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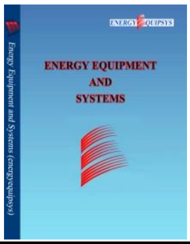

Experimental investigation of heat transfer, pressure drop, and efficiency of TiO_2/Oil nanofluid in alternating flattened tubes

Authors

Ahmadreza Sajadi[a*]
Sasan Talebi[a]

[a] Faculty of Engineering, Shahrekord University, Shahrekord, Iran

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ABSTRACT

In this study, the analysis of experimental results is used to investigate heat transfer and pressure drop characteristics of Titanium Oxide nanoparticles in an Alternating Flattened Tube. The impact of nanoparticles has not been studied before on Alternating Flattened tubes heat transfer characteristics. Experiments were conducted on 3 different AF tubes with heat transfer oil as base fluid with TiO_2 nanoparticles volumetric concentrations of 1% and 2% in 400 to1800 Re range. Our experiments show increasing in flattening leads to a heat transfer increase in AF tubes by a factor of 1.58, 2.08, and 2.21 compared to circular pipes. Pressure drop also increases by 1.08, 1.19 and 1.25 times. The addition of TiO_2 nanoparticles enhances heat transfer and pressure drop as well. We also found higher nanoparticle concentration provides more improvement. The most flattened tube with 2% particle concentration shows 2.85 and 1.32 times increase in heat transfer and pressure drop compared to the circular tube respectively. An efficiency parameter is used to study heat transfer and pressure drop simultaneously. Our analysis shows that the efficiency of the alternating flattened tube is higher than the circular tube and increases with the increase in flattening and nanoparticles concentration. The efficiency of alternating flattened tubes reads 1.26, 1.62 and 1.76 times that of a circular tube. The efficiency of nanofluid with a volume concentration of 2% in alternating flattened tubes is 1.76, 2.01 and 2.15 times the base fluid in a circular tube. This experiment concludes the presence of nanoparticles improves overall heat exchange performance at the alternating flattened tubes.

Keywords: Alternating Flattened Tube, Nanofluid, Heat Transfer, Pressure Drop, Eefficiency.

1. Introduction

Heat transfer is involved in a wide range of industrial processes, many of which use outdated technologies and are a prime candidate for redesign and improvement. Shell and Tube heat exchangers are among the most commonly used equipment in industries such as chemical, petrochemical, power generation and food. Since heat transfer takes place in tubes, they have received great attention in order to improve their heat transfer features. Researchers have studied changing the geometry of tubes and adding nanoparticles to base fluid in order to improve heat transfer rates. The following is an overview of the current literature in three sections 1- Changing the geometry of tubes, 2- Adding nanoparticles to the base fluid, and 3-

* Corresponding author: Ahmadreza Sajadi
Faculty of engineering, Shahrekord University, Shahrekord, Iran
Email: ar.sajadi@sku.ac.ir

Changing the geometry of tubes and adding nanoparticles simultaneously.

- Changing the geometry of the tube

Zhi et al. [1] examined the dimpled tubes. Their study, which was performed in the Reynolds number range from 5,000 to 30,000, shows an increase in thermal efficiency. The results showed that dimpled tubes have better thermal efficiency than circular tubes. The presence of protrusions and dimples mixes the boundary layer and also creates alternating rotational flows along with the flow inside the tube. Studies have also shown that the flow friction coefficient and the Nusselt number increase with increasing depth of dimples. In this study, the flow friction coefficient decreases first and then increases with increasing pitch length. In another numerical study, they compared teardrop-shaped dimples with oval and spherical dimples as well as the effect of step and depth of dimples on heat transfer [2]. The results showed that the amount and power of return flow in a tube with teardrop dimples is much less than tubes with spherical and oval dimples, which has a significant effect on improving the thermal efficiency of tubes with teardrop dimples. As expected, reducing the depth of the teardrop-shaped dimples reduces the system pressure drop. The coefficient of friction and the Nusselt number also increases with increasing depth and radius of the dimples and decrease with increasing the pitch of the dimples. Cheraghi et al. [3] numerically investigated the presence of deep dimples in the tube wall. In this study, the rate of change in heat transfer with three parameters of depth, pitch length and radius of dimples was measured. Their results also indicate that increasing the depth and radius and reducing the pitch length of the dimples on the pipe can increase the rate of heat transfer up to 600%. Many other studies have been conducted to investigate the effect of dimples on heat transfer and hydrodynamic efficiency, which can be found in the research of Dagdevir and Ozceyhan [4] in 2021, Gholami et al. [5] in 2020, AbdulWahid et al. [6] in 2020. And research by Xi et al. [7] in 2013.

Cattani L. et al. [8] investigated the thermal performance in ellipse and super ellipse-based double corrugated tubes numerically. An ellipse and super ellipse-based tubes were modeled at laminar, fully developed, and incompressible flow. The efficiency increased up to 11% for the tubes with super ellipse-base and up to 14% for the double corrugated tubes with an ellipse-base. Andrade F. et al. [9] investigated heat transfer and pressure drop of internal flow in corrugated tubes. The experiments were conducted in laminar, transitional, and turbulent regimes, with Reynolds numbers in the range from 429 to 6212. The heat flux ranged from 5.5 kW/m2 to 21.1 kW/m2 imposed on the tube wall. The results showed that the friction factor of the corrugated tubes presented a smoother transition than in the case of the circular tube. Corrugated tubes are more effective under a transitional flow regime. The highest heat transfer augmentation occurs at $Re \approx 2000$.

Sajadi et al. [10] introduced and investigated the thermal and hydrodynamic behavior of alternating flattened tubes experimentally. They performed their studies on Reynolds numbers between 400 and 1800 under constant wall temperature. They observed that the rate of heat transfer and pressure drop of alternating flattened tubes is higher than in circular and flattened tubes. The heat transfer and the pressure drop increase as the number of pitches and the amount of flattening increase at a constant length of tube. They concluded that the flow in the alternating flattened tubes became turbulent before reaching the Reynolds number 400. They defined the enhanced ratio to compare the efficiency of alternating flattened tubes with circular tubes. The results showed that in many cases the use of alternating flattened tubes instead of circular tubes can reduce energy consumption and the size of heat exchangers. Rukruang et al. [11] conducted a numerical and experimental study of heat transfer within the alternating flattened tube. Simulations and experiments were performed under constant wall heat flux. The results showed heat transfer was affected by the flow characteristics. Vorticities are formed in the curved wall of alternating flattened tubes and their intensity increases along the direction of flow. This made the heat transfer coefficient and pressure drop of the alternating flattened tubes larger than the circular tubes. However, the rate of increase in thermal performance is greater than the rate of pressure drop.

Sajadi et al. [12] experimentally and numerically studied the heat transfer and pressure drop of oil flow in alternating elliptical axis tube and circular tubes. The results showed that reducing the aspect ratio and increasing the number of pitches increases heat transfer and pressure drop. The results of the experimental study showed that the oil flow of alternating elliptical axis tubes in Reynolds numbers less than 400 was turbulent. It is also concluded that the thermal efficiency of the alternating elliptical axis tube is greater than the circular tube. Najafi and Nazif [13] numerically investigated the heat transfer of airflow in an alternating elliptical axis tube. The results of the numerical solution show due to the presence of longitudinal vorticities that the alternating elliptical axis tube has a higher pressure drop and heat transfer compared to the circular tube. Also, by comparing the experimental results with numerical ones, it was found that the friction factor has acceptable accuracy.

- Adding nanoparticles to the base fluid

In addition to changing and improving the geometric structure of tubes, improving the thermal properties of the fluid can also increase heat transfer and reduce the size of heat exchangers. Ahmed M. et al. [14] studied the heat transfer in a circular tube with constant wall temperature numerically in the presence of nanoparticles. Al2O3, CuO, and TiO2 were studied with concentrations from 0 to 10% wt. The Reynolds number varied from 500 to 2000. Results showed the maximum enhancement in Nusselt number was for Cu nanoparticle, at Re = 1000, with a maximum increase 20.5%. Chowdhury Z. et al. [15] investigated heat transfer of water-based nanofluid with 0.025% to 0.1% wt. concentrations. They synthesized ZnO Nanoparticles by the sonochemical method. Their tube was circular and at a constant wall temperature. For all concentrations, heat transfer is enhanced compared to base fluid. About fifty percent heat transfer enhancement for the nanofluid with 0.1% wt. ZnO nanoparticles were observed. In a review paper, Tehmina and Kim [16] compared the correlations for the heat transfer and pressure drop of various nanofluids in heat transfer tubes. Most studies confirm the effect of nanofluids on increased heat transfer, pressure drop and efficiency. Chaim et al. [17] and Samina et al. [18] investigated the studies of heat transfer and pressure drop of various nanofluids in heat transfer tubes. The results of the studies indicate an increase in heat transfer and pressure due to the use of nanofluids. Orlando et al.[19] Conducted experiments with constant heat flux on silver and SWCNT nanofluids in a circular tube. The volumetric concentration of silver particles was between .03 to .2 and the concentration of SWCNT particles was between .1 to .5. The Ag nanofluids showed an increase whereas the SWCNTs showed decrement of the heat transfer coefficient. Regarding the pressure drop, the nanofluids exhibited pressure drops between 5 and 8.7% greater than that of the base fluid. Sajadi and Kazemi [20] investigated the effect of adding low concentrations of titanium oxide nanoparticles on heat transfer and pressure drop in a circular tube. ‘The base fluid was water and the volumetric concentration of nanoparticles was less than .25%. The results showed that the addition of small amounts of nanoparticles to the base fluid augmented heat transfer remarkably. There was no much effect on heat transfer enhancement with increasing the volume fraction of nanoparticles. The results also indicated that the pressure drop of nanofluid was slightly higher than that of the base fluid and increased with increasing the volume concentration. Sajadi et al. [21] Investigated heat transfer and pressure drop of ZnO/water nanofluid. The volume fractions of nanoparticles in the base fluid were 1% and 2% and the Reynolds numbers ranging from 5000 to 30000. The results showed that the heat transfer coefficient increased by 11% and 18% with increasing volume fractions of nanoparticles, respectively. The measurements also showed that the pressure drop of nanofluids was, respectively, 45% and 145% higher than that of the base fluid.

- Changing the geometry and adding nanoparticles

Some studies have investigated the effect of changing the geometry of the tube and adding nanoparticles to the base fluid at increasing the heat transfer and pressure drop of the tubes simultaneously. Ahmad et al. [22] Experimentally investigated of heat transfer and pressure drop of aluminum oxide nanofluid in flat pipes. Reynolds number and nanoparticle concentration varied from 5000 to 20,000 and 0% to 1% by volume, respectively. They found the effect of nanoparticles on heat transfer is intensified at higher corrugation height and smaller corrugation pitch and as the concentration of nan. particles increases, the efficiency increases. Lee and Kumar [23] investigated the combined effect of simultaneous use of flat tubes and nanofluids. According to the results, flat tubes have a greater effect on increasing thermal efficiency than nanofluids. Also, the best cross-section and the most suitable nanofluid concentration were calculated in terms of the lowest entropy production. As a result, a flat tube with an aspect ratio of 6 and a nanofluid with a concentration of 1% reduces the entropy production of the system by 13.4%.

Gabriella and Angel Hiuminic [24] studied flattened tubes with nanofluids. The results indicate a significant increase in pressure drop with increasing nanofluid concentration as well as increasing the grade of flattening of the tube. However, this cost is not ineffective and the result of using nanofluid instead of the base fluid and replacing a circular tube with a flattened tube has a significant increase in heat transfer. The results also showed that the use of nanofluids in flattened tubes gives much better results for thermal efficiency compared to circular tubes.

Nakhchi and Isfahani [25] for the first time numerically studied the parameters of nanofluid flow in tubes equipped with perforated conical rings. In this study, the constant temperature boundary condition for the outer surface of the tube and the Reynolds number range is 5000 to 14000. The concentration of nanofluid used is between 0 and 1.5%. According to the results, the presence of perforated conical rings mixes the thermal boundary layer and increases the thermal efficiency. The increase in Nusselt number for conical rings with 4, 6, 8 and 10 holes is 278.2, 231.5, 196 and 152%, respectively. Maximum thermal efficiency is achieved when the nanofluid concentration is equal to 1.5% and 4-hole conical rings are used.

Naqibzadeh et al. [26] Numerically studied the thermal and hydrodynamic effects of nanofluids in helical coil with flattened cross-section. This study was conducted in Reynolds range from 360 to 2000 for different types of tube cross-sections. The laminar flow of water-alumina nanofluid with a concentration of 1% was simulated. The results show that the thermal efficiency of flattened tubes is higher than circular ones and the effect of flattening tubes on increasing thermal efficiency is more than the use of nanofluids.

Najafi and Nazif [27-29] numerically investigated the turbulent flow of heat transfer and the entropy production of water-aluminum oxide nanofluid and water fluid in an alternating elliptical axis tube under constant temperature boundary conditions. Their aim was to investigate the increase in heat transfer using nanofluids as well as to create longitudinal vorticities along the flow in an alternating elliptical axis tube. They also examined the nanofluid parameters on heat transfer, pressure drop and entropy generation. It was found that water-aluminum oxide nanofluid has a higher heat transfer coefficient and higher pressure drop than water-based fluid. Also with increasing the volume fraction of nanoparticles and decreasing their size, the heat transfer and the friction increase. According to the results, the entropy created in the system increases, with increasing Reynolds number.

Sajadi and Talebi [30] in 2020 for the first time experimentally investigated the heat transfer and pressure drop of oil-zinc dioxide nanofluid in alternating flattened tubes. Their study was performed at nanoparticle concentrations of 1 and 2% for constant tube wall temperature and Reynolds range 400-1900. The results showed that adding nanoparticles to the fluid or using alternating flattened tubes increases heat transfer and pressure drop. They used the efficiency parameter for the simultaneous comparison of heat transfer and pressure drop. Simultaneous use of flat tubes and nanofluids increases the system heat transfer from the third order and the system pressure drop from the second order and in general increases the efficiency of the system.

Sajadi et al. [12] showed that the efficiency of the alternating flattened tube is higher than the alternating elliptical axis tube, flattened tube, dimpled tube and corrugated tube. Also, the study of Sajadi and talebi [29] on alternating flattened tubes, Lee and kummar [22] on flattened tubess as well as other references such as [16], [23] and [24] show that the use of nanoparticles increases the efficiency in a circular tube and Geometrically changed tubes.

So far, no experimental work has been done to study the effect of nanoparticles on the heat transfer characteristics of alternating flattened tubes. In this study for the first time, we have investigated heat transfer, pressure drop, and efficiency of alternating flattened tubes with TiO2/Oil nanofluid.

2. Methodology

The method of this study was experimental and analysis of test results. For this purpose, TiO2/oil nanofluid has been prepared in volumetric concentrations of 1 and 2%. The thermophysical properties of each sample in the temperature range of 30 to 90 ° C have been investigated in the Materials and Energy Research Institute. To ensure that the nanoparticles do not stick to each other, the prepared nanofluids are exposed to ultrasonic waves with a frequency of 20 kHz and a power of 400 watts for one hour.

2.1. Test apparatus

The test apparatus consists of a 5liter oil storage tank from which the fluid is sucked by a gear pump and sent to the test tube. The test tube is passed through a steam tank. 4 electric heaters, each with the power of two kilowatts, are installed in the bottom of the steam tank. The steam tank guarantees saturated steam around the test tube. At the beginning and end of the test tube, the oil temperature is measured. The temperature on the surface of the test tube is also measured at four points. All the thermocouples are K-type and the accuracy of temperature measurement is .1°C. The pressure difference between the inlet and outlet of the test tube is measured by accuracy of 1Pa. Flow rate is measured by a one-liter glass balloon and a stopwatch with an accuracy of .01 seconds.

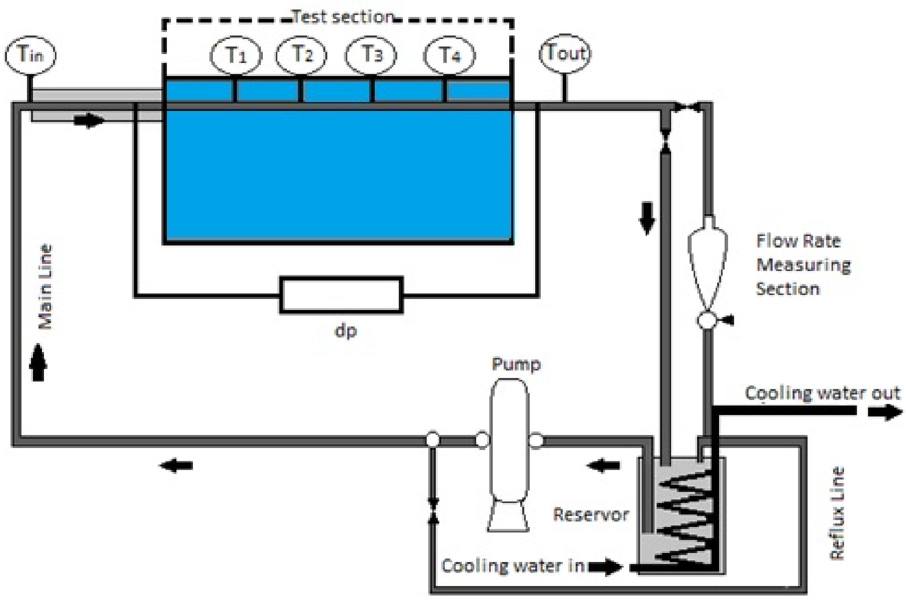

Fig. 1. Schematic of the test apparatus

According to the basic laws of heat transfer, the mean convective heat transfer coefficient is obtained from Equation 1 [31].

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

where $\dot{m}$ is mass flow rate, C_p is the specific heat capacity of the fluid, $T_{out} - T_{in}$ is the difference between outlet and inlet temperature, A_s is the lateral area of the tested tube, and ΔT_m is the logarithmic mean temperature that is calculated from equation (2) [31].

$$\Delta T_m = \frac{\Delta T_{out} - \Delta T_{in}}{ln \frac{\Delta T_{out}}{\Delta T_{in}}} \quad (2)$$

The mean Nusselt number and friction coefficient of the flow inside the test section are obtained from Equations (3) [31] and (4) [31], respectively.

$$\overline{Nu} = D_h \bar{h} / k \quad (3)$$

$$f = \frac{2D_h \Delta P}{\Delta L u^2} \quad (4)$$

Where D_h is hydraulic diameter, k is fluid conductivity, ΔP is pressure drop at the tube, ρ is the density of the fluid, L is tube length and u is the flow velocity.

In order to check the reliability of the test device's results, Hausen and Darcy relations, which are confirmed for the laminar flow of circular tubes, have been used. The Hausen relation, which is suitable for calculating the Nusselt number of laminar flow in a circular tube with constant surface temperature, is given in Equation 5 [31].

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

where Gz_D is Grates number.

$$f = \frac{2D_h \Delta P}{\Delta L u^2} \quad (6)$$

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

The Darcy relation that is appropriate for calculating the laminar flow friction factor coefficient in a circular tube is given in Equation (7) [31].

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

Figures 2 and 3 compare the results of the experimental apparatus with the Hausen and Darcy equations. The maximum of these errors compared to Hausen and Darcy equations were 5% and 4%, respectively.

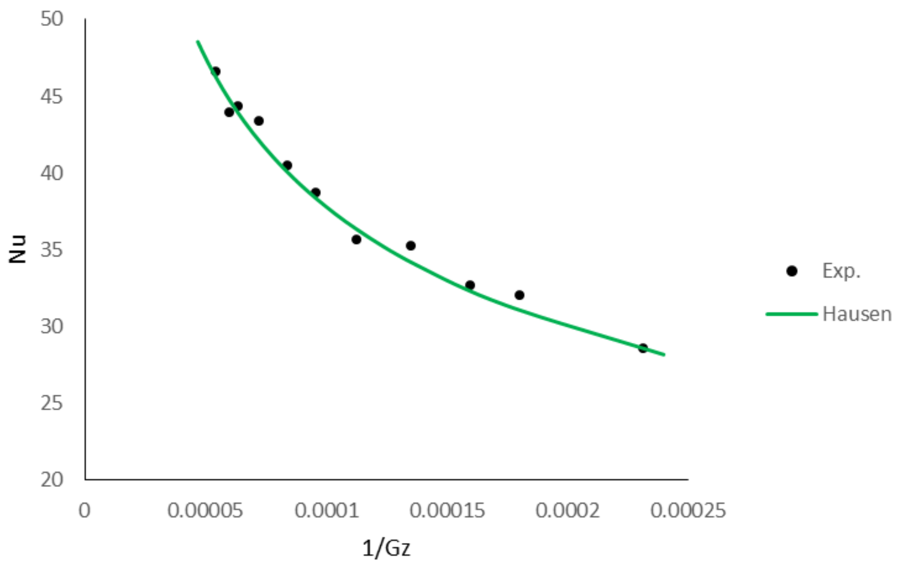

Fig. 2. Comparison of the heat transfer results of the test apparatus with the Hausen equation

The maximum errors of the convective heat transfer coefficient and friction factor coefficient were 5% and 3% respectively.

2.2. Test tube

The Alternating flattening tube consists of Consecutive circular and flattened segments. Each circular or flattened segment is connected to the next segment by a transition part. Fig.4 shows the geometry of AF tube.

Flattening the tube increases the presence possibility of fluid particles near the tube wall, and passing the fluid through the transition part increases the turbulence of the flow and creates secondary flows. These factors increase the heat transfer rate. Table 1 shows the geometric properties of the investigated tubes.

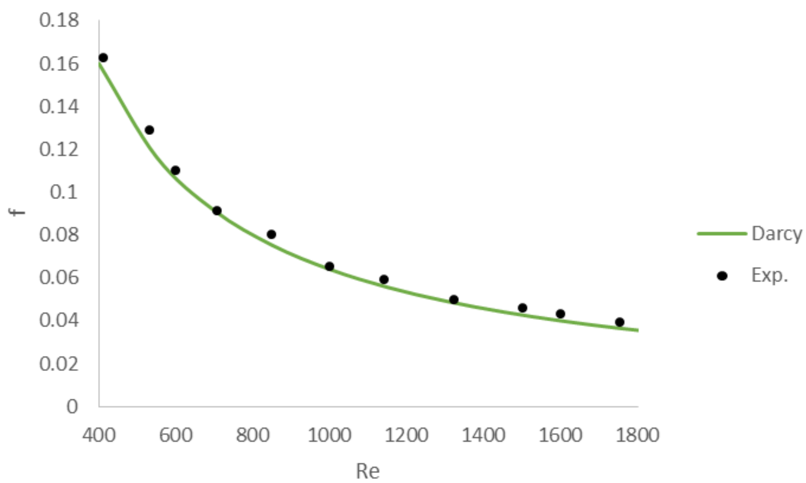

Fig. 3. Comparison of the pressure drop results from the test apparatus with the Darcy equation

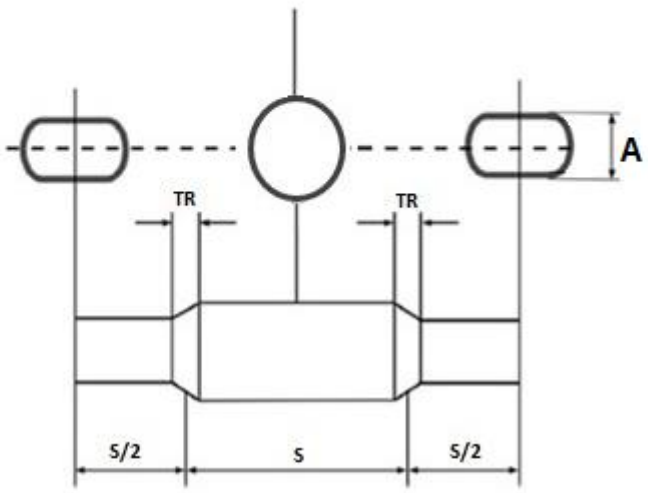

Fig. 4. Schematic of alternating flattened tube

Table 1. Geometric Properties of Test Tubes

Tube	A(mm)	TR(mm)	S(mm)
Circular	15.88	-	-
AF1	14	50	165
AF2	12	50	165
AF3	10	50	165

3. Results and discussion

Figure 5 shows the heat transfer of base oil in tubes. The heat transfer of the AF tubes is higher than circular one, and the heat transfer ratio increases by increasing the ratio of the flattening of the tubes from AF1 to AF3. These results are consistent with experimental observations of Sajadi et al. [10] and numerical results of Rukruang et al. [11] for alternating flattening tubes. At the Reynolds number 1000, the ratio of heat transfer of tubes AF1, AF2 and AF3 to the heat transfer of circular tube is 1.35, 1.74 and 1.95, respectively. By flattening the tubes, the possibility of the presence of fluid particles near the wall increases, and also the passing of fluid through transition parts causes the thermal boundary layer to be destroyed and also creates secondary flows. These factors increase the heat transfer rate. As the Reynolds number increases, the ratio of heat transfer growth of the AF tubes to the circular tube increases. For example, In AF3 tube, the heat transfer ratio increase for Reynolds numbers 400 and 1800 are equal to 1.9 and 2.21, respectively. The ratio of transfer in tubes AF1 and AF2 to the circular tube is 1.32 and 1.7 for Reynolds 400 and 1.59 and 2.08 for Reynolds 1800, respectively. As the Reynolds number increases, the momentum of the fluid particles increases, and more turbulence is imposed on the flow when the fluid particles collide with the walls of the transition parts and the heat transfer rate increases faster.

Figure 6 shows the pressure drop of the tubes. The pressure drop of AF tubes is more than circular tubes and increases with increasing flattening from tube AF1 to tube AF3. The effect of increasing the flattening on increasing the pressure drop can be seen in the results of Sajadi et al [10] and Najafi and Zarif [13] studies on alternating flattening tubes and alternating elliptical axis tubes, respectively. For Reynolds number 1000, the ratio of pressure drop of tubes AF1, AF2 and AF3 to the pressure drop of the circular tube is 1.07, 1.19 and 1.22, respectively. As the tube flattens, the velocity of the flow increases, and since the pressure drop is related to the second power of the velocity, the pressure drop increases with the flattening of the tube. Also, with the passing of flow through the transition parts due to the creation of secondary flow and growth of turbulence of the flow, the amount of pressure drop increases. For example, In AF3 tube, the pressure drop ratio increase for Reynolds numbers 400 and 1800 are equal to 1.18 and 1.33, respectively. The ratio of pressure drop in tubes AF1 and AF2 to the circular tube is 1.06 and 1.17 for Reynolds 400 and 1.08 and 1.27 for Reynolds 1800, respectively.

Figures 7 and 8 show the heat transfer nanofluids with concentrations of 1 and 2%, respectively.

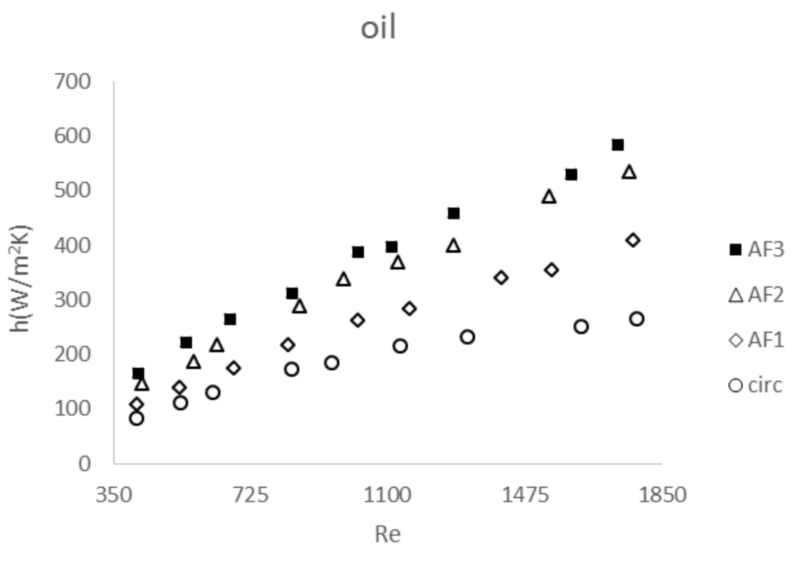

Fig. 5. Heat transfer of base oil in tubes

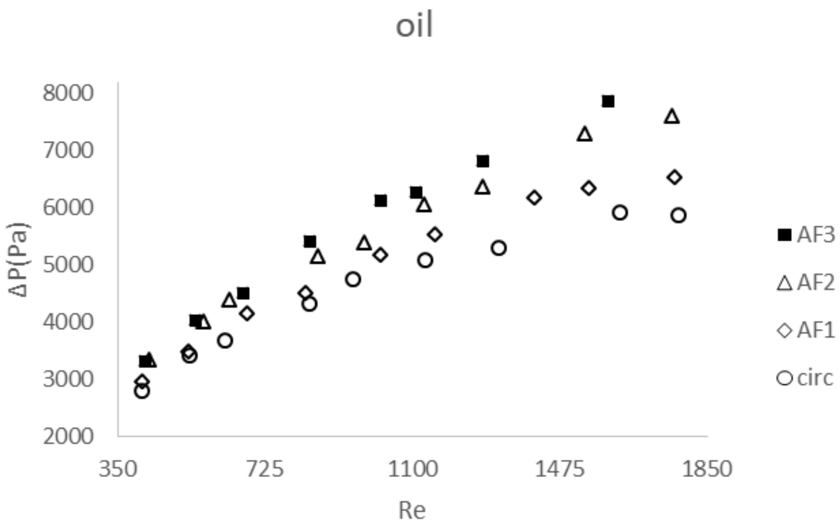

Fig. 6. pressure drop of the Base oil in tubes

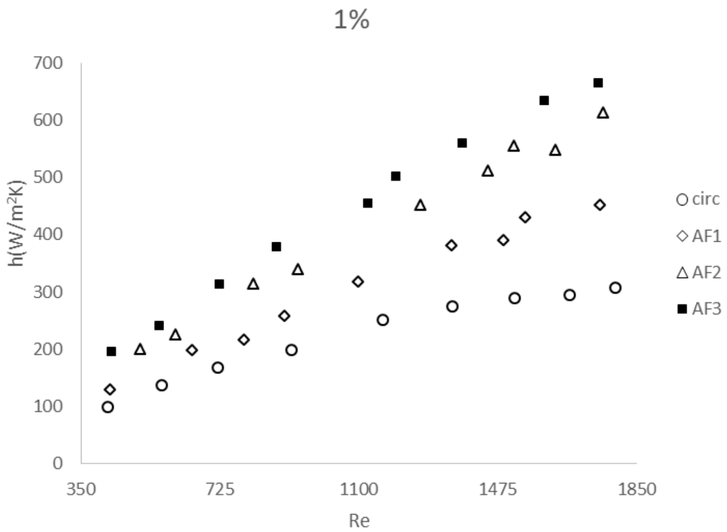

Fig. 7. heat transfer of nanofluid 1% in tubes

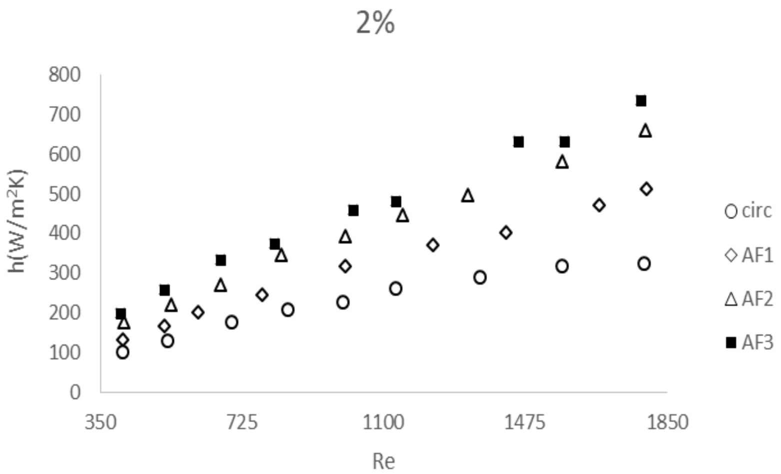

Fig. 8. heat transfer of nanofluid 2% in tubes

The heat transfer of the nanofluid is higher than the base fluid and increases with increasing the concentration of nanoparticles. Adding nanoparticles to the base fluid enhances its conductivity. In addition, the Brownian motions of nanoparticles cause the presence of nanoparticles with a low temperature near the tube wall and increase the temperature difference, and increasing the temperature difference, enhances heat transfer.

With increasing Reynolds number, the effect of nanoparticles on increasing heat transfer decreases. For example, in a circular tube, nanofluid heat transfer with the concentration of 2% in Reynolds numbers 400 and 1800 is 26% and 20% higher than the base fluid heat transfer, respectively. This increase is 22% and 17% for tube AF3, respectively. With increasing Reynolds number, the turbulence of the flow increases and as a result, the role of Brownian motions of nanoparticles in increasing heat transfer decreases.

Figures 9 and 10 show the nanofluid pressure drop with the concentration of 1 and 2%. The nanofluid pressure drop is greater than the base fluid pressure drop and increases with increasing nanoparticle concentration.

The pressure drop of nanofluid with concentrations of 1% and 2% is 6% and 11% higher than the base fluid, respectively. The amount of increase in pressure drop is constant for almost all tubes and in the Reynolds number range studied. By adding nanoparticles to the base fluid, its viscosity increases and as a result, the pressure drop increases.

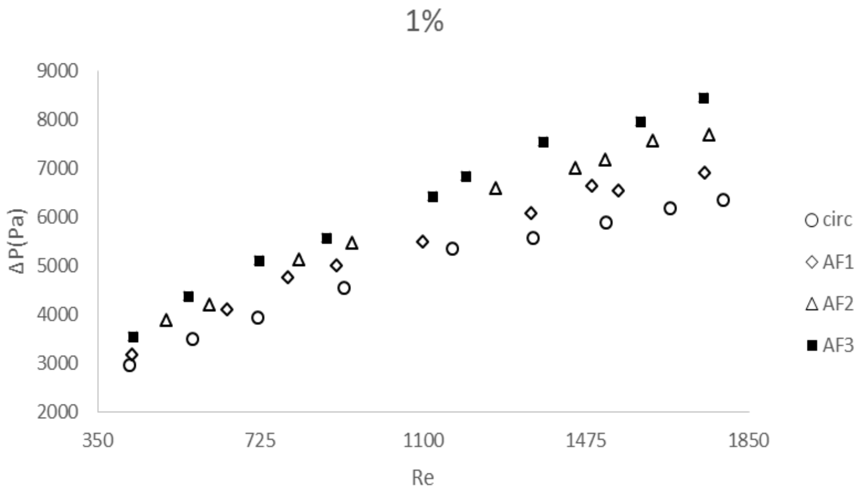

Fig. 9. pressure drop of nanofluid 1% in tubes

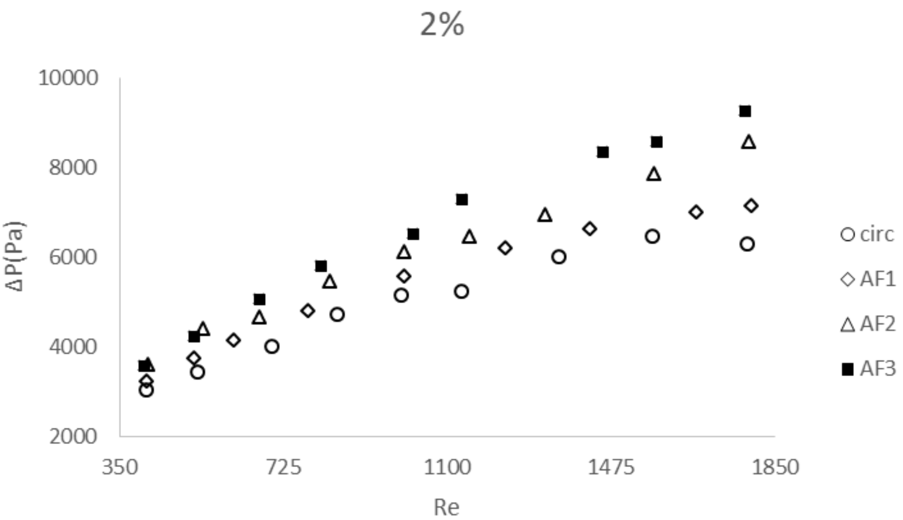

Fig. 10. pressure drop of nanofluid 2% in tubes

Changing the geometry of the tube and using nanoparticles both increase heat transfer and pressure drop simultaneously. Increasing the heat transfer is a favorable factor and increasing the pressure drop is an undesirable factor. The performance effective ratio (PER) is a parameter that compares heat transfer and pressure drop changes of two tubes simultaneously (Eq. 8) [32].

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

If the value of this parameter is greater than one, it means that the efficiency of tube a is higher than tube b and if this value is less than one, it means that the efficiency of the tube a is less than tube b.

Figure 11 shows the efficiency of AF tubes. The efficiency of AF tubes is higher than circular tube and the efficiency increases with increasing flattening. Lee and Kumar [22] at the flattened tubes and Sajadi and Talebi [29] at the alternating elliptical axis tubes found that increasing the flattening increase the efficiency but in the alternating elliptical axis tubes the highest increase in efficiency occurs at an optimal flattening point. For Reynolds number 1000, PER of tubes AF1, AF2 and AF3 is 1.26, 1.62 and 1.76, respectively

Figure 11 shows that efficiency first decreases and then increases. The amount of flattening, turbulence and secondary flows play role in the higher heat transfer and higher pressure drop of AF tubes. As the Reynolds number increases, the flow turbulence and secondary flows, which have a greater effect on the increase of heat transfer, accelerate. But the pressure drop, as shown in figure 5, is more affected by the amount of flattening. Thus the efficiency decreases at first but with increasing Reynolds increases. Since the performance effective ratio of the alternating flattened tubes is higher than the circular tube It is more economical to use alternating flattened tubes instead of a circular tube.

Figure 12 shows the efficiency of tube AF3 for different fluids. The results show that the use of nanoparticles increases the efficiency and this increasing efficiency trend continues by increasing the nanoparticle concentration. These results are consistent with the results of Sajjadi and Talebi [29] regarding alternating elliptical axis tubes. At the Reynolds number 1000, PER of base fluid, nanofluids 1% and 2% is 1.76, 2.01 and 2.15, respectively.

As mentioned, the effect of titanium oxide nanoparticles on increasing heat transfer is higher than their effect on increasing the pressure drop.

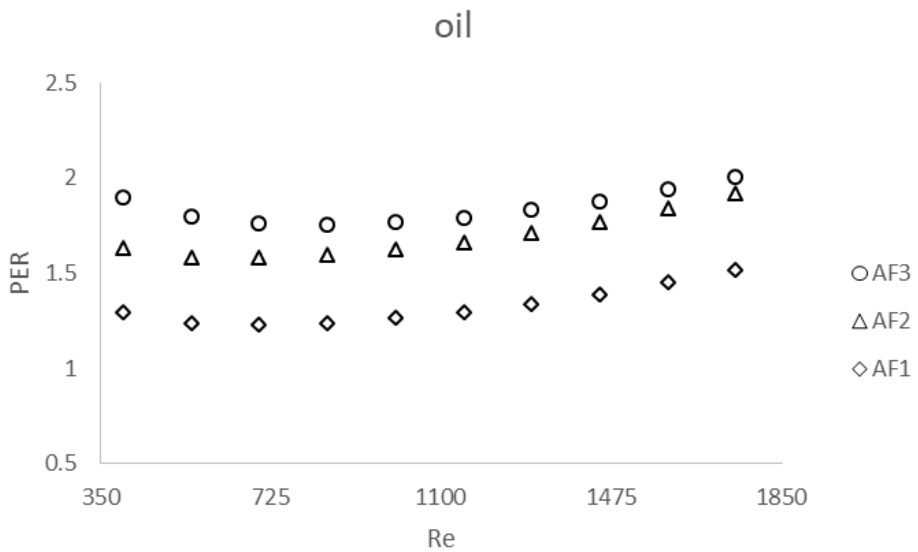

Fig. 11. Comparison of the Efficiency of AF tubes with Circular Tube

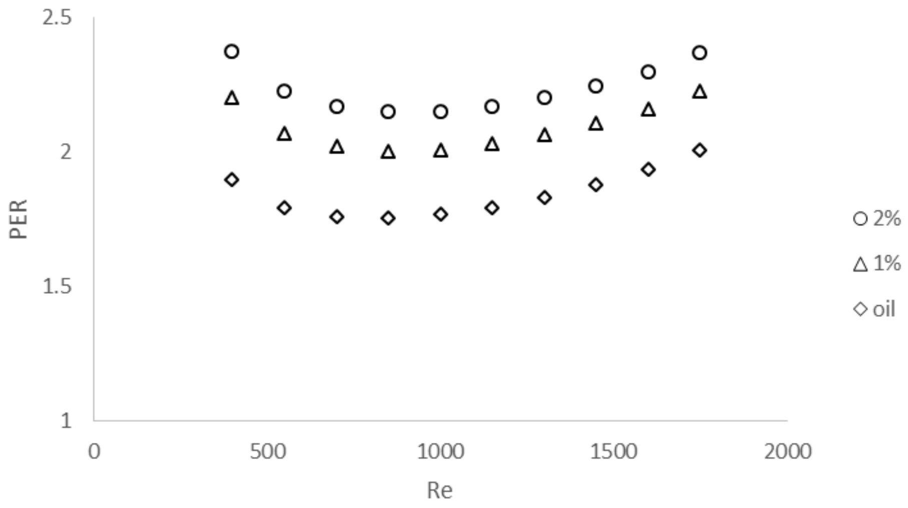

Fig. 12. Comparison of nanofluid efficiency with a base oil in tube AF3

4. Conclusion

In this study, for the first time, the effect of titanium oxide nanofluid on heat transfer, pressure drop and efficiency of the alternating flattened tube has been investigated experimentally. The alternating flattened tube consists of consecutive circular and flattened sections with a transition part in between them. The amount of tube flattening and concentration of nanoparticles have been studied as changing variables. Nanofluid is pumped into the test tube and the steam tank ensures saturated steam conditions around the test tube. To calculate the heat transfer amount in the tube, fluid temperature is measured at the inlet and outlet of the test tube as well as the wall temperature of the test section. Flow pressure drop is also measured along the test section.

The results show:

- The heat transfer of the AF tubes is higher than the circular tube and boosts with increasing flattening.
- Heat transfer enhances with the addition of nanoparticles. Also, increasing the concentration of nanoparticles increases heat transfer.
- The pressure drop of AF tubes is more than circular tube and increases with increasing flattening.
- The addition of nanoparticles increases the pressure drop in all tubes. Also increasing particles concentration increases the pressure drop.
- In the Reynolds number range of this study, the efficiency of the AF tubes is higher than the circular tube and an increase in flattening increases the efficiency.
- Adding nanoparticles to the base fluid increases the efficiency with a positive correlation to nanoparticle concentration.

Keeping the test tube wall temperature constant is the main limitation of this study because as the heat transfer rate rises with Reynolds numbers, more steam is required to keep the wall temperate e constant. Moreover, the effect of changing the length of flattened segments and use of other nanoparticles can be investigated in the future to complement this work.

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