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Thermodynamic Analyses of Shell and Tube Heat Exchanger Using Different Hybrid Nanofluid MWCNT-graphene/Water Concentrations

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Abstract

Current research involves investigating the heat transfer and thermal performances of a STHE utilizing MWCNT-Graphene/water HNF concentrations experimentally. MWCNT-Graphene nanoparticles are mixed with water (base fluid) to create different HNF test samples. Ultrasonication method is used to create three samples of HNF's with volume concentrations of 0.01%, 0.02%, and 0.03%. The tube side (hot fluid) and shell side (cold fluid) volumetric flow rates are the considered variables on which the entire analyses done. The overall heat transfer coefficient, actual heat exchange rate, convective heat transfer coefficient, energy efficiency, and exergy efficiency are the main objective parameters. It is found that for 0.03% volume concentration, maximum enhancement in various thermodynamic performance parameters is observed. The results concluded are the overall heat transfer coefficient improved by 23.14% and 24.65% for the shell and tube side, respectively, energy efficiency improved by 82.36% and 76.92% for the shell and tube side, respectively, and maximum exergy efficiency is obtained at 0.03% volume concentration, it is enhanced by 23.18% for shell side and by 28.47% for tube side, respectively.

Keywords

MWCNT-Graphene, Hybrid nanofluids, Heat transfer enhancement, Energy and exergy efficiencies

Abbreviations

HNF: Hybrid nanofluid; HX: Heat exchanger; LMTD: Logarithmic mean temperature difference; STHE: Shell tube heat exchanger; MWCNT: Multi walled carbon nano tube; PLC: Programmable logic controlled; VFR: Volumetric flow rate.

Nomenclature

A is Area of heat transfer (m^2); c_p is Specific heat (J/kgK); d is Diameter (m); m is Mass flow rate (kg/s); h is Heat transfer coefficient (W/m^2K); T is Temperature (K); k is Thermal conductivity (W/mK); q is Heat transfer rate (W); N is Number of tubes; n is Number of passes; U is Overall heat transfer coefficient (W/m^2K); η is Efficiency (%); h_{nf} is Convective heat transfer coefficient of hybrid nanofluid; h_f is Convective heat transfer coefficient of parent fluid.

Subscripts

a is Ambient; c,in is Coolant inlet; c,out is Coolant outlet; h,in is HNF inlet; h,out is HNF outlet; t,f is tube side fluid.

Introduction

Every sector including electricity generation, heating, cooling, manufacturing industries, food industries, biomedical, and pharmaceutical industries have been seen considerable developments in past few decades. Major challenges such as global warming, rising fuel prices and energy security has motivated the researchers to focus on energy efficient devices world-widely. In general, HX are the devices that is been utilized in almost all the sectors mentioned above. STHE one of the HX types has been widely employed in many of the sectors to meet the demands. As, STHE has proven themselves for better heat exchange rates with minimum pumping power at a reasonable cost. The STHE have a good market share and developed design experience which leads them to be utilized in different sectors with variable operating conditions at desired high pressure and temperature. In addition, while improvement in their heat transfer characteristic is critical for researchers without altering the design aspects. Many methods for heat transfer enhancement have been employed such as increasing the heat transfer area and agitating the heated surface. In past decades, nanofluids have been introduced as an improved heat transfer fluid to enhance the thermal performance of HX's without altering their design. Nanoparticles (1 - 100 nm in size) are suspended in a base fluid such as water to prepare nanofluids, highly conducting fluids due to improved heat conductivity [1]. Recently, HNFs have also gained attention due to their enhanced heat transfer characteristics because of hybridization. Heat transfer characteristics of nanofluid are dependent on nanoparticles size, shape, and volume concentration. HNF's are made by suspending various types of nanocomposites in a base fluid that exhibit improved physiochemical characteristics [2].

Sidik et al. [3] reviewed different HNF's based on their applications, preparation methods, and stability. Leong et al. [4] reviewed various HNF's based on their heat conductivity characteristics and synthesis. Sajid and Ali [5] conducted review on heat conductivity and heat transfer performances of different HNF's. Yang et al. [6] reviewed various HNF's based on their preparation, properties, and applications with environmental aspects. Muneeshwaran et al. [7] reviewed HNF's role in the increment of heat transfer and concluded that they have remarkable upgrade in heat transfer characteristics because of improved thermal conductivity. Hajjar et al. [8] enhanced the heat conductivity of base fluid by mixing graphene oxides nanoparticles for engineering applications. Esfi et al. [9] determined the dynamic viscosity and heat conductivity of Ag-MgO/water HNF experimentally. Hung et al. [10] enhanced the capacity of heat exchange and effectiveness of an air-cooled HX using hybrid carbon nanofluids. Additionally, researchers have been utilized different HNF's to enhance the heat exchange characteristics and thermodynamic efficiencies in various heat transfer systems. Some of them are presented in subsequent paragraphs.

Lotfi et al. [11] enhanced the heat exchange performance for a horizontal STHE utilizing MWCNT/water HNF experimentally. Ghazatloo et al. [12] improved the heat exchange coefficients and rates of STHE using graphene/water HNF experimentally. Megatif et al. [13] investigated the heat exchange coefficients and thermal performance for STHE using different TiO_2-CNT/water HNF's concentrations under laminar flow condition. Aghabozorg et al. [14] examined the heat exchange characteristics for horizontal STHE under different flow conditions using various Fe_2O_3-CNT/water HNF's concentrations and improved the heat exchange coefficients by 13.54% and by 27.69% for laminar and turbulent flow conditions, respectively. Shahrul et al. [15] compared the performance of STHE using oxide HNF's such as CuO/water, Al_2O_3/water, TiO_2/water, Fe_3O_4/water, SiO_2/water, and ZnO/water and revealed that SiO_2/water HNF has least effectiveness whereas ZnO/water has highest effectiveness. Esfahani and Languri [16] used graphene oxide HNF concentrations to investigate the thermodynamic performance of STHE under both turbulent and laminar flow conditions. Hajabdollahi and Hajabdollahi [17] studied the effect of different shapes of HNF to improve the thermoeconomic performance of STHE analytically. Singh and Sarkar [18] investigated thermodynamic performance of STHE using several HNF's and concluded that Al_2O_3-Ag/water HNF had higher performance among other studied HNF's. As the research is unlimited to enhance the performance of a system, considering this it becomes important to utilize the other HNF's in STHE to investigate the heat exchange characteristics and thermodynamic performances for further improvements. Keeping this in mind, authors are utilizing MWCNT-Graphene (yet to be utilized in STHE) in various volume concentrations to analyze the effects on heat exchange and thermal characteristics.

In present research, heat exchange and thermal characteristics of STHE are investigated utilizing different concentration of MWCNT-Graphene/water HNF experimentally. MWCNT-Graphene nanoparticles are mixed with base fluid (water) at different volume concentrations 0.01%, 0.02%, and 0.03%, respectively. Performance parameters are compared at extreme VFR in tube side and shell side of STHE. Tube side VFR and shell side VFR are main variables on which analyses are to be done. Actual heat exchange rate, convective heat exchange coefficient, overall heat exchange coefficient, average heat exchange rate, energy efficiency and exergy efficiency are main objective functions. Eventually, various parametric studies are performed for objective functions by varying the main variables individually.

Materials and Methodology

The preparation of HNF and experimental setup used are discussed in this context in detail. MWCNT and Graphene nanoparticles are suspended in water to prepare the different HNF concentrations in this experimental study.

HNF preparation

In this experiment, water is being used as the basic fluid. Different volume fractions of HNF MWCNT-Graphene are prepared at 0.01%, 0.02%, and 0.03%, respectively. A suitable amount of water is used to distribute MWCNT and Graphene nanoparticles (produced by the platonic nanotech lab in India) with average diameters of 60 nm and purity levels of 99.5%. The nanoparticles are first stirred with a magnetic stirrer for a predetermined amount of time before being ul-

trasonically sonicated for 120 minutes to prevent vaporisation and maintain the stability of HNF. To maintain the stability of MWCNT-Graphene HNF, sodium dodecyl sulphate is utilised as a catalyst. The temperature is maintained using a temperature-controlled bath. For 120 minutes, an ultrasonicator with amplitude of 80% is employed to confirm that the hybrid nanoparticles are thoroughly dissolved in the parent fluid. This process ensures consistent, uniform suspensions in the HNF preparation free of sedimentation and agglomeration. Each sample needs a minimum of 15 litres of HNF to fully sustain the proposed STHE. As a result, 15 litres of each HNF are made for separate studies.

Apparatus used

In this experimental study, a computerized PLC-based STHE is utilized. Figure 2 and figure 3 describe the actual experimental setup and front view layout of STHE. Experimental setup has one tank to store the hot fluid with two heaters to maintain the constant temperature. A single magnetic pump pumps the hot fluid throughout the tubes. This hot fluid returns to hot fluid tank after circulating in the tubes and exchanging heat with shell fluid. The heater wire is composed of Nickel-Chromium and is coupled to a programmable alternating current source. K-type thermocouples are equipped with setup to detect the temperatures at various locations. T_1 and T_2 detect the inlet and outlet temperature of tube fluid, T_3 and T_4 detect the inlet and outlet temperature of shell fluid and T_5 detects the temperature of hot fluid tank. Rotameters are inbuilt with sensors to measure the flow rates of hot and cold fluids. Control valves are provided at various location to regulate the flow rates. V_1 and V_5 regulate the inlet and outlet flows of cold fluid, V_3 and V_4 regulate the inlet and outlet flows of hot fluid, while V_2 is provided for bypass, and V_6 for discharge of hot fluid tank. This system has a primary controlling PLC with an inbuilt display for diagnostic and calibration purposes. This display indicates the temperatures at various location and volumetric flow rates of tube side fluid and shell side fluid. The system display may be linked to a computer/laptop via USB connector to allow the temperatures and flow rates data to be transferred and stored after certain interval of time for calculations. Two important factors as flow rate and temperature are checked and regulated.

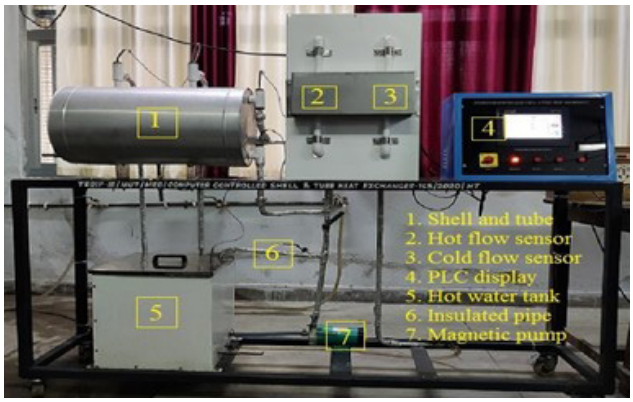

Figure 1: Experimental setup.

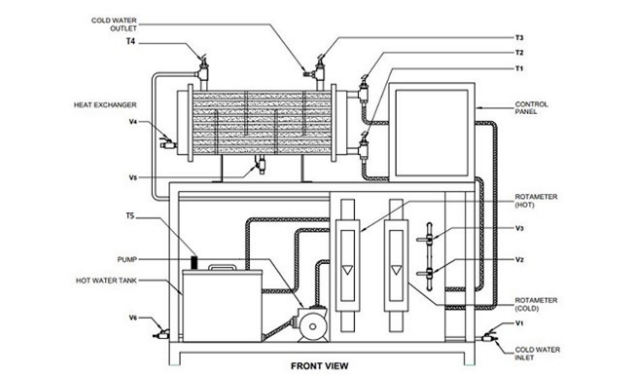

Figure 2: Front view layout of STHE.

To begin with the experiments of STHE merely have plain water flowing through them. The tank is filled with the needed amount of water, and then both the heaters are turned on. The temperature of hot water reaches 65 °C, whereas the temperature of cold water reaches 30 °C.

MWCNT-Graphene HNF, which is a hot fluid with 0.01, 0.02, and 0.03 Vol% concentrations, flows through the tube side, while water, which is a cold fluid, flows through the shell side. The hot fluid (water) is kept at 65 °C and passes through a tube side, while cold fluid (water) is kept at 30 °C and passes through a shell side. The same technique is performed for the second and third samples, i.e., 0.02 and 0.03 Vol% concentration of MWCNT-Graphene HNF, after the first sample, i.e., 0.01 Vol% concentration of MWCNT-Graphene HNF, has been completed. Tanks and pipes are properly rinsed and dried when an experiment is completed.

Mathematical formulation

In this section, the mathematical equations are discussed that are used to determine the heat exchange energy as well as exergy analysis of STHE.

Energy analysis

The energy analysis is done to determine the heat exchange coefficients and effectiveness of the STHE. The heat transfer rate by hot fluid (Q_H) and cold fluid (Q_c) can be calculated as: [18].

$$Q_H = \dot{m}_H \times C_p \left(T_{h,in} - T_{h,out}\right) \quad (1)$$

$$Q_C = \dot{m}_C \times C_p \left(T_{c,out} - T_{c,in}\right) \quad (2)$$

Average Heat Transfer

$$Q_{avg} = \frac{Q_H + Q_C}{2} \quad (3)$$

Logarithmic Mean Temperature Difference (ΔT_m)

$$\text{ÄMTÐ}\left(\quad_m\right) \quad \frac{\ddot{A}T_1 - \ddot{A}T_2}{\ln \frac{\ddot{A}T_1}{\ddot{A}T_2}} \quad (4)$$

Heat Transfer Area (A)

$$A = \left(\frac{d_0 + d_i}{2}\right) x\ N\ x\ n \quad (5)$$

Overall Heat Transfer Coefficient (U)

$$U = \frac{Q_{avg}}{(A\ x\ \Delta T_m)} \quad (6)$$

Variation of Convective Heat Transfer Coefficient (h_{nf})

$$\frac{1}{h_{nf}} = \frac{1}{U} - \frac{d_i\ x\ \ln\frac{d_o}{d_i}}{2k_{wall}} - \frac{d_o}{d_i}\ x\ \frac{1}{h_f} \quad (7)$$

Energy efficiency of the STHE can be calculated with respect to hot fluid as

$$\varepsilon_e = \frac{Q_{actual}}{Q_{max}} \quad (8)$$

$$\varepsilon_e = \frac{C_{Ph}\left(T_{h,in} - T_{h,out}\right)}{C_{min}\left(T_{h,in} - T_{c,in}\right)} \quad (9)$$

Exergy analysis

For qualitative analysis, the exergy analysis is being done. Availability of the fluid stream ($\Delta\psi$) can be calculated as

$$\Delta\psi = \left(h_{out} - h_{in}\right) - T_a\left(S_{out} - S_{in}\right) + \frac{u_{out}^2 - u_{in}^2}{2} + g\left(Z_{out} - Z_{in}\right) \quad (10)$$

The potential and kinetic energies are neglected; hence, the availability of fluid steam can be written as [18].

$$\Delta\psi = \left(h_{out} - h_{in}\right) - T_a\left(S_{out} - S_{in}\right) = c_p\left[\left(T_{out} - T_{in}\right) - T_a \ln\left(\frac{T_{out}}{T_{in}}\right)\right] \quad (11)$$

The exergy efficiency of STHE can be written as

$$\varepsilon_{ex} = \frac{\dot{m}_c c_{p,c}\left\{\left(T_{c,out} - T_{c,in}\right) - T_a \ln\left(\frac{T_{c,out}}{T_{c,in}}\right)\right\}}{\dot{m}_h c_{p,h}\left\{\left(T_{h,in} - T_{h,out}\right) - T_a \ln\left(\frac{T_{h,in}}{T_{h,out}}\right)\right\}} \quad (12)$$

Results and Discussion

In this section, heat transfer, energetic and exergetic performances of prepared HNF's is evaluated by changing the VFRs of the shell side and tube side individually.

Impact of varying the VFR of cold (shell side) fluids

Figure 3, figure 4, figure 5, and figure 6 depicts the actual heat transfer, average heat transfer, overall heat transfer coefficient, and convective heat transfer coefficient, respectively, with respect to shell side VFR utilizing different HNF concentrations of MWCNT-Graphene and compared with base fluid (water). Increased HNF concentration in base fluid increases the thermal conductivity and temperature difference results increase in the actual heat transfer, average heat transfer, overall heat transfer coefficient, and convective heat transfer coefficient. Maximum heat transfer occurs at

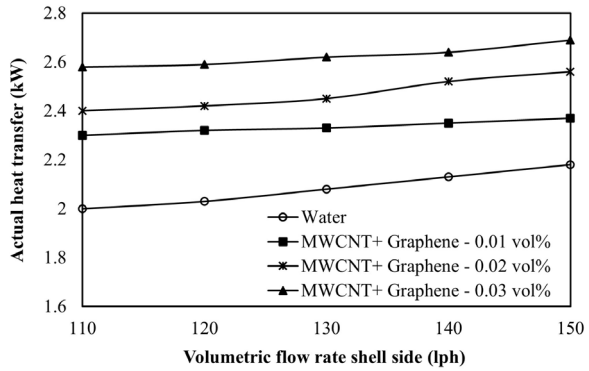

Figure 3: Impact on actual heat transfer by varying VFR on the shell side.

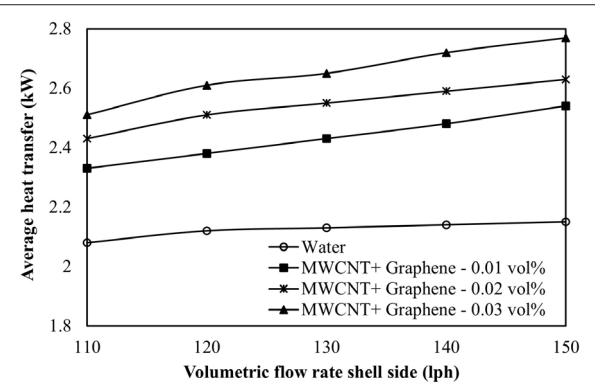

Figure 4: Impact on average heat transfer by varying VFR on the shell side.

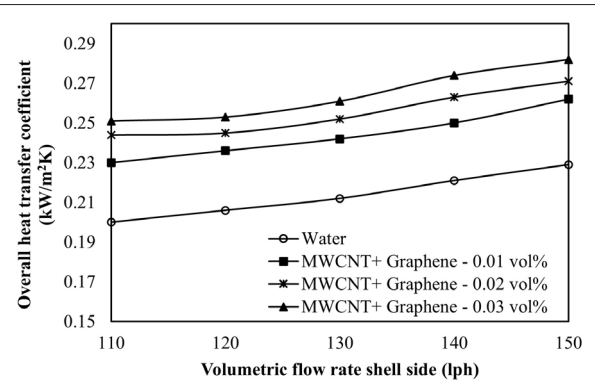

Figure 5: Impact on overall heat transfer coefficient by varying VFR on the shell side.

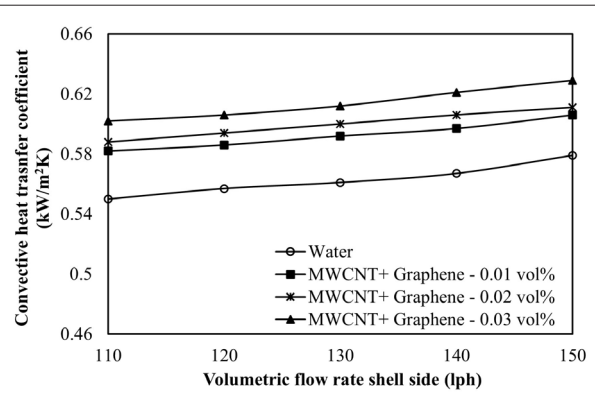

Figure 6: Impact on convective heat transfer coefficient by varying VFR on the shell side.

0.03 Vol% HNF concentration at 150 lph in contrast with other HNF concentration and base fluid.

Impact on energy and exergy efficiency by varying VFR for shell side

The energy and exergy efficiency of STHE is given in figure 7 and figure 8, respectively, and it can be observed that for 0.03 Vol% concentration energy and exergy efficiency is high when compared to the other samples i.e., 0.01 and 0.02 Vol% at 150 lph. The reason is, for energy efficiency when the concentration of HNF increases, the total heat transfer coefficient increases, leading to an increase in convective heat transfer coefficient, and consequently an improvement in energy efficiency and finally to an increase in exergy efficiency due to improvement in available energy. When all the samples were compared to water, energy efficiency for sample increases while exergy efficiency decreases. The reason for this is because cold fluid has a higher specific heat than hot fluid, and the temperature differential between ($T_{c,out}$ - $T_{c,in}$) is likewise higher ($T_{h,out}$ - $T_{h,in}$). As a result, water's exergy efficiency improves than the HNFs.

Impact of varying the VFR of hot (tube side) fluids

Figure 9, figure 10, figure 11, and figure 12 depicts the actual heat transfer, average heat transfer, overall heat transfer coefficient, and convective heat transfer coefficient, respectively, with respect to tube side VFR utilizing different HNF concentrations of MWCNT-Graphene and compared with base fluid (water). Increased HNF concentration in base fluid increases the thermal conductivity and temperature difference results increase in the actual heat transfer, average heat transfer, overall heat transfer coefficient, and convective heat transfer coefficient. Maximum heat transfer occurs at 0.03 Vol% HNF concentration at 150 lph in contrast with other HNF concentration and base fluid.

Impact on energy and exergy efficiency by varying VFR for tube side

The energy and exergy efficiency of STHE is given in figure 13 and figure 14, respectively, and it can be observed that for 0.03 Vol% concentration energy and exergy efficiency is high when compared to the other samples i.e., 0.01 and 0.02 Vol% at 150 lph. The reason is, for energy efficiency when the concentration of HNF increases, the total heat transfer coefficient increases, leading to an increase in convective heat transfer coefficient, and consequently an improvement in energy efficiency and finally to an increase in exergy efficiency due to improvement in available energy. When all the samples were compared to water, energy efficiency for sample increases while exergy efficiency decreases. The reason for this is because cold fluid has a higher specific heat than hot fluid, and the temperature differential between ($T_{c,out}$ - $T_{c,in}$) is likewise higher ($T_{h,out}$ - $T_{h,in}$). As a result, water's exergy efficiency improves than the HNFs.

Conclusion

Current research has been done to investigate the heat transfer and thermal performances of a STHE utilizing MWCNT-Graphene/water HNF's experimentally.

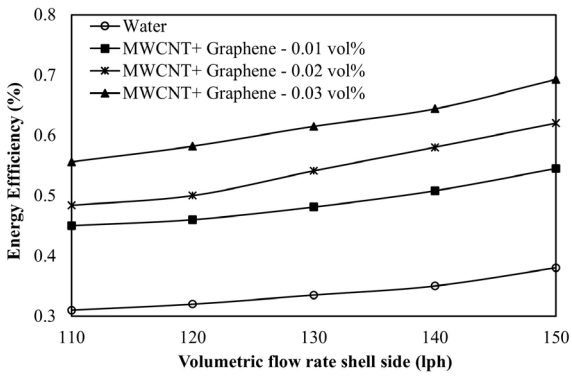

Figure 7: Impact on energy efficiency by varying VFR on the shell side.

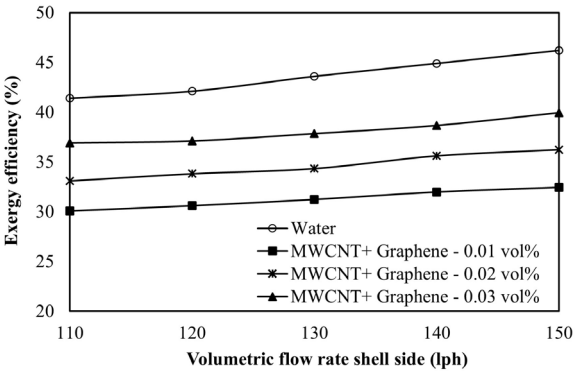

Figure 8: Impact on exergy efficiency by varying VFR on the shell side.

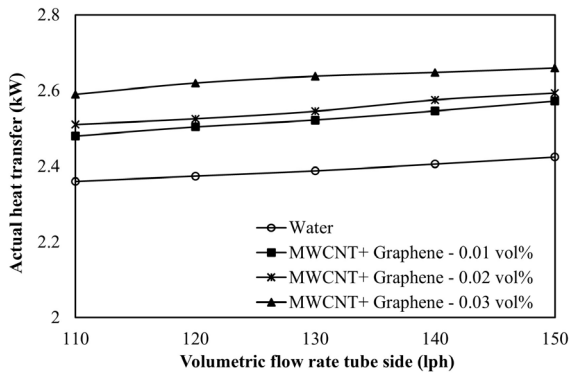

Figure 9: Impact on actual heat transfer by varying VFR within tube side.

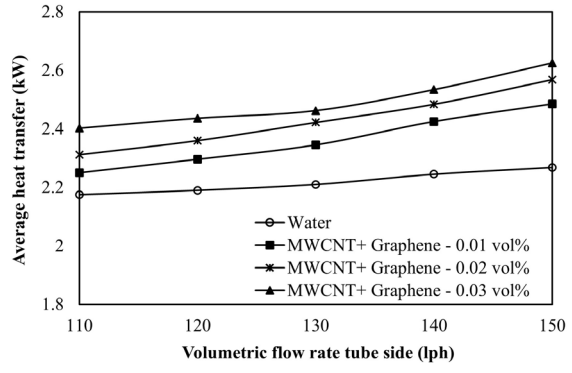

Figure 10: Impact on average heat transfer by varying VFR within tube side.

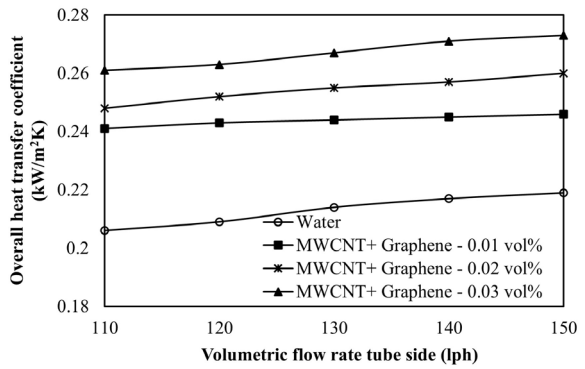

Figure 11: Impact on overall heat transfer coefficient by varying VFR within tube side.

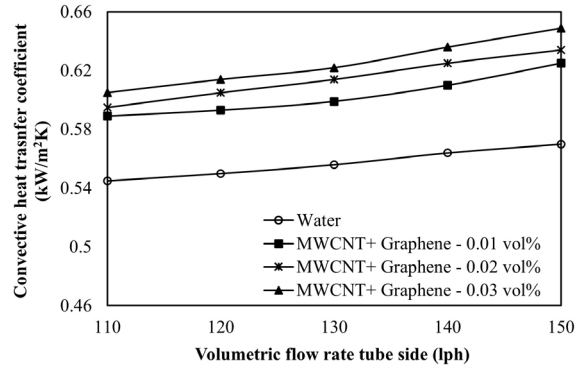

Figure 12: Impact on convective heat transfer coefficient by varying VFR within tube side.

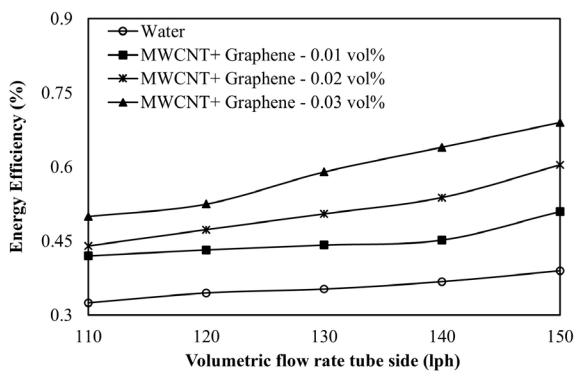

Figure 13: Impact of energy efficiency on varying VFR within tube side.

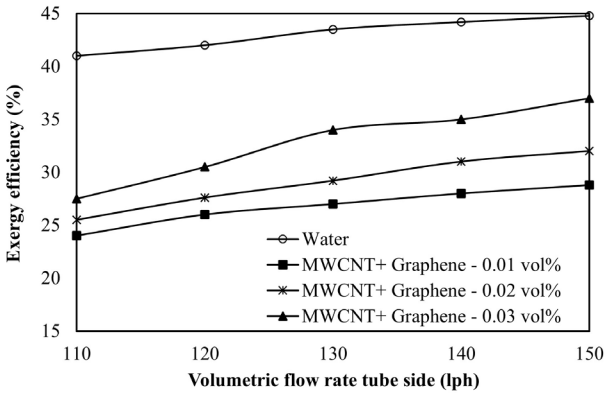

Figure 14: Impact of exergy efficiency on varying VFR within tube side.

MWCNT-Graphene nanoparticles have been mixed with water at different volume concentrations 0.01%, 0.02%, and 0.03%, respectively. Tube side VFR and shell side VFR have been taken the variables. Various parametric studies have been performed for the heat transfer and thermal performance parameters by varying the main variables individually. Finally, following conclusions were drawn:

- On varying volumetric flow of the shell side at extreme operating conditions (150 lph), 0.03 Vol% of Graphene-MWCNT resulted in a 23.14% rise in the overall heat transfer coefficient, a 23.39% increase in actual heat transfer, a 8.63% increase in the coefficient of convective heat transfer, and an 82.36% increase in energy efficiency when compared to water.
- On varying volumetric flow of tube side at extreme operating conditions (150 lph), about 24.65% improvement in overall heat transfer coefficient, about 9.69% improvement in actual heat transfer, around 13.85% convective heat transfer coefficient improvement and about 76.92% improvement in energy efficiency has been seen for 0.03 Vol% of Graphene-MWCNT as compared to water.
- With increased HNF concentration, the exergy efficiency has been found to be increased for 0.03 Vol% by 23.18% and 28.47% at maximum shell side and tube side VFR, respectively, respect to 0.01 Vol%.

Table 1: Operating conditions and specific characteristics of STHE.

Parameters	Specifications	Unit
Type	Single pass	-
Shell material	Stainless steel	-
Shell outside, Inside diameter, Shell thickness, Length of shell	220, 215, 5, 500	mm
Tube material	Copper	-
Tube outside, Inside diameter, Tube thickness, Tube length	13, 9, 4, 500	mm
Number of tubes inside the shell	12	-
VFR of hot fluid, VFR of cold fluid	110 - 150, 110 - 150	lph
Hot fluid temperature in the tank, Cold fluid temperature in the tank	65, 30	°C

Conflict of Interest

The authors declare no conflict of interest.

Credit Author Statement

Azharuddin: Conceptualization, Methodology, Investigation, Formal analysis; Prashant Saini: Writing - review and editing, Supervision; Jeeoot Singh: Writing - review and editing; Mohd Khurshed Rashid: Writing - original draft preparation; Ram Ji Tripathi: Writing - original draft preparation; Shahid Jamal: Resources. All the authors read and approved the manuscript.

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