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Study on heat transfer, pressure drop and efficiency of ZnO/Oil nanofluid in a novel hexagonal tube

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ABSTRACT

In this study, alternating hexagonal tube as a new form is introduced. The research method is experimental. Experiments were performed on 3 AH tubes in the 600 to 1500 Re range. The base fluid was heat transfer oil and ZnO/oil nanofluids with volumetric concentrations of 1% and 2%. Experiments indicate reducing in segments' length leads to increasing heat transfer in AH tubes by a factor of 1.5, 1.8, and 1.9 compared to circular tubes. Also, pressure drop increases by 1.07, 1.1 and 1.12 times. The use of nanoparticles and also increasing the concentration of them enhances heat transfer and pressure drop. The shortest segment's length with 2% particle concentration results in a 1.25 and 2.21 times increase in pressure drop and heat transfer compared to the circular tube respectively. Performance Enhanced Ratio is used to investigate the pressure drop and heat transfer simultaneously. Our results indicate that the efficiency of the alternating hexagonal tube is higher than the circular tube and enhances with the increase in the number of segments and nanoparticles concentration. The efficiency ratio of alternating hexagonal tubes to circular tubes is 1.17, 1.3 and 1.5, respectively. The highest efficiency ratio of nanofluid is 1.77 times the base fluid in a circular tube. The result of this study is that the use of alternating hexagonal tubes and nanoparticles improves performance.

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1. Introduction

Increasing heat transfer plays an important role in improving energy efficiency as well as developing thermal systems. One of the most important pieces of equipment that are widely used in chemical, power plant, petrochemical, food, etc. industries is the heat exchanger. In heat exchangers, a flow of thermal energy is exchanged between two or more fluids at different temperatures. In fact, during the heat transfer process, a fluid at a higher temperature transfers its energy as heat to another flow at a lower temperature.

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Some studies, such as Liu S. and Sakr M [1] and Chen L. and Dung W. [2], have classified the heat transfer enhancement methods into three categories: active, passive and combined. In active methods, an external force or power is applied to the system to increase heat transfer.

- Active methods

Setareh M. et al. [3] investigated the heat transfer and pressure drop of the double-tube heat exchanger numerically and experimentally. They also used ultrasonic waves in their study. Their results show that the use of ultrasonic waves increases the amount of heat transfer and pressure drop by 55% and 21%, respectively. Their results showed that crossflows are the most effective parameter for increasing heat transfer and pressure drop. Goharkhah et al [4] studied the effects of the constant and alternating fields on the heat transfer of laminar flow of magnetic ferrofluid (water and iron) experimentally. The results of their investigation showed that the use of magnetic ferrofluid increases heat transfer by 13.5% without the presence of a magnetic field. But by using the alternating field, the rate of heat transfer increases up to 20%. To see more studies on increasing heat transfer using active methods, you can refer to the studies of Bezaatpour and Goharkhah [5] in 2021, Jafari and Mohammad [6] in 2020 and Ramezani [7] in 2022.

- Passive Methods

- Changing the Geometry

Andrade F et al. [8] experimentally investigated pressure drop and heat transfer in corrugated tubes. The experiments were performed at a constant heat flux on the surface of the tube. And the range of Reynolds number was from 400 to 6500 including all three regimes of flow laminar, transient and turbulent. The results show that the heat transfer and pressure drop of corrugated tubes are higher than those of circular tubes, and the effect of using corrugated tubes is greater in the Reynolds number of 2000, which is related to transient flow. Cattani L. et al. [9] studied two corrugated tubes with different groove depths. Their study was carried out in the laminar and developed flow regime. The results of their work show that by increasing the depth of the grooves, the thermal efficiency of the tubes improves by 3%.

Xie et al. [10] in a numerical study investigated dimpled tubes in the Reynolds number range from 5000 to 300000. Their study was done on water and the results of their work show that the thermal efficiency of dimpled tubes is higher than circular ones. The presence of dimples on the surface of the tubes causes disturbances in the thermal boundary layer and creates secondary flows in the fluid. The intensity of the secondary flows increases with the increase of the Reynolds number and the depth of the dimples. The results of their work show that the friction factor increases with the depth of the dimples. In another study, they compared spherical dimples with teardrop-shaped dimples as well as the effect of step and depth of dimples on heat transfer [11]. The results show that the pressure drop and heat transfer enhancement of teardrop-shaped dimples are less than spherical dimples, and the thermal efficiency of the tubes increases with the growth of dimple depth.

Sajadi et al. [12-13] invented and studied alternative flattened and alternative elliptical axis tubes experimentally. They studied these tubes at a constant wall temperature and Reynolds numbers between 400 and 1800. The results of their studies show that this change in the geometry causes a simultaneous increase in heat transfer and pressure drop. But the known criteria show that the efficiency of alternative elliptical axis tubes and alternative flattened tubes are 1.7 and 1.9 higher than circular ones. Rukruang, A., et al [14] conducted a numerical and experimental study on alternative flattened tubes. The results of their numerical study show that the vortices that are created in the curved part of the tubes increase the heat transfer rate and pressure drop. Of course, the rate of heat transfer increase is higher than the pressure drop.

Najafi and Nazif [15] did a numerical study on alternating elliptical axis tubes. Their study was done in the range of laminar flow. The results of their work show that the longitudinal vortices that occur in deformed tubes are the main factor in increasing heat transfer and pressure drop. Their numerical results are highly accurate compared to experimental studies.

- Adding nanoparticles

Sajadi et al. [16] investigated the pressure drop and heat transfer of ZnO/water nanofluid in a circular tube experimentally. The volume concentration of nanoparticles was 1 and 2% and the experiments were performed at Reynolds numbers range of 5000 to 30000. The results showed that increasing the concentration of particles causes an increase in heat transfer and pressure drop up to 30% and 19% respectively. Choi J. et al. [17] investigated the migration effects of aluminum oxide nanofluid particles in heat transfer. They conducted their study experimentally in a circular tube and measured the physical properties of the nanofluid such as viscosity and conductivity. The results of their work show that the heat transfer of aluminum oxide due to the migration of nanoparticles is up to 12 % higher than the base fluid with measured properties. Sundar.S et al [18] investigated the heat transfer and pressure drop of water with iron oxide nanoparticles and carbon nanoparticles. The volumetric concentration of nanoparticles has been up to 0.3. The experiments were carried out in the regime of turbulent flow and constant heat flux. The results show that the use of nanoparticles increases heat transfer and pressure drop by up to 31% and 18%, respectively. Ahmad et al [19] investigated nanofluids with copper oxide, titanium oxide and aluminum oxide particles. Their study was experimental and used nanoparticles with a concentration of up to 10% by weight. The flow regime they studied was laminar. The results of the study show that zinc oxide particles have the highest increase in heat transfer, which is about 20%. Chowdhury Z. et al [20] studied the heat transfer of zinc oxide nanoparticles with weight concentration of 0.25 % up to 0.1%. The results of their work show that the heat transfer of all concentrations of nanoparticles is higher than the base fluid and groves with the increase in the concentration of nanoparticles. The highest heat transfers up to 50% and occur in the highest concentration of nanoparticles. Sajadi and Kazemi [21] studied the low concentration of titanium oxide nanoparticles in water. The results of their research show that even a low concentration of nanoparticles causes a significant increase in heat transfer and also increases the pressure drop to some extent. They also presented an experimental formula for the heat transfer of titanium oxide nanofluid.

- Both changing the geometry and adding nanoparticles

In some studies, the combination of active and passive methods of increasing heat transfer or the use of several passive methods at the same time has been used. Lee and Kumar [22] studied the heat transfer and pressure drop of ZnO/water nanofluid in flat tubes. Their study method was to minimize entropy production. The research results show that in volume concentration of 1% and aspect ratio of 6, entropy production decreases by 14%. Ahmed et al [23] investigated heat transfer and pressure drop of Al2O3/water nanofluid in corrugated tubes. Their research method was experimental and in the Reynolds number range of 5000 to 20000. Two nanofluids with volume concentrations of 1% and 2% were investigated. The results of their research showed that increasing the concentration of nanofluid, reducing the pitch length of the tube and increasing the depth of the grooves increase the thermal efficiency. Naqibzadeh et al. [24] used coils inside flattened tubes. They also studied the Al2O3/water nanofluid up to a volume concentration of 1% inside these tubes. Their study was done numerically in the Reynolds number range of 350 to 2000. The results of the study show that the flattening of the pipes has a greater effect than the nanofluid at increasing thermal efficiency. Huminic, G. and Huminic, A. [25] investigated heat transfer and pressure drop in flattened tubes in the presence of nanoparticles. The results of the study showed that increasing the concentration of nanoparticles increases heat transfer significantly. They found that the effect of nanofluids in improving the efficiency of flat tubes is more than circular tubes.

Najafi and Nazif [26-28] studied alternating elliptical axis tubes using zinc oxide nanofluid. Their study was done numerically and they investigated the vortices and entropy produced along the tubes. They found that heat transfer and pressure drop increase with increasing concentration of nanoparticles and decreasing tube pitch length. The use of nanoparticles with a smaller diameter increases the pressure drop in the tubes by 5%. Nakhchi and Isfahani [29] conducted a numerical study of perforated conical rings inside circular tubes. They also used CuO/water nanofluid up to a volume concentration of 1.5%. They used cones with 4, 6, 8 and 10 holes. The results of their study show that the highest efficiency rate is related to the cone with the least number of holes and the highest concentration of nanoparticles, which was equal to 278%. Sajadi and Talebi [30-31] studied alternative flattened and alternative elliptical axis tubes in a laboratory. They also used nanofluid TiO2/oil and Al2O3/oil instead of the base fluid. The results of their work show that the addition of nanoparticles increases the heat transfer, pressure drop and efficiency of tubes. Increasing the concentration of nanoparticles boosts the efficiency of these tubes up to 2.15 and 2.03 times that of the circular tube.

As described in previous studies, changing the geometry of tubes is used to create secondary flows and destroy thermal boundary layers. One method for changing the geometry of tubes is to repeat a constant cross-section alternatively [10,11]. Also, the use of nanoparticles improves the conductive properties of the base fluid. In this study, for the first time, the use of alternating hexagonal tubes and the effect of zinc oxide nanoparticles on the heat transfer rate, pressure drop and thermal efficiency have been studied.

2. Methodology

The method of this research was to analyze the data obtained from the experiment. Zinc oxide nanofluid was prepared in volume concentrations of 1% and 2%. Before each test, to ensure the dispersion and non-adherence of nanoparticles, the samples were exposed to ultrasonic waves with a power of 400 watts and a frequency of 20 kHz for 40 minutes. The thermophysical properties of each nanofluid were measured in the temperature range of 50 to 90 degrees Celsius at the Materials and Energy Research Institute.

2.1. Experimental Setup

The experimental setup includes a 10-liter container for oil storage. A gear pump sucks oil from the storage tank and pumps it into the test tube. To ensure a constant surface temperature on the surface of the test tube, the tube is placed in a saturated steam tank. Four electric elements each with a power of 2 kW guarantee saturated steam inside the steam tank and around the test tube. The temperature of the fluid at the entrance and exit of the test tube is measured by two K-type thermocouples with an accuracy of 0.1 Celsius degree. Also, the temperature of the surface of the test tube, it is measured at four points. The pressure difference between the inlet and outlet of the test tube is measured by a differential pressure gauge with an accuracy of 1 Pa. The flow rate is measured by recording the time required to fill a 2-liter glass balloon.

According to the laws of heat transfer, the mean convective heat transfer coefficient is calculated from [32]

$$\bar{h}=\frac{\dot{m}C_p\left(T_{out}-T_{in}\right)}{A_s\Delta T_m} \tag{1}$$

The logarithmic mean temperature $\Delta \mathbf{T_m}$ is calculated from [32]

$$\Delta T_m=\frac{\Delta T_{out}-\Delta T_{in}}{\ln\frac{\Delta T_{out}}{\Delta T_{in}}}. \tag{2}$$

The mean Nusselt number and friction coefficient of the flow are calculated using [32], respectively,

$$\overline{Nu}=\frac{D_h\bar{h}}{k}, \tag{3}$$

And

$$f=\frac{2D_h\Delta P}{\Delta L u^2}. \tag{4}$$

At the above equations, C_p , k and ρ are specific heat capacity, fluid conductivity and the density of the fluid respectively. And $\dot{m}$ is the mass flow rate, A_s is the lateral area of the tube, $T_{out}-T_{in}$ is the temperature difference between outlet and inlet, D_h is hydraulic diameter, ΔP is pressure drop, L is tube length and u is the velocity of the flow.

The Hausen and the Darcy relations have been used to ensure the accuracy of the test device. The Hausen equation that is used to calculate the Nusselt number in laminar flow with constant surface temperature conditions, is given by [32]

$$\overline{Nu}=3.66+\frac{.0668Gz_D}{1+.04Gz_D^{\frac{2}{3}}} \tag{5}$$

The Graetz number Gz_D is defined as [32]

$$Gz_D=\left(D_h/X\right)RePr \tag{6}$$

where X is the axial distance from the beginning of the tube.

The suitable formula for calculating the friction factor of laminar flow at a circular tube is given by [32]

$$f = \frac{64}{Re}. \quad (7)$$

Figures 2 and 3 compare the Nusselt number and the friction factor related to the experimental setup with Hausen and Darcy relations, respectively.

The maximum deviation of the Nusselt number and friction coefficient from Hausen and Darcy relations was 5% and 4%, respectively.

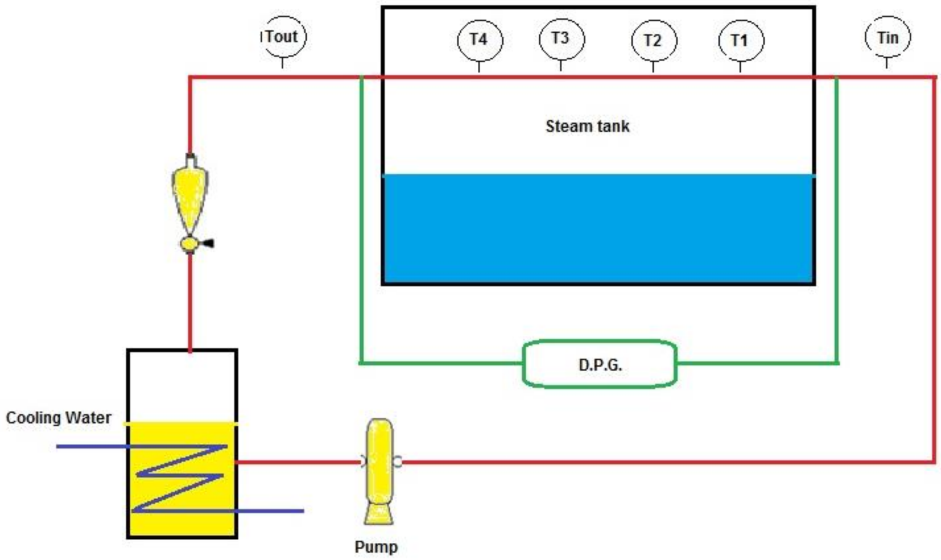

Fig. 1. Schematic of the experimental setup

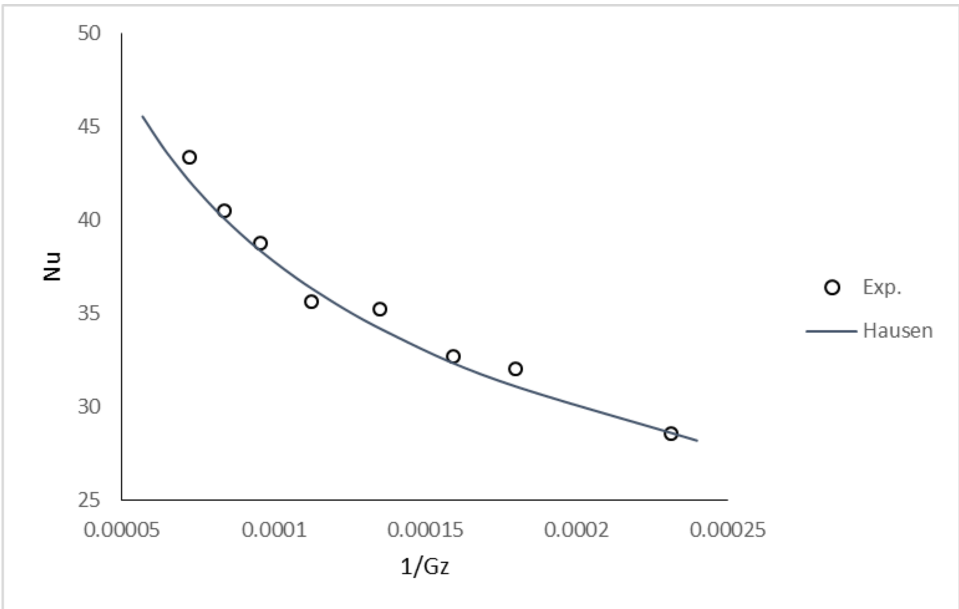

Fig. 2. Comparison of the heat transfer results of the experimental setup with the Hausen equation

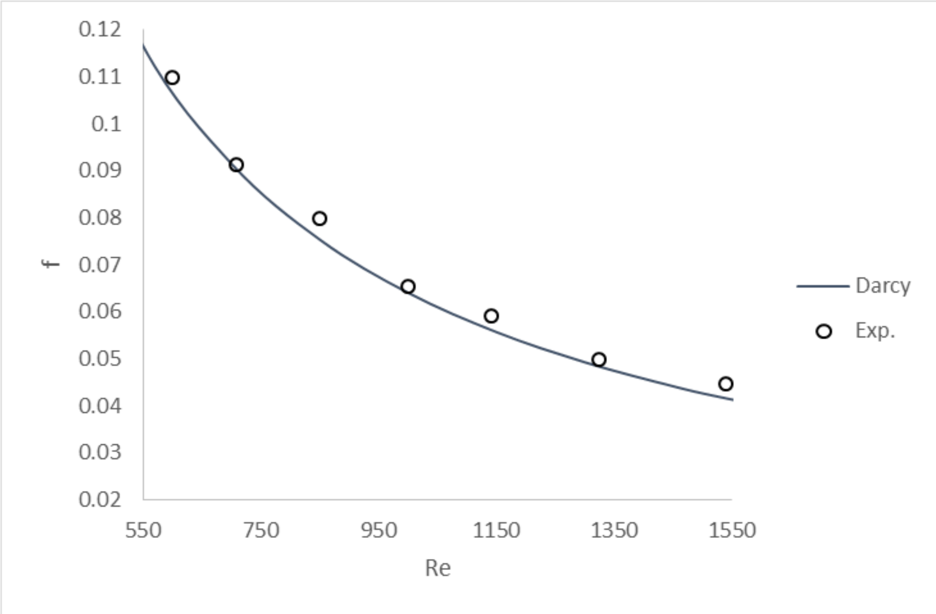

Fig. 3. Comparison of the results from the test apparatus with the Darcy equation

2.2. Alternating hexagonal tube

alternating hexagonal tubes (AHt) are created from a sequence of circular and hexagonal segments. These circular and hexagonal segments are connected by transition parts to each other. Fig.4 shows the geometry of the AH tube.

The passing of flow through each of the transition parts causes the creation of secondary flows and the destruction of thermal boundary layers. These factors increase the temperature gradient and thus increase the heat transfer rate.

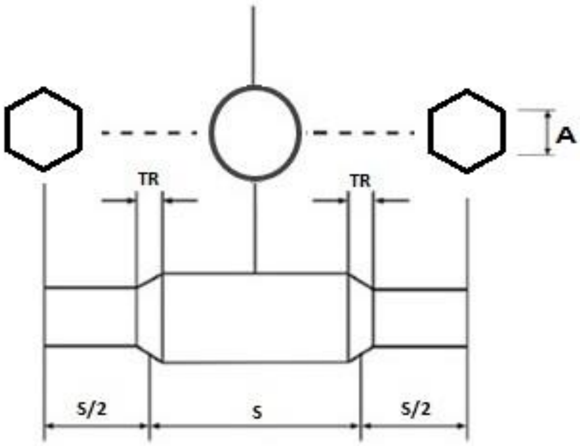

Fig. 4. Schematic of Alternating Hexagonal tube

Table 1. Geometric Properties of AH Tubes

Tube	A(mm)	TR(mm)	S(mm)
Circular	15.88	-	-
AH1	8.3	10	60
AH2	8.3	10	40
AH3	8.3	10	20

3. Results and discussion

Figure 5 compares the heat transfer of the AH tubes with the circular tube. The heat transfer of the AH tubes is higher than the circular one, and in a constant Reynolds number, heat transfer increases with growing the number of segments. After the fluid passes through each transition part, longitudinal vortices are created in the flow, which are a factor in boosting the temperature gradient and as a result, increasing the heat transfer. But when the fluid passes through a circular or hexagonal segment again, these vortices disappear. By adding the number of segments, the vortices of flow increase which boosts the heat transfer rate. Sajadi et al [12] and Najafi and Nazif [28] have also reported similar results about alternating flattened tubes. The heat transfer ratio of AH tubes to circular tubes increases with increasing Reynolds number. Because increasing the flow speed in the tube amplifies the vortices. For example, the heat transfers of tube AH3 at Reynolds 600 and 1500 are 1.9 and 1.6 times that of a circular tube, respectively. At the Reynolds number of 600 and for tubes AH1 and AH2, the heat transfer ratio to the circular tube is 1.5 and 1.6 times, respectively. These ratios at Reynolds number 1500 are 1.8 and 1.9 times, respectively.

Figure 6 compares the pressure drop in AH tubes with circular tubes. The pressure drop in all AH tubes is higher than the circular one, and at a constant Reynolds number, the pressure drop increases by decreasing the segments' length. The pressure drop of AH tubes is higher than that of round tubes due to the local pressure drop in the transition parts. and the boost with the increase in the number of these transition parts. As the flow speed increases, the local pressure drops in the transition parts also increase, for example, the pressure drop of an AH3 tube at the Reynolds number 600 and 1500 is 1.1 and 1.2 of a circular tube, respectively. At the Reynolds number of 600 and for tubes AH1 and AH2, the pressure drop ratio to the circular tube is 1.07 and 1.11 times, respectively. These ratios at Reynolds number 1500 are 1.1 and 1.16 times, respectively. The results related to the pressure drop of AH tubes are consistent with the studies of Sajadi et al [12] and Rukruang et al [14] regarding alternating flattened tubes.

Figures 7 and 8 compare the heat transfer of nanofluid with 1% and 2% concentration in AH tubes, respectively.

A comparison of graphs shows that nanoparticles increase heat transfer. Also, increasing the concentration of nanoparticles intensifies the increase in heat transfer. Nanoparticles increase heat transfer in two ways. 1. They improve the thermophysical properties of the base fluid. 2. Through random movements in the fluid, they increase the temperature gradient near the tube surface.

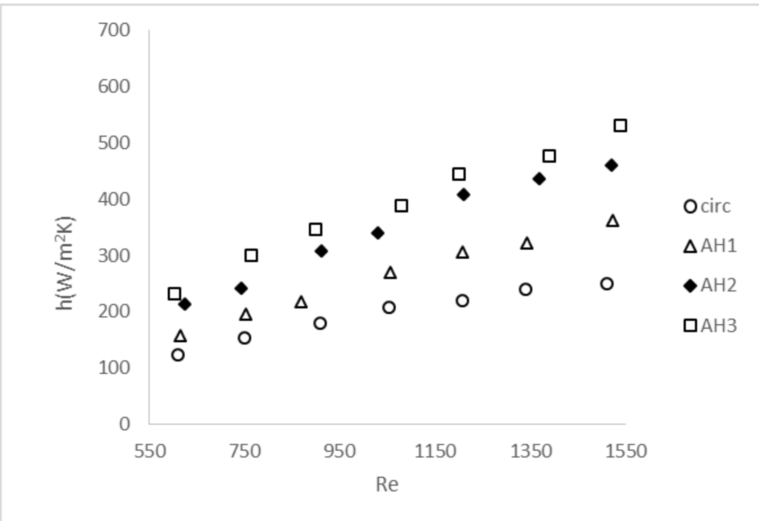

Fig. 5. Comparison of heat transfer of base oil in AH tubes

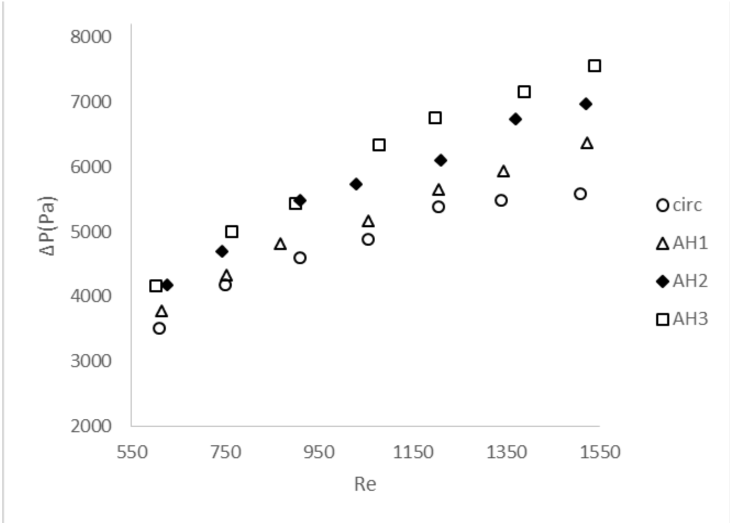

Fig. 6. Comparison of pressure drop of the Base oil in AH tubes

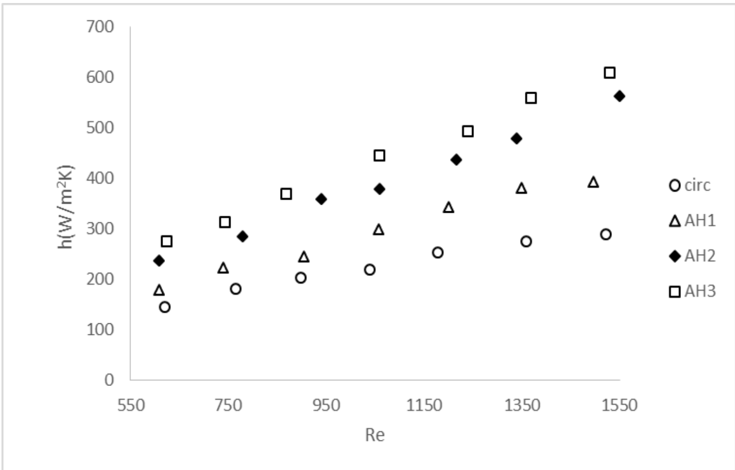

Fig. 7. Comparison of heat transfer of nanofluid 1% in AH tubes

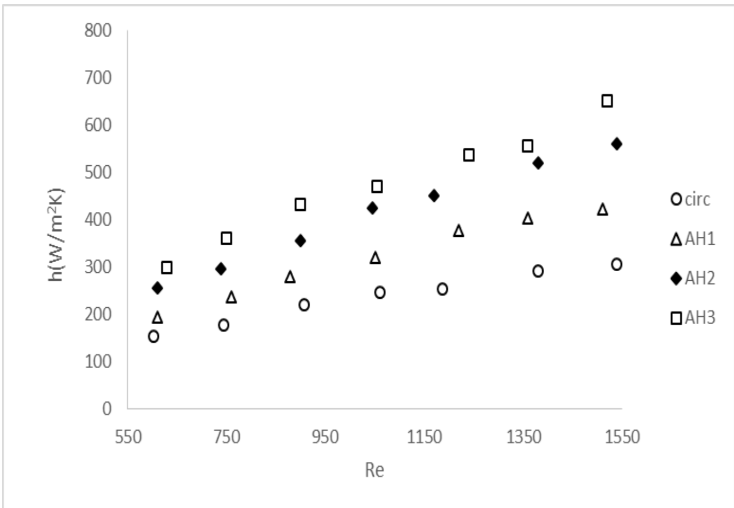

Fig. 8. Comparison of heat transfer of nanofluid 2% in AH tubes

By increasing the flow rate inside the tube, the effects of random movements of nanoparticles are reduced. For example, in the AH3 tube and nanofluid with a concentration of 2% at Reynolds 600 and 1500, the increase in heat transfer compared to the base fluid is 18% and 15%, respectively. At Reynolds numbers of 600 and 1500, For tube Ah3 and nanoparticle concentration of 1% this heat transfer increase is 12% and 8%, respectively. Gabriela and Angel [25] and Sajadi and Talebi[30] have also reported the reduction of the effect of nanoparticles , by increasing the flow rate.

Figures 9 and 10 show the pressure drop of nanofluids with a concentration of 1% and 2% in AH tubes.

Comparing the graphs shows that increasing the concentration of nanoparticles enhances the pressure drop because nanoparticles increase the viscosity of the base fluid. This pressure drop increase is almost constant that are 5% and 9% for nanofluid 1% and 2%, respectively. These results are consistent with the reports of Talebi and Sajadi [31] about alternating flattened tubes.

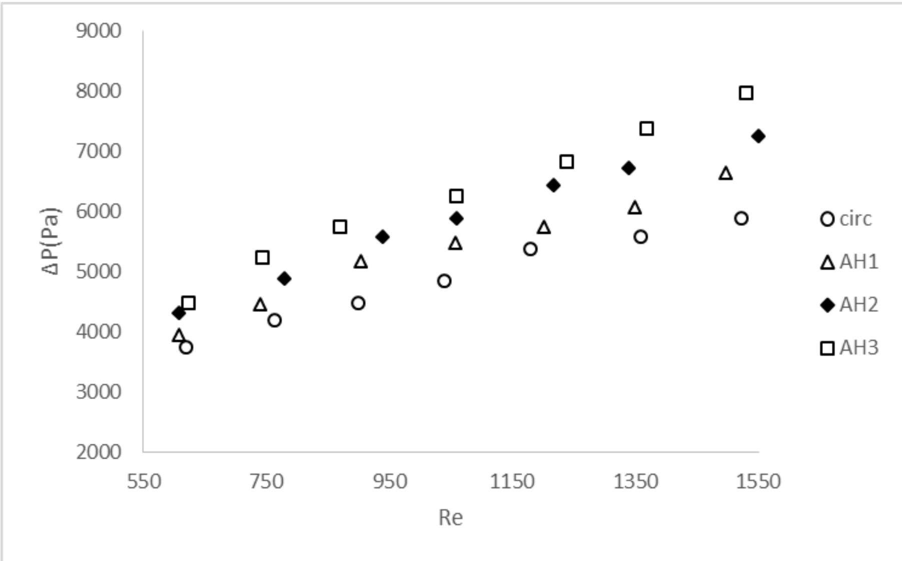

Fig. 9. Comparison of pressure drop of nanofluid increase of 1% in AH tubes

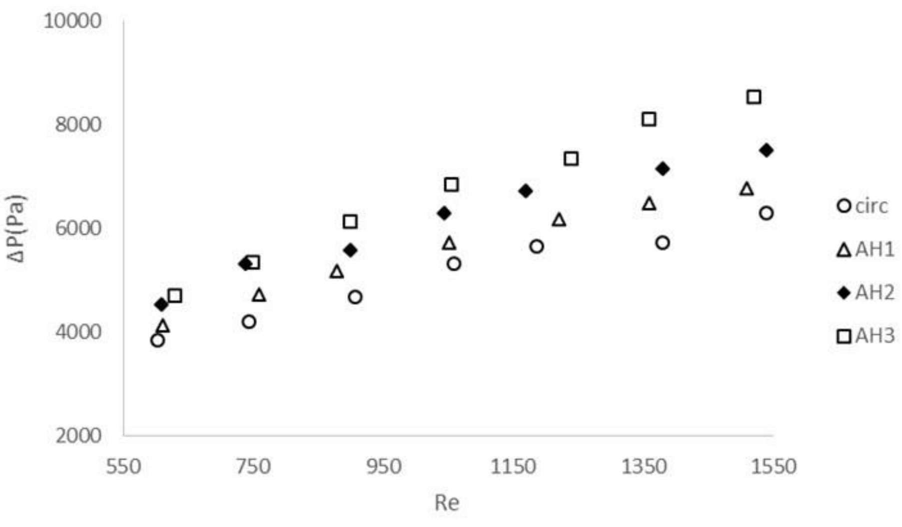

Fig. 10. Comparison of pressure drop of nanofluid causes 2% in AH tubes

The use of nanofluid and changing the geometry of the tubes causes a simultaneous increase in heat transfer and pressure drop. Since heat transfer augmentation is desirable while the other is unpleasant, a parameter that considers these increases simultaneously is needed. The effective performance ratio (PER), which is defined as

$$PER=\frac{\left(\frac{Nu_a}{Nu_b}\right)}{\left(\frac{f_a}{f_b}\right)^{(1/3)}}, \tag{8}$$

compares two tubes by considering simultaneously both their pressure drop and heat transfer. If the value of PER is greater than one, the efficiency of tube a is higher than tube b and if PER is less than one, the efficiency of tube b is higher than tube a.

Figure 11 compares the efficiency of AH tubes. at all tubes, efficiency increases with increasing Reynolds number. Because with the increase in the flow rate, the growth rate of heat transfer is higher than the pressure drop. Also, efficiency increases by reducing the length of segments. At Reynolds number 1000 the efficiency of tubes AH1, AH2 and AH3 compared to the circular tube is equal to 1.17, 1.3 and 1.5 respectively.

Figure 12 compares the efficiency of nanofluids with different concentrations at AH3 tube. The graph shows that the efficiency increases by increasing in the concentration of nanoparticles because the effect of nanoparticles in improving the thermophysical quality of the fluid is higher than their effect on the pressure drop.

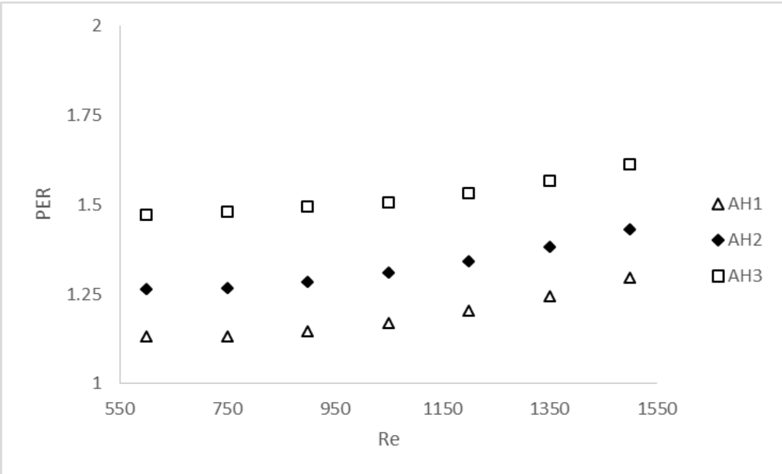

Fig. 11. Comparison of the Efficiency of Circular Tube with AH tubes

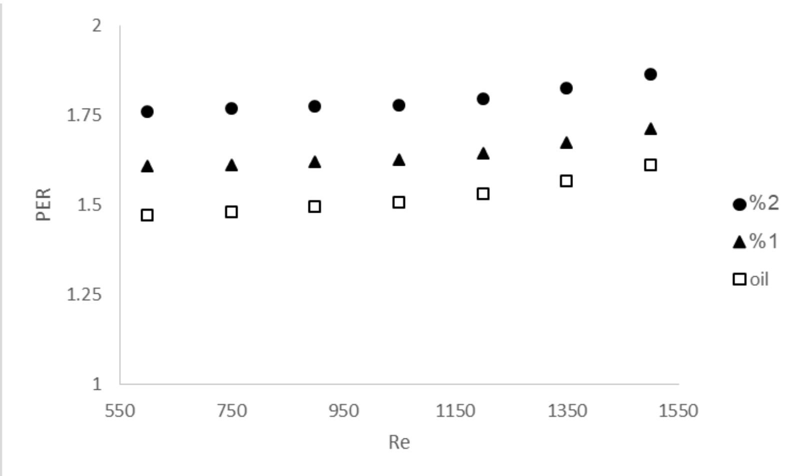

Fig. 12. efficiency of nanofluid in tube AH3

At the Reynolds number of 1000 and for tube AH3 at concentrations of 0%, 1% and 2% of nanoparticles, the efficiency is equal to 1.5, 1.62 and 1.77, respectively. These results agree with the studies of Sajadi and Talebi [30-31] about alternative flattened and alternative elliptical axis tubes.

4. Conclusions

In this study, for the first time, alternating hexagonal tubes have been introduced. Also, the heat transfer, pressure drop and efficiency of these tubes have been compared with the circular tube. And finally, the effect of copper oxide nanoparticles on these parameters has been investigated. Alternating hexagonal tubes (AHt) are created from a sequence of circular and hexagonal segments. These circular and hexagonal segments are connected by transition parts to each other. The research method was experimental with constant surface temperature conditions. The concentration of nanoparticles and length of tube segments have been studied as changing variables. A gear pump pumped the fluid into the test tube and the temperature of the fluid at the inlet and outlet of the test section were recorded to calculate the heat transfer rate. The fluid pressure drop due to passing through the tube is also recorded by a differential pressure gauge.

The results show:

- The heat transfer of AH tubes is higher than that of circular ones. By reducing the length of segments, heat transfer increases.
- Zinc oxide nanoparticles improve the thermophysical quality of the fluid and increase the heat transfer rate. Increasing the concentration of nanoparticles augments the heat transfer rate.
- The pressure drop of AH tubes is higher than the circular tube, and reducing the length of segments increases the pressure drop.
- adding nanoparticles and increasing the concentration of particles increases the pressure drop in all tubes.
- The efficiency of AH tubes is higher than the circular tube and the efficiency increases with the decrease of the segments' length.
- Nanoparticles improve efficiency and increasing their concentration increases efficiency.

By increasing the flow rate of the tubes, the heat transfer rate increases, hence the supply of saturated steam to keep the constant surface temperature of the test tubes was the most important challenge of this study. The use of non-metallic nanoparticles or changing the length of the transition parts is recommended for future works.

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