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Experimental Study of Triple Pipe Heat Exchanger with Nanofluids

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Abstract

Experimental study is worked out on experimental system in which a concentric triple pipe heat exchanger made of copper consist the main part of it. The triple pipe heat exchanger consists of inner tube of 2 m length with inner and outer diameters of 1.27 cm and 1.5 cm respectively, the intermediate pipe of 1.5 m length with inner and outer diameters of 2.22 cm and 2.54 cm respectively and the outer pipe of 1m length with inner and diameters of 3.81 cm and 4.13 cm respectively. Nano-silicon dioxide (SiO_2), nano-copper oxide (CuO) and nano-black iron oxide (Fe_3O_4) are used in different volume percent concentrations (0.1, 0.2, 0.3, 0.4 and 0.5) in water (base fluid), as a cooling (nano) fluid. The cooling (nano) fluid flows in different five-volume flow rates (100, 150, 200, 250 and 300 cm^3/s) in inner and outer pipes countercurrently to hot water flowing at constant volume flow rate of 50 cm^3/s in the middle pipe of the triple pipe heat exchanger. Experimentally, there were a dual advantageous effect on the heat transfer coefficient consequently on heat transfer rates achieved, one due to, the contact surface area between the cold and hot fluids offered by the triple pipe heat exchanger compared with double pipe of heat exchanger, and the second due to, adding the nanomaterials to cold fluid. These effects, led to increase in heat transfer rates and overall heat transfer coefficients. The increment in heat transfer rates reached to 24.2, 28.3 and 31.8% with using SiO_2, CuO and Fe_3O_4 respectively. Whereas, the increment in combined overall heat transfer coefficients reached to 44.7, 53.9 and 62.2% with using SiO_2, CuO and Fe_3O_4 respectively. Wherefore, the effectiveness, reached to 63, 65 and 67% with using SiO_2, CuO and Fe_3O_4 respectively.

Keywords: Triple pipe heat exchanger, combined overall heat transfer coefficients, nanofluids, nanomaterials.

1. Introduction

Heat exchangers in different designs and shapes are widely used in different operations and processes to transfer the heat from hot fluid to cold fluid. Among these heat exchangers, is the triple pipe heat exchanger (TPHE), which is considered evolution to double pipe heat exchanger, through the transfer of energy of hot fluid, which is flowing in the intermediate tube in two opposite directions to the cold fluid(s), which's flowing in the inner and outer tubes. Therefore, the triple pipe heat exchanger has more heat transfer area and less length compared to double pipe heat exchanger (DPHE), which result in increasing heat transfer rate and heat exchange efficiency. Triple pipe heat exchangers are used in various applications, such as food, chemical, and pharmaceutical industries, etc. [1-5].

A number of researchers dealing with TPHE theoretically and experimentally. Batmaz and Sandeep [6] developed a more common method of determining overall heat transfer coefficients in a TPHE and specify the axial direction profiles of temperature of all streams in the exchanger. In order to facilitate the comparison between TPHE and DPHE, they also determined an effective overall heat transfer coefficient is based on total resistance to heat transfer. Radulescu et al. [7] experimentally proved that the TPHE gives better off than DPHE whence heat transfer efficiencies in cooling petroleum product by water. Radulescu et al. [8] developed a methodology to calculate the effective overall heat transfer coefficient based on case study using two different TPHEs, due to useful equation, both in design and control of TPHEs as they concluded. Vocale et al. [9] proposed a novel discrimination procedure to estimate the thermal behavior of the TPHE, where it bases on the measurements of fluids temperatures in four sections. The suggested procedure is simple and numerically proved and contrasted to the full one. Hasan [10] used deionized water DIW at constant inlet temperature of 25ºC and different flow rates, to cool oil-40 which is enter at constant flow rate of 20 L/h and different temperatures. She experimentally showed good results in cooling process concerning the convective and overall heat transfer coefficients consequently Nusselt number, in addition to pressure drop. Gomez et al. [11] gives theoretical model to calculate thermal parameters of TPHE similar to that used in DPHE. Depending on the flow properties and inlet conditions, the exit temperatures, heat exchange and thermal efficiency of TPHE could be analyzed under different conditions in a simple and efficient way.

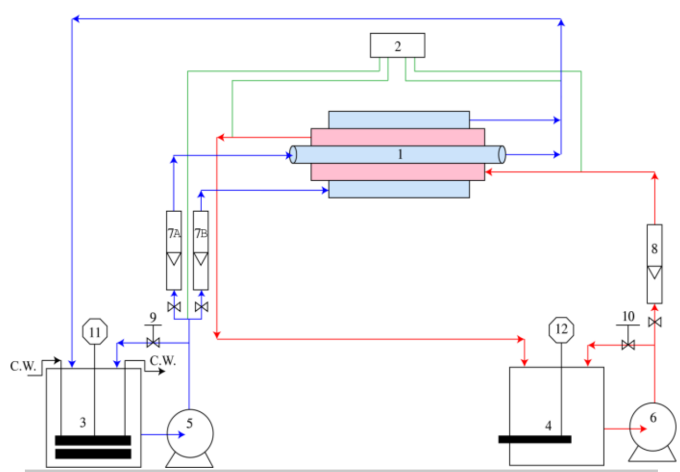
Concerning TPHEs using nanofluids are limited, some of them will be surveyed. Wafelkar and Raut [12] used nanofluids of CuO and of Al_2O_3 as a hot fluids in 0.033 % volume concentration with different flow rates, while the cold fluid flow rate is kept constant at 420 L/h. They found that maximum performance ratios of TPHE are at 0.033% in Reynolds number range between 11800 and 28000. Afzal et al. [13] carried their experimental work in TPHE consisting of straight central tube for air flow and helical tube for hot fluid (water) flow contained in a straight shell tube for cold fluid flow (water and titanium dioxide TiO_2). They found after analyzing heat transfer data for parallel and counter flow compared with hot fluid, that the effectiveness reduced for parallel flow as the flow of hot fluid increased while the overall heat transfer coefficient increased. Whereas, during counter flow, the effectiveness slightly remained between compared with parallel flow as the flow of hot fluid increased. While the overall heat transfer coefficients is doubled when using nano TiO_2 in cold fluid (150-200 $W/m^2{\cdot}K$) compared without using nanomaterial (50-100 $W/m^2{\cdot}K$). Reddy et al. [14] worked in concentric TPHE made of stainless steel tubes. they indicated that the heat transfer coefficients and consequently heat transfer rates in TPHE was higher compared to DPHE for same heat transfer area. The flow configuration was counter current and using different concentrations of nano TiO_2 with cold fluid. Kumar and Hariprasatha [15] added microwave carbon nanotube (MWCNT) to water in 0.2 %, 0.4 % and 0.6 % volume concentrations to study it as a coolant nanofluid in TPHE made up of copper. They noticed that the Nusselt number of nanofluid increased by 15 %, 23 % and 28 % for concentrations of 0.2 %, 0.4 % and 0.6 % respectively, whereas the effectiveness of TPHE was improved by 27 %, and belonged this improvement to higher thermal conductivity, lower heat capacity of the nanofluid used. Hariprasatha and Kumar [16] experimentally studied parallel flow TPHE with multi-walled carbon nanotubes dispersed in water in 0.2, 0.4 and 0.6 vol.% concentrations. They found that the enhancement in Nusselt number, the overall heat transfer coefficient and pressure drop are higher 10% at Reynolds number of 7500, 15% at Reynolds number of 9500 and 15% at Reynolds number of 6500 compared with pure water respectively.

As we had the opportunity to review it, limited works concerning TPHEs with nanofluids of (CuO, Al2O3, TiO2 and MWCNT) are carried, yet, they differ in enhancement ratio in heat transfer rates. So this work may introduced as a trial to contribute in this subject to explore the effect of using different characterized nanomaterials on heat transfer rates in TPHE fabricated to this purpose. The nanomaterials used are (SiO2, CuO and Fe3O4) with different volume percent concentrations in water (0.1, 0.2, 0.3, 0.4 and 0.5), for each. As well as, to compare the thermal effects of TPHE with that of DPHE, which is the subject of our previous work [18].

2. Experimental Work

2.1. Experimental system

Experimental system is shown in Figure 1, which is mainly consist of a concentric triple pipe heat exchanger (1) which is made of copper and thermally insulated, loop of hot fluid, loop of cooling (nano) fluid, and temperature monitoring device. The triple pipe heat exchanger (1) consist of inner tube of 2 m length with inner and outer diameters of 1.27 cm and 1.5 cm respectively. The intermediate pipe of 1.5 m length with inner and outer diameters of 2.22 cm and 2.54 cm respectively. The outer pipe of 1m length with inner and diameters of 3.81 cm and 4.13 cm respectively. The cooling (nano) fluid contained in a cube-shaped tank (3) of 35 × 35 × 40 cm, provided with cooling water system, controlled by temperature controller (11). The cooling (nano) fluid passes to inner and outer pipes of the exchanger by means of circulating pump (5) via rotameters (7A and 7B). The hot fluid contained in cube-shaped tank (4) of 35 × 35 × 40 cm, provided with heating system of 2kW heater, controlled by temperature controller (12). The hot fluid passes to the intermediate pipe of the exchanger by means of a circulating pump (6) via rotameter (8). To attain steady state condition, the delivery line of pumps (5 and 6) are provided with globe valve (9 and 10), through a tee branch for mixing some the pumped fluid with the returned from the exchanger. The temperature reading system comprises of four thermocouples of type K connected to digital temperature reader (2).



1. Triple pipe heat exchanger 2. Temperature reader 3. Cold (nano) fluid tank 4. Hot fluid tank 5. & 6. Pump 7A. & 7B. Rotameters of cold (nano) fluid 8. Rotameter of hot fluid 9. &10. Globe valve 11 & 12. Temperature controlling system
C. W. Cooling Water, → Cooling (nano) fluid path, → Hot fluid path, — Thermocouples wires

Figure 1. Experimental system.

2.2. Materials

The work is done on the same nanomaterials and concentrations used in our previous work [17] in order to clarify their effect on the thermal performance of TPHE and compare it with that of DPHE.

2.3. Experimentation

The cooling (nano) fluid is pumped to the inner and outer pipes of the TPHE heat exchanger (1) from cooling (nano) fluid tank (3), through a rotameters (7A & 7B), at a constant temperature of 25 °C. Some of pumped cold (nano) fluid are recycled to the tank (3) via globe valve (9), to mix with the returned from the heat exchanger to achieve steady state condition. Five different flow rates (100, 150, 200, 250 and 300 cm3/s) for the cooling (nano) fluids, were used. Whereas, the hot fluid is pumped to the intermediate pipe of the triple pipe heat exchanger (1) from hot fluid tank (4), through a rotameter (8), with constant flow rate of 50 cm3/s, and constant temperature of 50 °C. Some of pumped hot fluid are recycled to the tank (4) via globe valve (10), to mix with the returned from the triple pipe heat exchanger (1) to achieve steady state condition. The outlets and inlet temperatures of cooling (nano) fluids, as well as the outlets and inlet temperatures of hot fluid, were measured, using four thermocouples of type K, connected with a four channels digital temperature reader (2). The experimental procedure could be represented in figure 2.

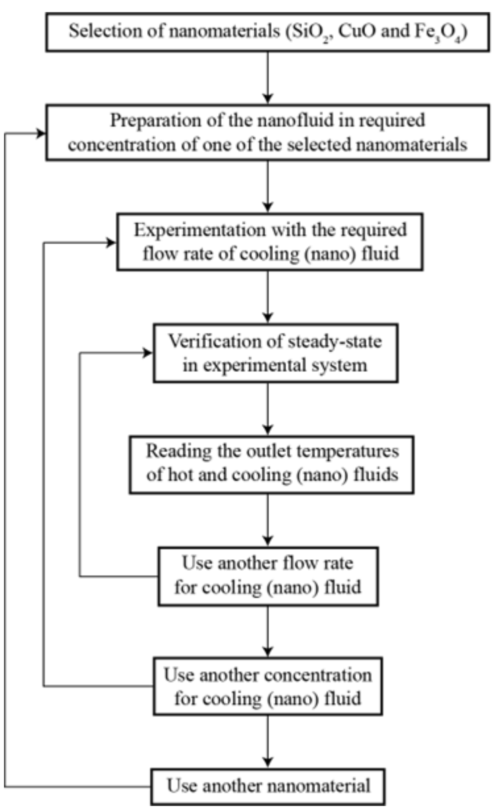


Figure 2. Flow chart of experimentation procedure.

3. Calculations

The calculations will be carried out depending upon the temperatures data obtained from temperature reader for hot and cooling (nano) fluids, according to the following procedure [6,18-21], and schematically represented in figure 3.

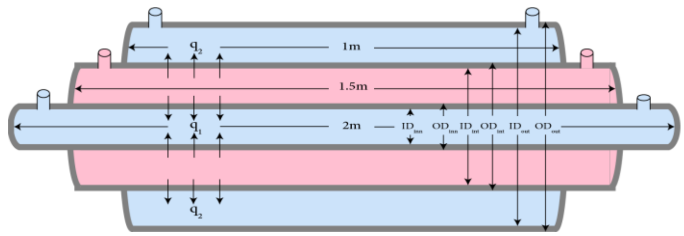


Figure 3. Scheme of TPHE

Heat transfer rates

$$\dot{q}_1 + \dot{q}_2 = \dot{q}_{total} = \dot{q}_{hot} = \dot{m}_h c_{p_h}(T_{hi} - T_{ho})$$

Where $\dot{q}_1$ is the heat transferred rate from hot fluid flowing in the intermediate pipe to cooling (nano) fluid flowing in the inner pipe, $\dot{q}_2$ is the heat transferred rate from hot fluid flowing in the intermediate pipe to cooling (nano) fluid flowing in the outer pipe, $\dot{q}_{total}$ is the total heat transferred rate between hot fluid and cooling (nano) fluid, which is equal to $\dot{q}_{hot}$ (W), $\dot{m}_h$ is the mass flow rate of hot fluid (kg/s), c_{ph} is the heat capacity of hot fluid (J/kg·ºC), T_{hi} is the inlet temperature of hot fluid; (constant at 50 ºC), and T_{ho} is the outlet temperature of hot fluid (ºC); as indicated by temperature reader.

Overall heat transfer coefficient

The surface area through which the heat is transferred from intermediate pipe to inner pipe is

$$A_{LMSA,1} = \frac{OD_{\text{inn}} - ID_{\text{inn}}}{ln(OD_{\text{inn}}/ID_{\text{inn}})} \times \pi L_{int\rightarrow inn}$$

Where OD_{inn} is the outside diameter of the inner pipe (1.5×10^{-2} m), ID_{inn} is the inside diameter of the inner pipe (1.27×10^{-2} m), $L_{int\rightarrow inn}$ is the contact length between inner and intermediate pipes (1.5 m).

The surface area through which the heat is transferred from intermediate pipe to outer pipe is

$$A_{LMSA,2} = \frac{OD_{\text{int}} - ID_{\text{int}}}{ln(OD_{\text{int}}/ID_{\text{int}})} \times \pi L_{int\rightarrow out}$$

Where OD_{int} is the outside diameter of the intermediate pipe (2.54×10^{-2} m), ID_{int} is the inside diameter of the intermediate pipe (2.2225×10^{-2} m), $L_{int\rightarrow out}$ is the contact length between intermediate and outer pipes (1 m).

Then, physically, there were two overall heat transfer coefficients, one with $A_{LMSA,1}$ and other with $A_{LMSA,2}$, which are combined in a single parameter named combined overall heat transfer coefficient $U_{overall,com}$; where we chose this method to keep things simple, and calculated as

$$U_{overall,com} = \frac{q_{total}}{(A_{LMSA,1} + A_{LMSA,2})\Delta T_{LMTD,com}}$$

Where $U_{overall,com}$ is the combined overall heat transfer coefficient between hot and cooling Nano) fluids ($W/m^{2}\cdot{}^{o}C$), $A_{LMSA,1}$ is the log mean surface area between inner pipe and intermediate pipe (m^2), $A_{LMSA,2}$ is the log mean surface area between intermediate pipe and outer pipe (m^2), $\Delta T_{LMSA,com}$ is the combined log mean temperature difference between hot and cooling (nano) fluids (ºC).

The combined log mean temperature difference between hot fluid and cooling (nano) fluids is calculated as

$$\Delta T_{LMTD,com} = \frac{(T_{hi}-T_{co})-(T_{ho}-T_{ci})}{ln\left\{\frac{(T_{hi}-T_{co})}{(T_{ho}-T_{ci})}\right\}}$$

Where T_{co} is the outlet temperature of cooling (nano) fluid; as indicated by temperature reader (ºC), T_{ci} is the inlet temperature of cooling (nano) fluid (25 ºC).

4. Results and Discussion

The results of the experimental work could be displayed and discussed as follow.

4.1.Outlet Temperatures of Cooling (nano) Fluid

The outlet temperatures of cooling (nano) fluid containing SiO_2, CuO and Fe_3O_4, with their volume flow rates as a function of concentrations are represented in figures 4, 5, and 6 respectively. These figures (4, 5 and 6) shows the increase in outlet temperatures attained with the addition of nanomaterials and the drop-in volume flow rates compared with that of pure water. But the increment for fluid containing CuO are more than that for fluid containing SiO_2, and that for fluid containing Fe_3O_4 are more than that for fluid containing CuO.

This is implying, that the effect of adding nanomaterials to the cold fluid, where it becoming a more extractive to heat from hot fluid, therefore, its temperature (cold fluid) is raised more compared with cold pure water. Also, it is clearly noticeable that the temperatures of cold fluid with Fe_3O_4 are rising more than with CuO, and cold fluid with CuO are rising more than with SiO_2. This means, that the cold fluid with Fe_3O_4 draw out more heat than that with CuO, which is in turn draw out more heat than that with SiO_2.

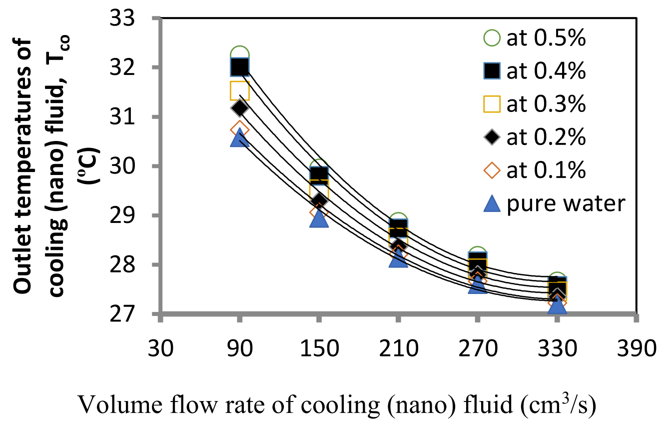


Figure 4. Outlet temperatures variation of cooling (nano) fluid with their volume flow rates at different volume concentrations of nano SiO_2.

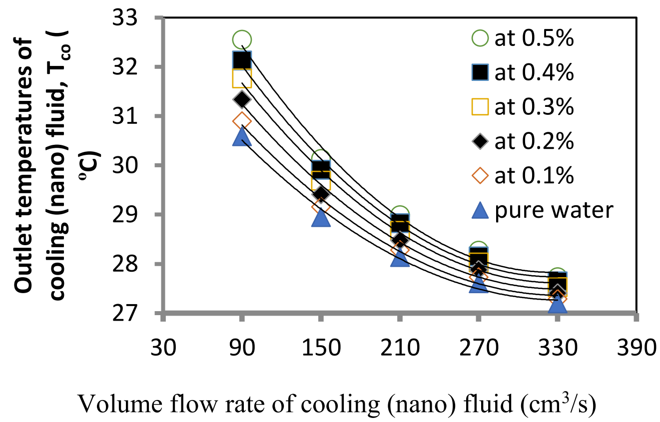


Figure 5. Outlet temperatures variation of cooling (nano) fluid with their volume flow rates at different volume concentrations of nano CuO.

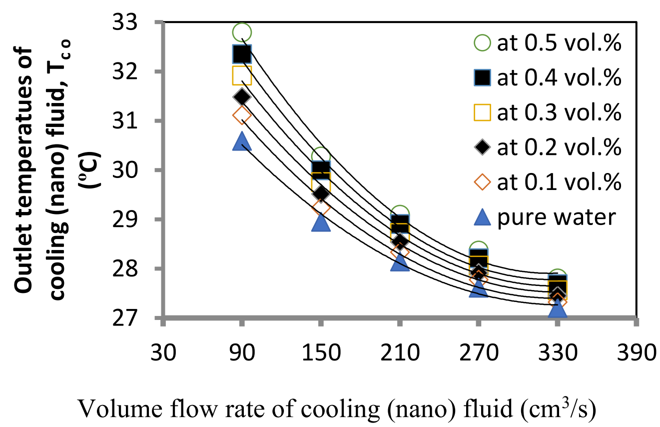


Figure 6. Outlet temperatures variation of cooling (nano) fluid with their volume flow rates at different volume concentrations of nano Fe_3O_4.

4.2. Outlet Temperatures of Hot Fluid

The outlet temperatures of hot with volume flow rates of cooling (nano) fluid containing SiO_2, CuO and Fe_3O_4, as a function of concentrations are represented in figures 7, 8, and 9 respectively. These figures (7, 8 and 9) shows the decrease in outlet temperatures attained with the addition of nanomaterials and the increase in volume flow rates compared with that of pure water. This is a consequence to the heat transferred to cold fluid, where it (hot fluid) become coldest. But the decrement for CuO are more than that for SiO_2, and that for Fe_3O_4 are more than that for CuO, which could be refer to that the cold fluid containing Fe_3O_4 draw out heat more than fluid containing CuO, and cold fluid containing CuO draw out heat more than fluid containing SiO_2.

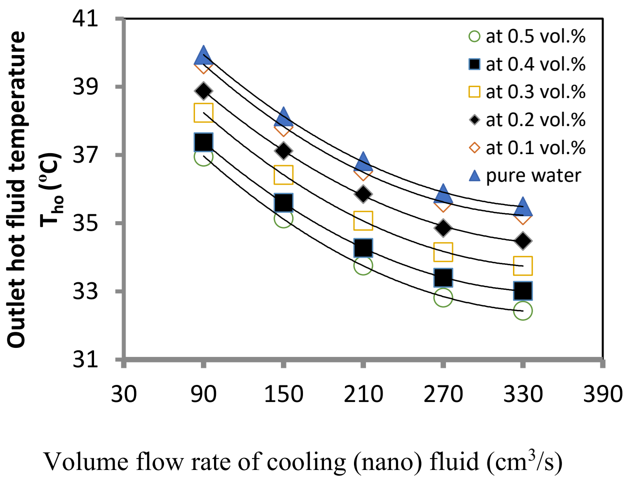


Figure 7. Outlet temperatures of hot fluid variation with volume flow rates of cooling (nano) fluid at different volume concentrations of nano SiO_2.

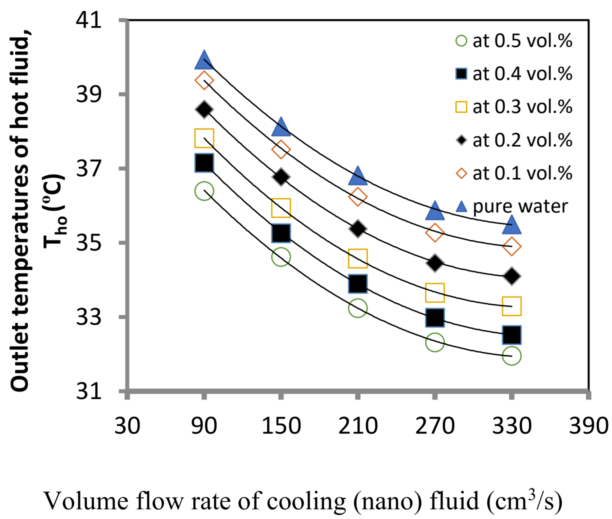


Figure 8. Outlet temperatures of hot fluid variation with volume flow rates of cooling (nano) fluid at different volume concentrations of nano CuO.

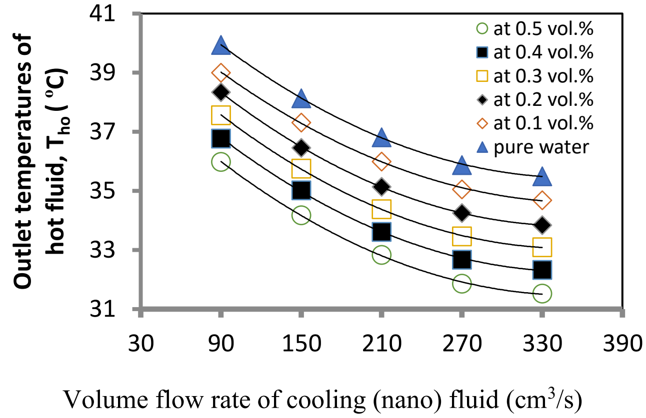


Figure 9. Outlet temperatures of hot fluid variation with volume flow rates of cooling (nano) fluid at different volume concentrations of nano Fe_3O_4.

4.3. Heat Transfer Rates

As seen from figures 10, 11, and 12 the heat transfer rates are increased with increasing volume flow rates of cooling (nano) fluid and volume concentrations on nanomaterials. Which could be refer to that the heat transfer is directly proportional with volume flow rates of fluid, and secondly become clear, that the addition of nanomaterials enhances heat transfer exchanged between hot and cold fluids, which is the findings of works uses nanomaterials. These figures (10, 11 and 12) shows that the increase in heat transfer rates attained with the addition of nanomaterials and the increase in volume flow rates compared with that of pure water. But the increment for fluid with CuO are more than that for fluid with SiO_2, and that for fluid with Fe_3O_4 are more than that for fluid with CuO.

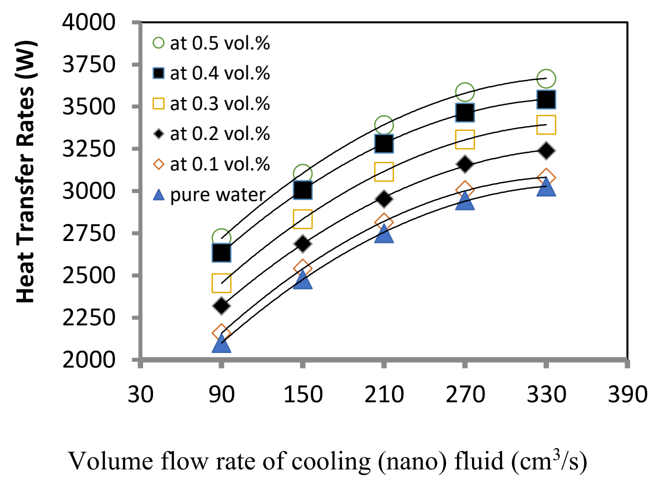


Figure 10. Heat transfer rates variation with volume flow rates of cooling (nano) fluid at different volume concentrations of nano SiO_2.

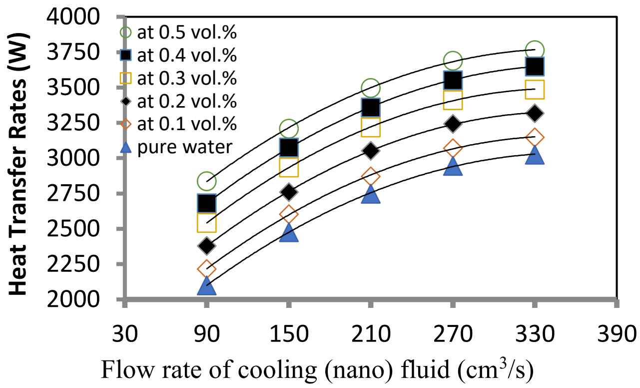


Figure 11. Heat transfer rates variation with volume flow rates of cooling (nano) fluid at different volume concentrations of nano CuO.

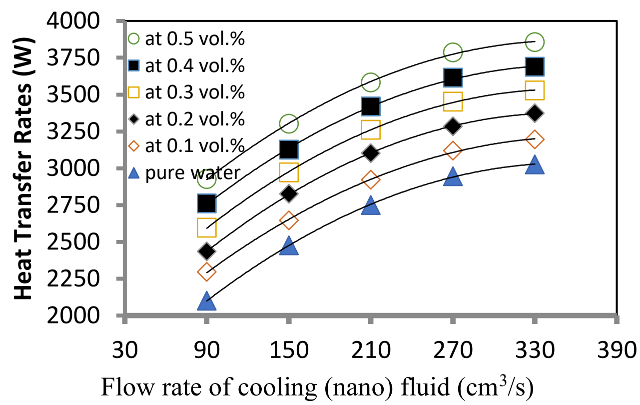


Figure 12. Heat transfer rates variation with volume flow rates of cooling (nano) fluid at different volume concentrations of nano Fe_3O_4.

4.4. Increase in Heat Transfer Rates

Figure 13 summarizes the effects of adding different nanomaterials to the cold fluid on the average percent increase in heat transferred rates between hot fluid and cooling (nano) fluid. It is noted from figure 13 there were sequential liner increase in heat transfer rates with volume percent of nanomaterials SiO_2, CuO and Fe_3O_4 in cold fluid.

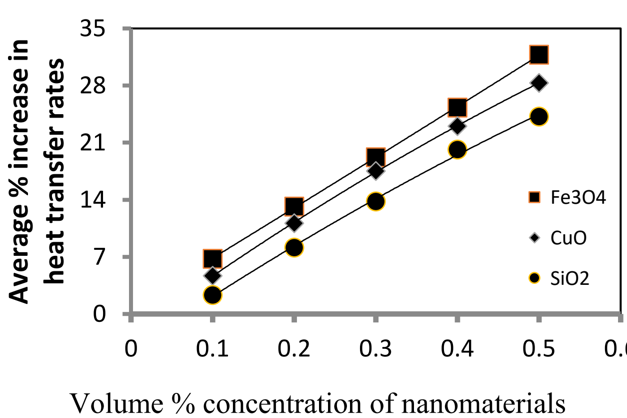


Figure 13. Average percent increase in heat transfer rates variation with volume percent concentrations of cooling (nano) fluid at different nanomaterials.

4.5. Combined overall Heat Transfer Coefficients

As depicted in figures 14, 15, and 16, the combined overall heat transfer coefficients are increased with increasing volume flow rates of cooling (nano) fluid and volume concentrations in nanomaterials. But the incrememt become lesser whenever the flow rate and concentration increased. These figures (14, 15 and 16) shows that the increase in combined overall heat transfer coefficients attained with the addition of nanomaterials and the increase in volume flow rates compared with that of pure water. But the increment for CuO are more than that for SiO_2, and that for Fe_3O_4 are more than that for CuO. This behaviour of combined overall heat transfer coefficients as seems its reflect the behavior of heat transfer rates appeared in figures10, 11 and 12. Therefore, figure 17 be similar to figure 13.

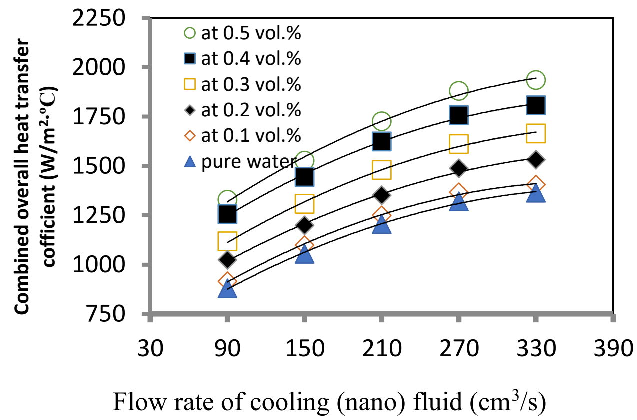


Figure 14. Combined overall heat transfer coefficients variation with volume flow rates of cooling (nano) fluid at different volume concentrations of SiO_2.

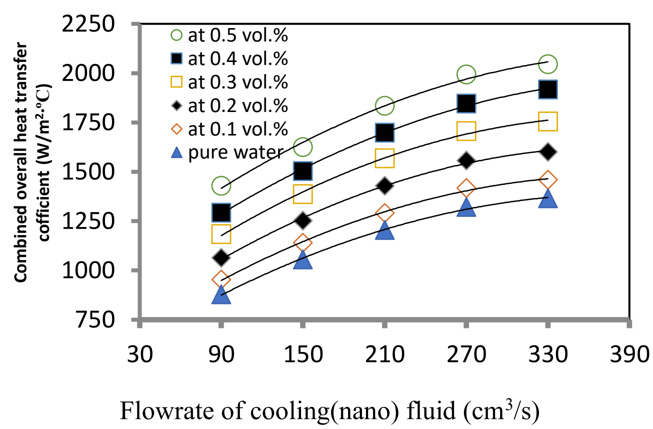


Figure 15. Combined overall heat transfer coefficients variation with volume flow rates of cooling (nano) fluid at different volume concentrations of CuO.

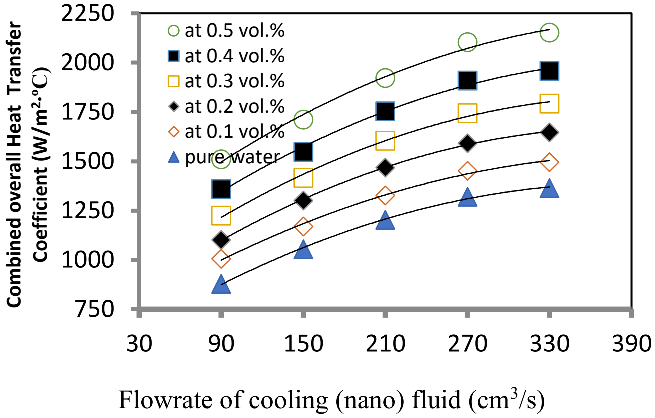


Figure 16. Combined overall heat transfer coefficients variation with volume flow rates of cooling (nano) fluid at different volume concentrations of Fe_3O_4 .

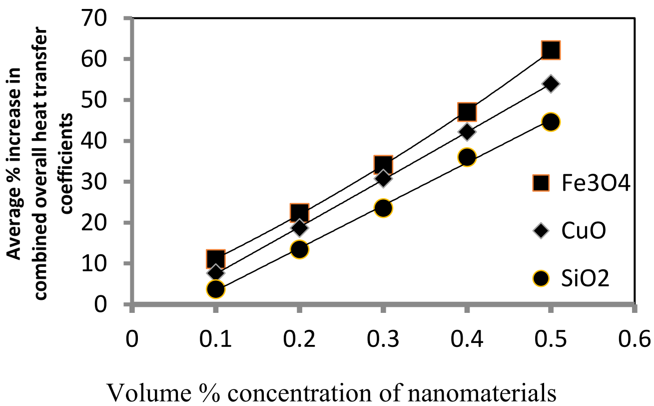


Figure 17. Average percent increase in combined overall heat transfer coefficients variation with volume percent concentrations of cooling (nano) fluid at different nanomaterials.

4.6. Heat Exchanger Effectiveness

It could be totalize the effects of heat transfer rates on the on the effectiveness of heat exchanger in one figure, through the effect of volume percent concentration of nanomaterials in cold fluid on the average percent increase effectiveness of heat exchanger, in figure 18, which is also exhibited the same behaviors as the previous figures 13 and 17, which confirms the accuracy of the calculations.

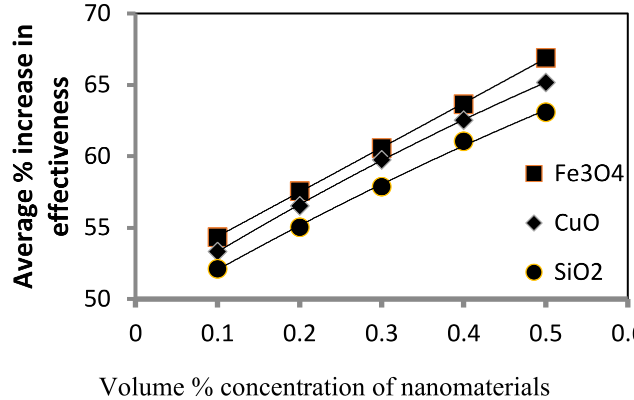


Figure 18. Average percent increase in effectiveness variation with volume percent concentrations of cooling (nano) fluid at different nanomaterials.

5. Conclusions

Experimental results carried out on the TPHE in which cold fluid (water) containing nanomaterials of SiO_2, CuO and Fe_3O_4 in volume percent concentrations of (0.1, 0.2, 0.3, 0.4 and 0.5) for each, showed there were an increase in outlet temperatures of cold fluid attained with the addition of nanomaterials compared with that of pure water. But the increment with adding CuO are more than that with adding SiO_2, and that with adding Fe_3O_4 are more than that with adding CuO. Consequently, the outlet temperatures of hot fluid decreased due to the heat transferred from it to the cold fluid. These effects on temperatures led to an increase in heat transfer rates. Where the average increase in heat transfer rates ranged among 2.3 to 24.2%, 4.7 to 28.3% and 6.8 to 31.8% for used concentrations of SiO_2, CuO and Fe_3O_4 respectively. This causes that the average increase in combined overall heat transfer coefficients ranged among 3.7 to 44.7%, 7.6 to 53.9% and 11 to 62.2% for used concentrations of SiO_2, CuO and Fe_3O_4 respectively. Whereas the average increase in effectiveness of the exchanger ranged from 52 to 63%, 53.3 to 65% and 54.3 to 67% for used concentrations of SiO_2, CuO and Fe_3O_4 respectively. Comparing with our previous work [17], its noted that the heat transfer rates, heat transfer coefficients and effectiveness was increased whereof DPHE which could be attributed to the dual advantageous effects, one due to, the contact surface area between the cold and hot fluids offered by the triple pipe heat exchanger compared with double pipe of heat exchanger, and the second due to, adding the nanomaterials to cold fluid. These effects, led to increase in heat transfer rates, heat transfer coefficients and heat exchanger effectiveness.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

Author Contribution Statement

AH. Majeed and Y.H. Abd: Proposed the research problem; developed the theory and performed the computations; verified the analytical methods. Both authors discussed the results and contributed to the final manuscript.

AI Declaration Statement

The author confirm that the manuscript has been written without the assistance of generative AI or AI-based writing tools.

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