Experimental Investigation of Heat Transfer of Nanofluid in Elliptical and Circular Tubes

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ABSTRACT

The paper presents experimental comparison of forced convection for steady state turbulent flow of nanofluid (Al_2O_3-distilled water) inside circular and elliptical (aspect ratio of 0.75) cross section tubes of identical circumference and tube surface area. Convection coefficient, pressure change, and fiction factor were compared at different Reynolds number (3,000-9,230) with different nanoparticles volume concentration (0.5%, 1.0%, and 1.5%). The results showed that Nusselt number increases with increasing Reynolds number and nanoparticle volume concentration. The pressure drops and friction factor of nanofluid are higher than the distilled water and are increasing as the volume concentration increases. Furthermore, the elliptical tube provided small increase in Nusselt number compared to that of circular cross sectional tube. However, the friction factor in the elliptical tube was slightly higher.

1. INTRODUCTION

The recent technological advancement in electronic devices and data processing equipment has led to an urgent need for reliable and efficient cooling systems while keeping the size and weight as minimal as possible. Accordingly, numerous studies have been published proposing various techniques to increase the rate of heat transfer. For instance, using corrugated channels, rough tube walls and/or adding nanoparticles of high thermal conductivity to the conventional cooling fluids increasing the heat transfer rate [1-7].

Various experimental studies were published on nanofluid heat transfer behavior inside tubes of circular cross section with laminar forced convection flow [8-12]. Zanjani et al. [13] investigated the effect of graphene-water inside (4.2 mm) circular tube at Re= 1850, and their results showed that using only 0.02% graphene increased the thermal conductivity of the nanofluid by 10.3%. Gwon et al. [10] experimentally investigated the viscosity and pressure change of carbon nanofluid inside a 10.7 mm diameter circular tube. They observed that by inserting the nanoparticles, higher friction factor is obtained for laminar flow, while under turbulent conditions there was insignificant increase in friction factor. Yang et al. [14] studied experimentally the effect of graphite nanofluid flowing through circular tube and showed that Nusselt number is affected by size of nanoparticles, their temperature, particle loading and base fluid chemistry.

An experimental study using aqueous copper (Cu) nanofluid inside a circular tube was conducted by Wusiman et al. [15] to investigate the forced heat transfer characteristics for Reynold's Number varying from 300 to 16000. For Re= 2000, using Cu/water increased the heat transfer coefficient by 62% at 1% volume fraction. Azmi et al. [16] investigated the effects of TiO_2-water and SiO_2-water flowing in horizontal circular tube with uniform heat flux on Nusselt number and pressure drop. The result showed that SiO_2-water nanofluids provided maximum heat transfer enhancement of 33% at 3.0% volume concentration while the pressure drop was proportional to nanofluid density. Duangthongsuk et al. [17] studied the effect of TiO_2-water nanofluid (volume concentration between 0.2% and 2.0%) in circular tube with turbulent flow conditions. In their study they showed that higher Nusselt number values are obtained when volume concentration of less than 1.0% is used.

One of the advantages of elliptical cross sectional tubes is that they have smaller resistance to the fluid than that of that of circular cross section tube, and this helps reducing the required power for pumping the fluid in the tube. Accordingly, elliptical tubes have become an increased interest by many researchers [18, 19]. Shariat et al. [19] performed three dimensional numerical study using Al_2O_3-Water nanofluid to investigate the laminar mixed convection flow inside elliptical tube. In their study, Nusselt number increased and the skin friction factor decreased with increasing nanoparticles volume fraction at a given Reynolds number. They also showed increasing the aspect ratio of the elliptic tube resulted in local skin friction factor reduction. Similarly, Hussein et al. [20] conducted a numerical investigation on the effect of elliptical tube on heat transfer and friction characteristics by using TiO_2-water nanofluid with turbulent flow, and their data showed a 4% enhancement of friction factor and a 9% enhancement of Nusset number when compared to data of circular tube at similar flow Reynolds numbers.

From above literature and to the best of authors' knowledge, there has been no experimental study investigating the effect of using Al_2O_3-distilled water nanofluid on forced heat transfer characteristics inside an elliptical tube. The present study is experimental investigation of nanofluid flow through elliptical and circular cross sectional tubes of similar tube perimeter and surface area. The effect of tube geometry

(circular and elliptical), (Al₂O₃-distilled water) nanofluid volume fraction and flow Reynold's number on average Nusselt number, friction factor and pressure drop are compared and discussed.

2. EXPERIMENTAL PROCEDURE

2.1 Experimental facility

The experimental facility shown in Figure 1 consists of a test section, pump, reservoir tank, cooling system, flow meter, digital manometer, bypass and control box. This component setup is built as a closed-loop system. Two copper tubes, one of a circle cross section and the other is elliptical cross section, of 1 mm thickness and the total length of 2000 mm were used in the test section to study the effects of tube cross sectional geometry on the heat transfer performance as shown in Figure 2. The detailed dimensions of both tubes are listed in Table 1.
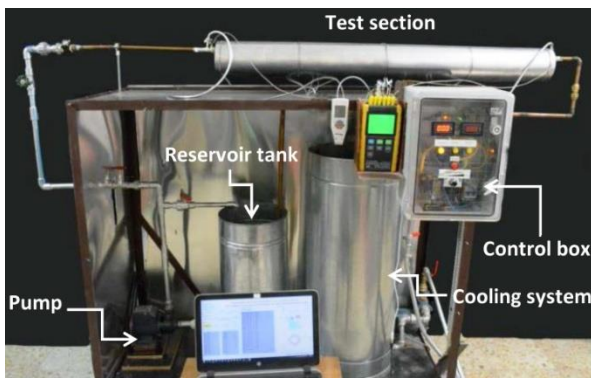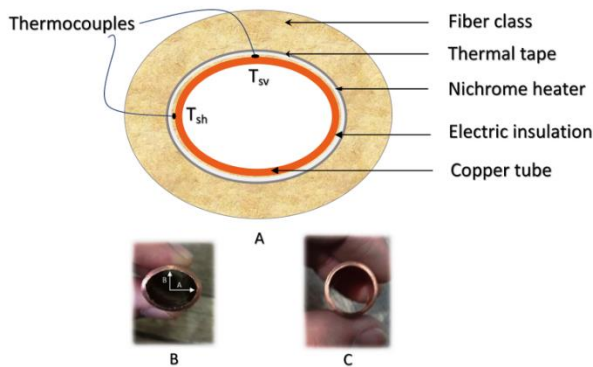

Figure 1. The experimental facility

Figure 2. (a) Schematic of the test section, (b) image of the elliptical tube, (c) image of the circular tube

Table 1. The elliptical and circular tube dimensions

Parameter	Elliptical tube	Circular tube
Internal radius	A=8 mm, B= 6 mm	7 mm
Aspect ratio	B/A=0.75	B/A=1
Hydraulic dimeter	13 mm	14 mm
Cross sectional area	150 mm²	156 mm²
Circumference	44 mm	44 mm
Length	1300 mm	1300 mm
Surface area	57856 mm	57856 mm

The bulk temperature is measured using two type-k thermocouples (model number TH-M6-K and measuring range of 0 to 400℃) installed at the inlet and outlet of the test section. For the circular tube five thermocouples (numbered 1 to 5 in Figure 3) were installed at distances of 150, 400, 650, 900 and 1150 mm from the tube inlet. For elliptical cross section tube, since there will be difference in temperature between the horizontal and vertical axis due to difference in transverse and conjugate diameters, another five thermocouples (numbered from 6 to 10 in Figure 3) are inserted in the horizontal plane at the distances of 150, 400, 650, 900 and 1150 mm from the inlet. Thus, the average temperature is considered at each distance from the vertical and horizontal thermocouple.

1500 Watt Nickel chrome AWG20 heater was used in order to obtain uniform heat flux boundary condition, and to minimize heat loss to the ambient, the test section was insulated with non-flammable blankest. Cooling system was used to reduce the nanofluid temperature after exiting the test section to ensure that the inlet flow temperature to the test section remains constant. Digital manometer is used to monitor the differential pressure.
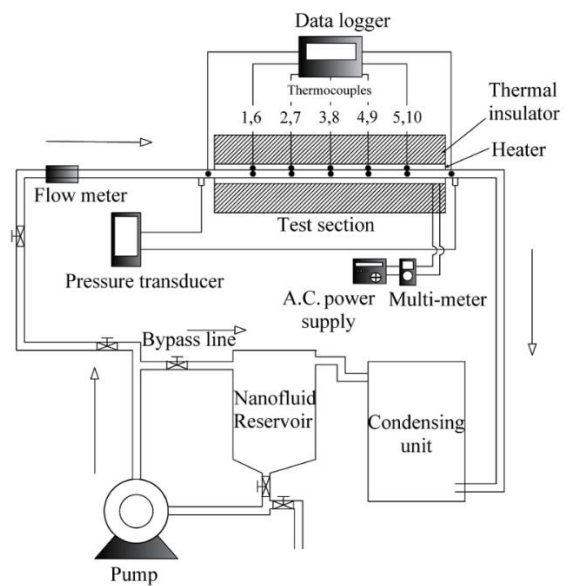

Figure 3. Schematic of the test facility

2.2 Nanofluid preparation

Volume concentrations of (φ=0.5%, 1.0%, and 1.5%) were selected to prepare the Al₂O₃ - distilled water Nanofluid and to study the effect of using different concentrations on the average Nusselt number and pressure drop in the test section. Table 2 presents the distilled water and Al₂O₃ nanoparticles Thermo-physical properties.

Table 2. Thermo-physical properties at T=318 K

Properties	Water	Al₂O₃
Density ρ (kg/m^3)	989	3900
Specific heat Cp (J/kg k)	4180.5	890
Thermal conductivity k (W/m.k)	0.6412	40

After preparing the nanofluid at specific volume concentration, its thermo-physical properties were measured using Hot Disk method and listed in Table 3. In order to determine its dynamic viscosity, capillary tube viscometer was used at different volume concentration, and to measure the density, pycnometer was used. All thermo-physical properties were obtained at temperature of 318 K.

Table 3. Thermo-physical properties of Al_2O_3 nanofluid at different volume concentrations T=318 K

Properties	Distilled water	φ=0.5%	φ=1.0%	φ=1.5%
Density (kg/m^3)	989	1005	1009	1024
Specific heat (J/kg·k)	4180.5	4018	3790	3410
Thermal conductivity (W/m.k)	0.6412	0.659	0.6812	0.7097
Dynamic viscosity (kg/m·s)	566×10⁻⁶	973×10⁻⁶	977×10⁻⁶	992×10⁻⁶

2.3 Data analysis

Constant heat flux is applied on the elliptical and circular tubes (Figure 4) and the heat transfer coefficient and Nusselt number were calculated based on the following:

The local heat transfer coefficient equation for circular tube is [17]:

$$h(x) = \frac{\dot{q}}{T_s(x) - T_m(x)} \quad (1)$$

where, $\dot{q}$ is the heat flux, T_s is the surface temperature and T_m is the bulk mean temperature. For elliptical tube in every section there are two thermocouples so we take average surface temperature in every section. Thus, for elliptical tube the local heat transfer coefficient is calculated from:

$$h(x) = \frac{\dot{q}}{T_{sav}(x) - T_m(x)} \quad (2)$$

where, T_{sav} is the average surface temperature, which is given by:

$$T_{sav}(x) = \frac{T_{sh}(x) - T_{sv}(x)}{2} \quad (3)$$

where, T_{sh} and T_{sv} are the horizontal and the vertical surface temperatures, respectively. The local Nusselt Number is found from:

$$Nu(x) = \frac{h_x D_h}{k} \quad (4)$$

For thermal fully developed flow, the average Nusselt number is calculated from:

$$Nu = \frac{1}{L} \int_0^L Nu(x).dx \quad (5)$$

Simpson rule of 1/3 is used to calculate the integration. The experimental result then compared with theoretical calculations of Gnielinsk's correlation [21] of fully developed turbulent flow inside as follows:

$$Nu = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7(f/8)^{1/2}\left(Pr^{\frac{2}{3}} - 1\right)} \quad (6)$$

For 1.5≤Pr≤2000, 3000≤Re≤500000.

where: $f = (1.58 lnRe - 3.82)^{-2}$

The Reynold's number and Prandtl's number were calculated from:

$$Re = \frac{\rho\, u\, D_h}{\mu} \quad (7)$$

$$Pr = \frac{C_p\, \mu}{k} \quad (8)$$

The fiction factor was calculated by using Darcy equation [21]:

$$f = \frac{2 \times \Delta p \times D_h}{u^2 \times L \times \rho} \quad (9)$$

The friction factor of the present work was compared with Petukov's equation [21].

$$f = (0.79 \times \ln(Re) - 1.64)^{-2} \quad (10)$$
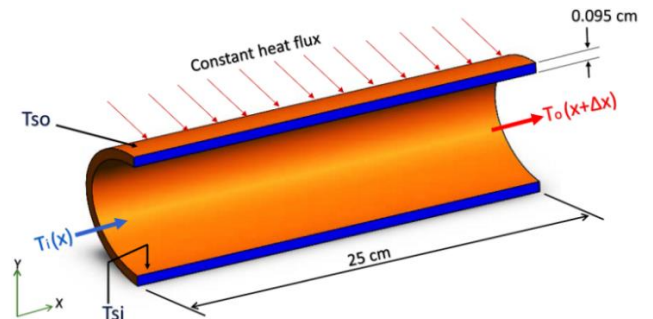
For 3000≤ Re ≤5000000.


Figure 4. Boundary conditions

3. RESULTS AND DISCUSSION

In order to assess the accuracy of the experimental results, comparisons between the obtained data and Gnielinsk's correlation and Petukov's equation [21, 22] were carried out using distilled water for Nusselt number and friction factor at turbulent flow as shown in Figure 5, and the results showed good agreement.

Figure 6 shows the effect of nanofluid volume concentration on the average Nusselt number for circular and elliptical cross section tubes. The Nusselt number increases by increasing nanofluid volume concentration and the highest average Nusselt number of 116 was obtained at nanofluid volume concentration of φ=1.5% in the circular tube, while in the elliptical tube, the average Nusselt number was of about 120. However, further increase in Nusselt number can be obtained by increasing the volume concentration to an upper limit of φ=4% in water based Al_2O_3 nanofluids as reported by Sridhara et al. [23]. Furthermore, increasing the nanofluid volume concertation showed a significant increase in the friction factor and pressure drop at lower Reynold's number as shown in Figure 7 and Figure 8 respectively.
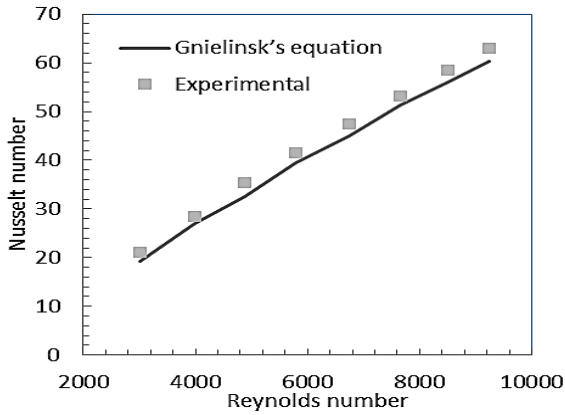
(a) Nusselt number vs. Re
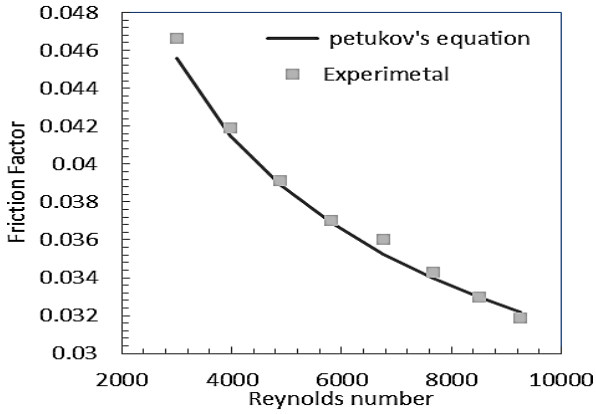
(b) Friction factor vs. Re

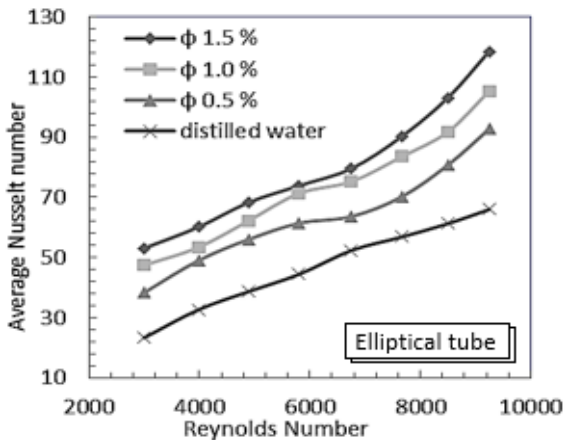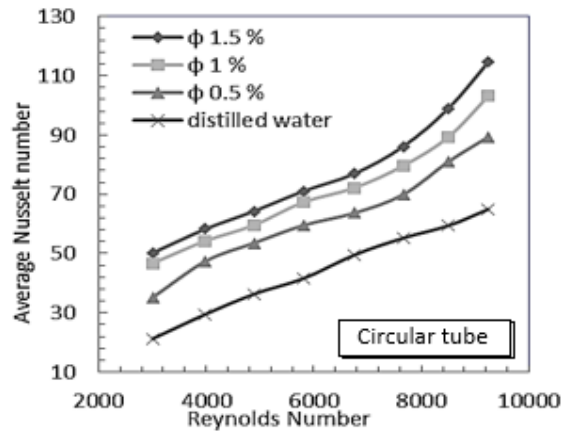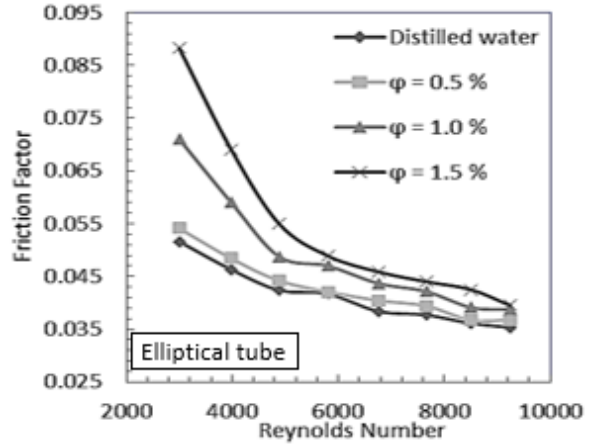**Figure 5.** Experimental results vs. Gnielinsk's correlation and Petukov's equation

Figure 7. Friction factor vs. Re at different concentration
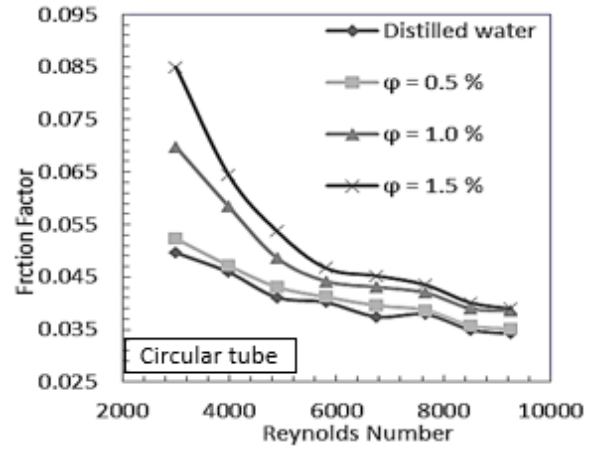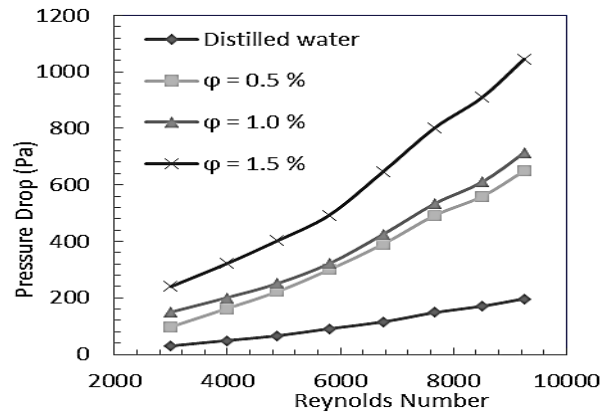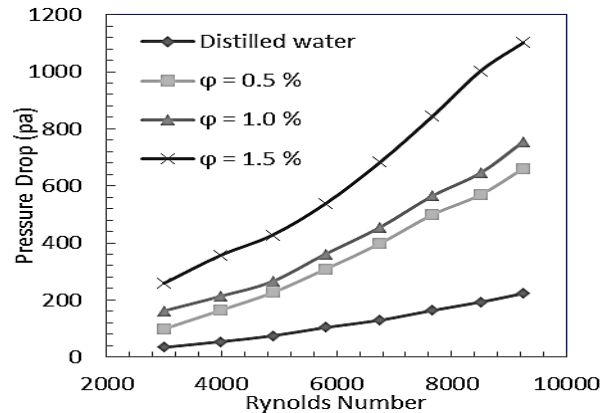

Figure 6. Nusselt number vs. Re at different concentration

(a) Circular Tube

(b) Elliptical Tube

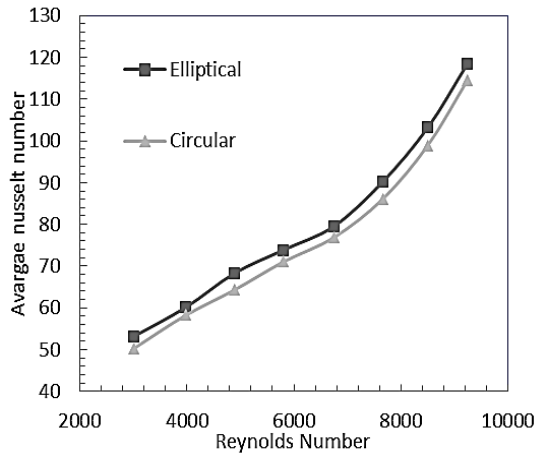**Figure 8.** Pressure drop vs. Re

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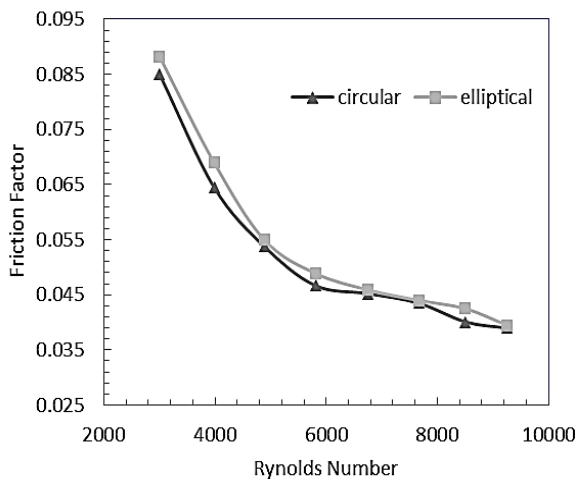**Figure 9.** Nusselt number in circular and elliptical tubes

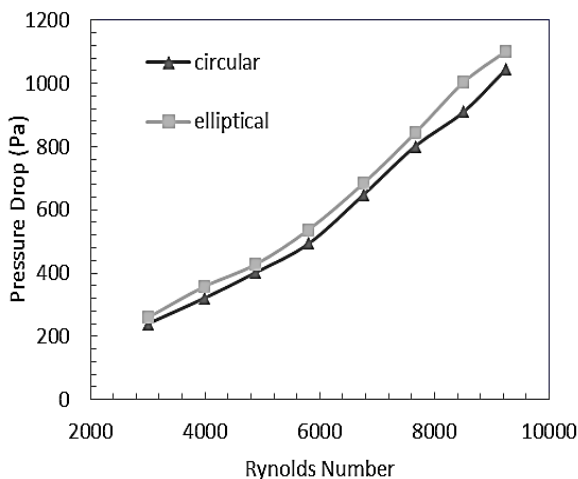**Figure 10.** Friction factor in circular and elliptical tubes

Figure 11. Pressure drop in circular and elliptical tubes

The effect of tube geometry (circular versus elliptical cross section) on Nusselt number, friction factor and pressure drop were studied for nanofluid volume concentration of $\varphi=1.5\%$ and Reynolds number ranging from 3,000 to 9,230 as shown in Figures 9 to 11 respectively. It can be noticed from Figure 9 that the elliptical cross section tube has highest average Nusselt number range as compared to the circular cross section tube, with maximum enhancement 5.7%. Furthermore, there is a slight increase in fiction factor due change in the cross

sectional geometry as illustrated in Figure 10, which is caused by change in boundary layer form due to elliptic cross section shape. It is also noted that there is a small increase in pressure drop due to using elliptical tube at same volume concentration as shown in Figure 11.

The thermal efficiency is considered one of the most important relationships through which the efficiency of the pipes used in comparison as shown in the following relationship [20]:

$$\eta = \frac{\dfrac{Nu_{nf}}{Nu_w}}{\dfrac{f_{nf}}{f_w}} \qquad (11)$$

where, Nu_{nf} and Nu_w are Nusselt number for nanofluid and distilled water respectively, f_{nf} and f_w are friction factor for nanofluid and distilled water respectively.

We can tell if the elliptical tube is more efficient for heat transfer systems compared to the circular tubes within the range of Reynolds number and nanofluid volume concentrations. In Figure 12, the thermal efficiency of the elliptical tube is higher than the circular tube at low Reynold's number (of about 3000) since the Nusselt number in elliptical tube is higher. However, the efficiency decreases with increasing Reynolds number as the fiction factor increases (Eq. (11)) shows that the friction factor and efficiency are inversely proportional).
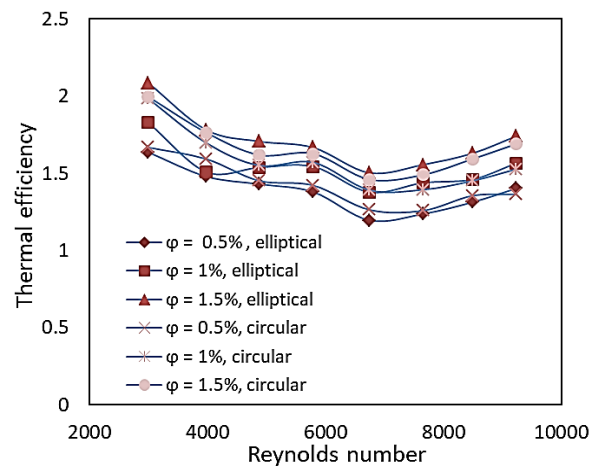

Figure 12. Thermal efficiency

The logarithmic values of Nusselt number to friction factor relation have been depicted in Figure 13. This relation shows the effect of Nusselt number to friction factor of elliptical and circular cross-sectional tubes for different nanofluid volume concentrations and different Reynold's number values. The Log (Nu/f) for distilled water for elliptical and circular tube increased with increasing Reynolds number since the Nusselt number increased and friction factor decreased. It is clearly shown that the elliptical tube introduces better heat transfer performance at low velocities. However, at higher flow velocities (Reynold's number above 8000) the values of Log (Nu/f) are quite comparable, and this is due to the fact that the friction factor in the elliptical tube is increasing at the higher Reynold's number and therefore increasing the obtained values of Log (Nu/f).
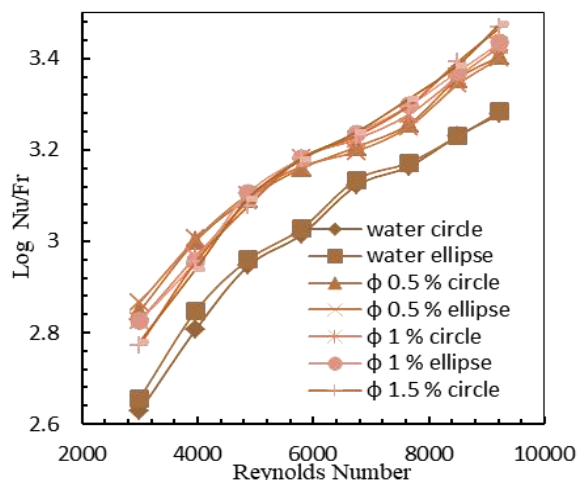
Figure 13. Log Nu/f vs. Re

4. CONCLUSIONS

The effects of tube cross sectional geometry on the heat transfer performance in circular and elliptical (aspect ratio of 0.75) cross sectional tubes of identical circumference and surface areas have been studied and compared in this paper. Nusselt number, pressure drop and friction factor were investigated using Nanofluid (Al_2O_3-distilled water) of different volume concentration with Reynold's number ranging from 3,000 to 9,230. Fully developed turbulent flow conditions were applied at uniform heat flux. The result showed that heat transfer coefficient and Nusselt number increased when increasing the Reynold's number and the nanoparticle volume concentration to 1.5%. Pressure drop and friction factor were also increased. Additionally, the elliptical tube showed small enhancement in heat transfer since the obtained Nusselt number was higher compared to that of circular cross sectional tube, while the pressure drop and friction factor in the elliptical tube were slightly higher.

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NOMENCLATURE

AR	aspect ratio
A	major radius of ellipse, m
B	minor radius of ellipse, m
T_m	mean bulk temperature, k
Q	heat flux, W/m^2
p	circumference, m
$\dot{m}$	mass flow rate, kg/s
x,y,z	coordinates
C	constant
Cp	specific heat, kJ/kg · k
T_i	inlet fluid temperature, k
T_o	outlet fluid temperature, k
T_s	surface temperature, k
T_m	bulk meat temperature, k
L	tube length, m
Re	Reynolds number`
T_{si}	inlet surface temperature, k
T_{so}	outlet surface temperature, k
Nu	Nusselt number
D_h	hydraulic diameter, m
h_x	local heat transfer coefficient, W/m^2 k
k	thermal conductivity, W/m.k
Δp	pressure drop, Pa
U	fluid velocity, m/s
f	friction factor
Pr	Prandtl number

Greek symbols

ρ	fluid density, kg/m^3
η	performance factor
μ	Dynamic viscosity, N.s/m^2
φ	nanofluid volume consternation