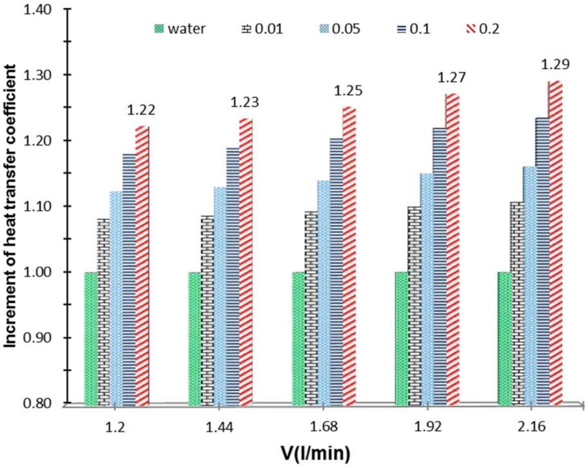

Fig. 5. Increment of heat transfer coefficient.

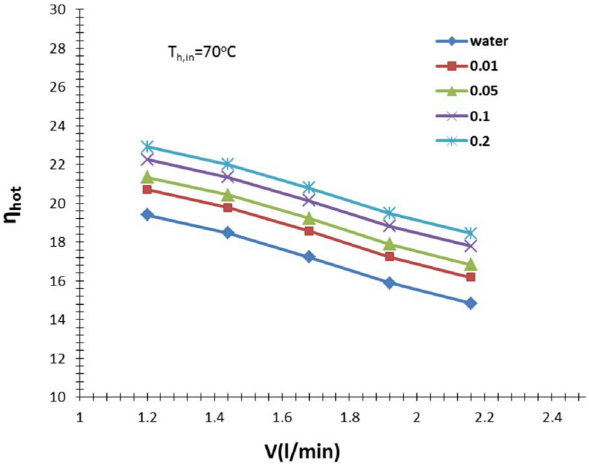

Fig. 6. Thermal efficiency of the hot fluid.

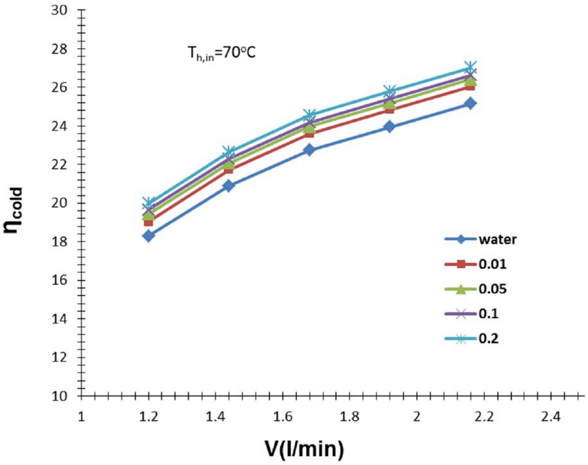

Fig. 7. Thermal efficiency of cold fluid.

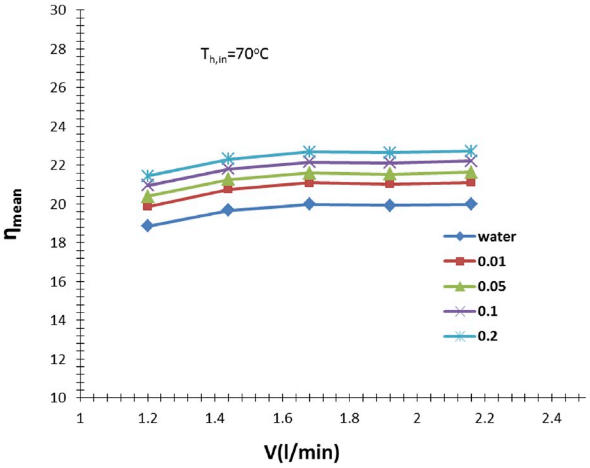

Fig. 8. Mean thermal efficiency.

increase in the GFN concentration significantly enhances U_o. The results also indicate that the influence of GFN concentration was slightly higher at higher tube side flow rate.

Fig. 5 shows the increase in the overall convective heat transfer coefficient as a function nanofluids concentration. Compared to water, the maximum increase in the overall heat transfer coefficient was 29% at nanofluids concentration of 0.2 wt% and flow rate and inlet temperature of 2.16 l/min and 70 °C respectively. The increase in the overall heat transfer coefficient could be attributed to the increase in the heat transfer performance of graphene/water nanofluid, namely thermal conductivity compared to water [18]. The results show that the enhancement in the heat transfer coefficient of a vertical shell and tube heat exchanger was less compared to the values produced by Ghozatloo et al. [12]. where an increase of 35% in the heat transfer coefficient was achieved for a horizontal shell and tube heat exchanger.

4.3. Effect of graphene/water nanofluids on the thermal efficiency of tube side fluid

Fig. 6 presents the change in the thermal efficiency of tube side fluid (η_{hot}) as a function of tube side flow rate at different concentrations of graphene/water nanofluid. As flow rate increases, η_{hot} decreases. On the other hand, at constant flow rate, the increase in the concentration of nanofluid results in an increase in η_{hot}. Nanofluid with a higher graphene concentration has a higher heat transfer coefficient which leads to an increase in the temperature difference of the tube side fluid which in turn increases η_{hot}.

4.4. Effect of graphene/water nanofluids on the thermal efficiency of shell side fluid

The effect of nanofluids on the thermal efficiency of the shell side fluid (η_{cold}) is presented in Fig. 7. The thermal efficiency of shell side fluid is drawn against nanofluid flow rate at different concentrations of graphene/water nanofluid. The figure shows that, the increase in the tube side flow rate results in an increase in η_{cold}. Furthermore, at constant flow rate, the increase in the concentration of nanofluid results in an increase in η_{cold}. As it previously shown, increasing nanofluid concentrations increases the convective heat transfer coefficient which results in higher values of temperature difference of the shell side fluid and in turn higher η_{cold}.

4.5. Effect of graphene/water nanofluids on the mean thermal efficiency (η_{mean})

Fig. 8 presents the mean thermal efficiency (η_{mean}) of the exchanger as a function of tube side flow rate. The results show a slight increase in η_{mean} with the increase in tube side flow rate. On the other hand, higher concentrations of nanofluids result in higher efficiency at all values of flow rates. Furthermore, it is noted that η_{mean} was almost constant at flow rate higher than 1.68 l/min.

5. Conclusion

Operating heat exchangers with nanofluids shows promise as a way to enhance heat transfer and reduce energy consumption. In this study, the heat transfer coefficient was improved by as maximum as 29% in a vertical configuration of a shell and tube heat exchanger using 0.2 wt% graphene/water nanofluids as a hot fluid on the tube side compared to water as a base fluid. Furthermore, the thermal efficiency is an important indicator of energy performance for heat exchangers. Using nanofluids with a concentration of 0.2 wt% enhanced the thermal efficiency of hot (tube) and cold (shell) sides by 24.4 and 7.3% respectively. In addition, the maximum increase in the mean thermal efficiency was 13.7% using nanofluids concentration and flow rate of 0.2 and 2.16 l/min.

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