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Assessment the Effect of Nanofluid on Turbulent Heat Transfer and Pressure Drop in Bend Finned Tube

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Abstract: An experimental study of using Al_2O_3 -water nanofluid that flows in a finned bend tube cross flow heat exchanger on heat transfer and pressure drop was implemented. The experimental part consists of closed loop of water or nanofluid that flows in the bend tube heat exchanger that inserted in an air wind tunnel. The effect of different nanoparticles volume fraction of (0, 0.01, 0.05, 0.1 and 0.2%Vol.) were depressed in deionized water. The hot water or nanofluid flow in the two types of smooth and finned bend tube heat exchanger with different inlet Reynolds numbers for the range of (450-920) for laminar flow and (6900-10000) for turbulent flow. The experimental results were presented as a friction factor, local and average Nusselt number for the water and air side respectively for the smooth and finned bend tubes. The results show that the inner average Nusselt number of Al_2O_3 -water nanofluid that flows in heat exchanger enhanced by up (34.6 %) for smooth tube heat exchanger and about (44.1 %) for finned bend tube heat exchanger compared to pure water. Also, the friction factor of the nanofluid flow inside the heat exchanger increase by up (13.9 %) for smooth bend tube heat exchanger and (22%) for finned bend tube as compared with the use of pure water.

Keywords: Nanofluid, Annular Fin, Bend Tube, Cross Flow Heat Exchanger.

1. Introduction

For all aspects of economy, saving energy is a critical problem for enhancement and optimization. Thus, the cost of the heat efficiency and the optimization process during the heat exchanger design is considerably taking into account. Heat transfer equipment is one of the most important units operates in many industries. In food and chemical processing industries, there are various types of heat exchangers such as plate heat exchangers, double pipe and cross flow heat exchanger are used. The heat exchangers with circular finned tube have been used due to their low manufacturing cost. One of the well-known methods to increase the heat transfer in the heat exchangers is using the high thermal conductivity that so called nanofluid. The nanofluids are created by suspension of high thermal conductivity materials nanoparticles (1-100 nm) such as Al_2O_3 into a suitable base fluid such as water [1]. Many efforts have been carried out to improve and optimize the equipment and operation, but there are few works focused on the fluid of heat transfer improvement in the cross-flow heat exchanger. Several studies have investigated



nanofluid in a pipe with a return bend heat exchanger. Choi and Zhang [2] used the finite element technique to investigate the heat transfer by the forced convection by using nanofluid of Al_2O_3 -water that flows in a pipe with a return bend. It was found that Nusselt number was higher at the bend section than that in the inlet and outlet sections of the pipes, and the pressure drop in the pipe largely increases with the increment of nanoparticle volume concentration. Abbas [3] presented a numerical and experimental study for U-longitudinal finned tube heat exchanger by using nanofluid TiO_2 and Al_2O_3 nanoparticles with water as a working fluid. It was found that as the nanoparticles concentration and Reynolds number increased Nusselt number was increased. Ranjith et al. [4] presented an experimental study on friction factor and heat transfer by using Al_2O_3 nanofluid that flows in a heat exchanger with concentric tube U-bend of with and without helical tape inserting in the inner tube. They found that the average Nusselt number increased with increasing of Reynolds number and Prandtl number, and augmentation of thermal conductivity in the nanofluid contributes to heat transfer enhancement. Sultan [5] investigated experimentally the effect of silver and oxide zirconium.oil nanofluids on enhancement of heat transfer in a heat exchanger with and without fins by changing flow directions. Two types of nanofluids at different particle volume concentration were used. It was found that silver with oil nanofluid gave maximum heat transfer enhancement compared with oxide zirconium (ZrO_2) nanofluid. Zena et al. [6] investigated experimentally the heat transfer enhancement when using MgO nanofluid that flows in heat exchanger with cross flow low integral finned tube. They showed that the nanoparticle concentration increasing in the water led to increase the heat dissipation rate. Ranjbarzadeh et al. [7] used the water-graphene oxide nanofluid that flows in a single tube air cross-flow in wind tunnel heat exchanger to investigate the effect of the nanofluids on pressure drop and heat transfer with different concentrations. It was found that increasing of air flow Reynolds number and nanoparticles concentrations led to increase the amount of the heat transfer enhancement. In this study, the effect of using Al_2O_3 nanofluids flow in two heat exchanger configurations of smooth and finned bend on the heat transfer enhancement characteristics for the cross-flow heat exchanger by using different nanoparticles concentrations, different water inlet Reynolds number, different air inlet Reynolds number and different water inlet temperatures. The study includes recording the bend tube surface temperature and pressure drop in order to data analysis and calculate Nusselt number and friction factor respectively.

2. Experimental Apparatus

2.1 Experimental Setup

The schematic diagram and a photo of the present experimental test rig are shown in Figure 1 and 2. It includes an air subsonic wind tunnel (horizontal duct) with an inserted test section in the middle of the duct that constructed from transparent acrylic plastic with dimension of (360mm x 360mm x 220mm). The airflow equipped with a fan driven by an axial motor with power of 2.2 kW. Also, the rig includes measurement devices, and water tank, two models of smooth and finned bend tube heat exchanger. The smooth tube has (55cm) long, (18mm) inner diameter, (19mm) outer diameter and (1mm) thickness. The circular fins were manufactured from high thermal conductivity copper thin sheets of (376 W/m. $^{\circ}\text{C}$). Number of fins (49 fins) was arranged uniformly and perfectly on the external surface of the smooth tube, the pitch between the fins is (5.5mm), the fins inner diameter is (17 mm), the fins outer diameter (44mm) with fins thickness (0.5mm). The tubes have equal longitudinal pitch of tubes; thus, the type of the heat exchangers can be considered as inline heat exchangers. The bend tube used in this work was constructed and welded which consists of inlet and outlet sections with 180-degree bend section to obtain a U shape bend tube as shown in Figure 3 that inserted in the stream of the air flow in the duct. The

hot working fluids (water or nanofluid) loop includes a centrifugal pump, electrical heater and an insulated tank with dimensions of (20cm x 20cm x 40cm). Eight thermocouples (Type-K) were connected to a digital thermometer with $\pm 0.2\%$ accuracy were used to measure the temperatures along the external surface of the bend tube. Also, another two thermocouples were used to measure the air inlet and outlet temperature of the duct. In addition, an inclined manometer was employed to measure the small differential pressure across the test section of the heat exchanger in the air tunnel. The pressure drops across the bend tube was measured by using two differential pressure transducers (manufactured by Endress Hauser) with an uncertainty of ± 1 Pa connected to a digital screen. Finally, the velocity of the air inlet to the test section was measured by a digital anemometer vane-type (model AR826).

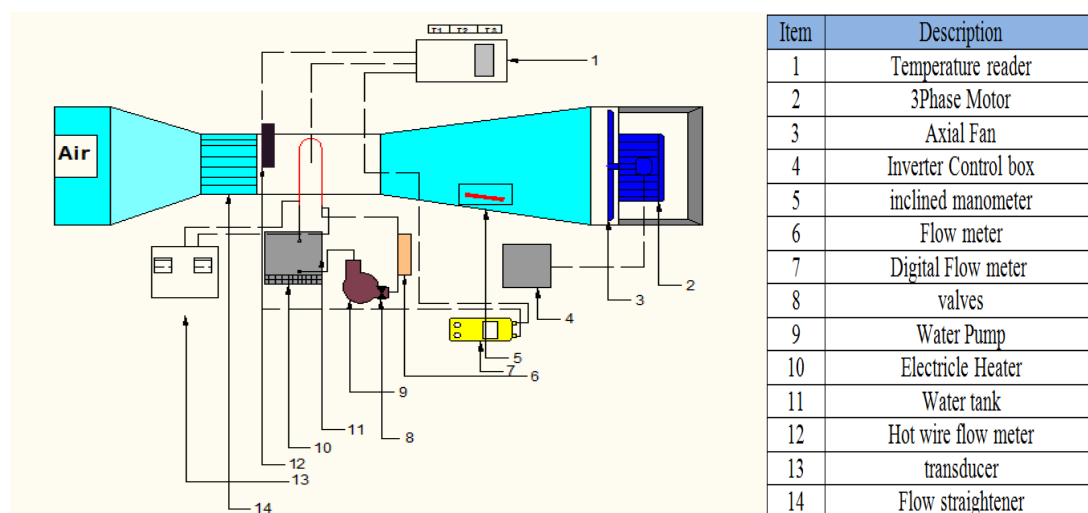
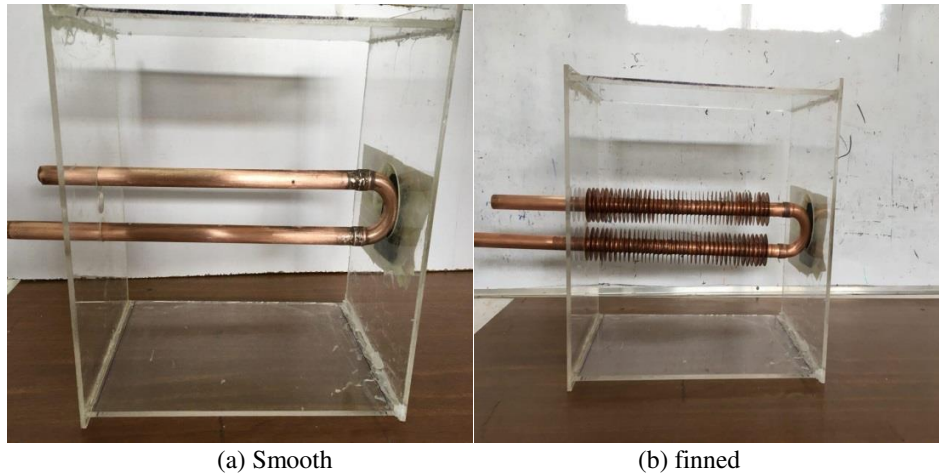


Figure .1 Schematic diagram of the experimental set up.



Figure .2 Photograph of the experimental rig.



(a) Smooth (b) finned
Figure .3 Models of heat exchanger

2.2 Nanofluid Preparation

Two-step method was employed for nanofluid preparation in the present work. This method includes producing nanoparticle by using any method for this purpose and adding a suitable quantity of water in the container, and then the ultrasonic vibration homogenizer device was used to mix the water with the (Al_2O_3) nanoparticles. To make sure no damage will happen to the device as recommended by the instructions of the supplier, the ultrasonic device was filled with water, and then the basket was put inside the bath Karamallah and Jehhef [8]. In this work, three liters of water was used to prepare the nanofluids in all volume fractions. Four volume fractions of Al_2O_3 - water nanofluid of (0.01%, 0.05%, 0.1%, and 0.2%) were used in this study.

2.3 Data Analysis

The heat transfer rate from hot fluid (water or nanofluids) that flows in the bend tube can be calculated by:

$$Q = \dot{m}_a C_{pa} (T_{a,e} - T_{a,i}) \quad (1)$$

$$Q = \dot{m}_w C_{pw} (T_{w,i} - T_{w,e}) \quad (2)$$

The rate of heat transfer from an isothermal surface can be determined from:

$$Q = h_{av} A_s (T_{s,av} - T_{LMT}) \quad (3)$$

Then the heat transfer rate can be determined from:

$$h_{av} A_s (T_{s,av} - T_{LMT}) = \dot{m}_w C_{pw} (T_{w,i} - T_{w,e})$$

$$\therefore h_{av} = \frac{\dot{m}_w C_{pw} (T_{w,i} - T_{w,e})}{A_s (T_{s,av} - T_{LMT})} \quad (4)$$

$$T_{LMT} = \frac{(T_s + T_e) - (T_s + T_i)}{\ln \frac{(T_s + T_e)}{(T_s + T_i)}} \quad (5)$$

The surface area of two models of the cross-flow heat exchanger can be calculated as:

For smooth bend tube:

$$A_s = N * \pi * d_r * L + A_{\text{elbow}} \quad (6)$$

For finned bend tube:

$$A_s = A_{s \text{ no fin}} + A_{s \text{ fin}} + A_{\text{elbow}} \quad (7)$$

$$A_{s \text{ no fin}} = \pi \times d_r \times P_f \times N_f + A_{s \text{ term.}} \quad (8)$$

$$A_{s \text{ term.}} = \pi \times d_r \times 0.02 \quad (9)$$

$$A_{s \text{ fin}} = N_f \times \left[\frac{\pi}{2} (d_f^2 - d_r^2) + \pi \times d_f \times t_f \right] \quad (10)$$

$$A_{\text{elbow}} = \pi^2 * d_r * R * \frac{\theta}{180} \quad (11)$$

For air side Nusselt number is given by:

$$Nu_{av} = \frac{h_{av} d_h}{k_a} \quad (12)$$

$$Re = \frac{\rho_a V_{\text{max}} d_h}{\mu_a} \quad (13)$$

For hot fluid (water or Nanofluid) side Nusselt number is given by:

$$Nu_{nf} = \frac{h_{av} d_h}{K_{nf}} \quad (14)$$

$$Re_{nf} = \frac{\rho_{nf} V_{\text{max}} d_h}{\mu_{nf}} \quad (15)$$

In this, study, the fins hydraulic diameter (d_h) is given by [9]:

$d_h = (d_f - d_r)$ For finned bend tube.

$d_h = d_r$ For smooth bend tube.

The air side friction factor is given by [10]:

$$f = \frac{\Delta P}{n \rho_{\text{air}} V_{\text{max}}^2} \quad (16)$$

The pressure drops across the bend tube heat exchanger test section is given by ΔP and can be expressed as:

$$\Delta P = P_{\text{in}} - P_{\text{out}} \quad (17)$$

By using the Darcy-Weisbach equation, the water side friction factor formed as:

$$f = \frac{\Delta P}{\frac{L}{D_i} \frac{\rho_{\text{water}} V_{\text{max}}^2}{2}} \quad (18)$$

To validate the present experimental test apparatus, the test was performed on a smooth bend tube, and the results were compared using [11], for the average Nusselt number for forced convection of cross flow, the Friction factor f and correction factor x for tube banks from [12]. And Blasius equation for friction factor [13], for a turbulent flow at constant wall temperature.

$$Nu = 0.193 Re^{0.618} Pr^{1/3} \quad (19)$$

$$f = \frac{0.316}{Re^{0.25}} \quad (20)$$

$$f = \frac{2\Delta P}{n \times \rho_{air} V_{max}^2} \quad (21)$$

Heat exchanger effectiveness for cross-flow unmixed fluid [14]:

$$\varepsilon = 1 - \exp\left[-\frac{NTU^{0.22}}{C}\right] [\exp(-C NTU^{0.78}) - 1] \quad (22)$$

Where

$$C = \frac{c_{min}}{c_{max}}$$

$$NTU = \frac{A_s U}{C_{mix}}$$

Overall heat transfer coefficient based on air side.

$$U = \frac{Q_{air}}{A_s F \Delta T_{in}}$$

By introducing the nanofluid volume fraction (ϕ), the thermophysical properties equations of the Nanofluid are presented in Table 1, namely the density and heat capacity.

Table 1. The thermophysical properties equations used in numerical simulations.

Thermophysical property	Equation	Reference
Density	$\rho_{nf} = \phi \rho_p + (1 - \phi) \rho_f$	Pak and Cho [15], Ghassan [16]
Specific heat	$C_{p,nf} = \frac{\phi \rho_p C_{p,p} + (1 - \phi) \rho_f C_{p,f}}{\rho_{nf}}$	Pak and Cho [15], Ghassan [16]
Dynamic viscosity	$\mu_{nf} = \frac{\mu_f}{(1 - \phi)^{2.5}}$	Wang [17]
Thermal conductivity	$k_{nf} = \left[\frac{k_p + 2k_f - 2\phi(k_f - k_p)}{k_p + 2k_f + \phi(k_f - k_p)} \right] k_f$	Maxwell [18]

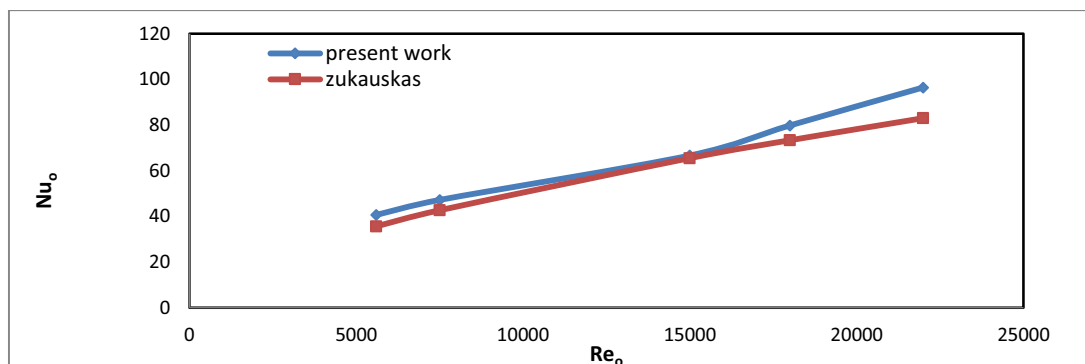
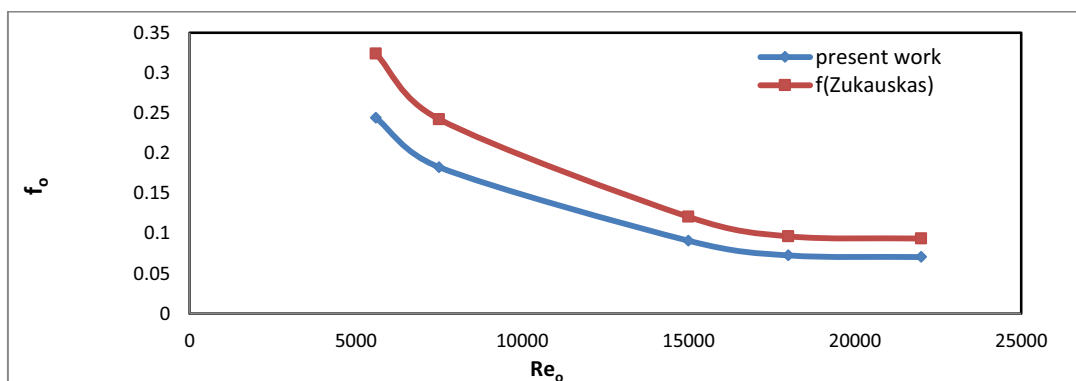
In the present work, (Al_2O_3) nanoparticles were used and Table 2 illustrates all the needed thermophysical properties of nanoparticles and water [19].

Table 2. Specification thermophysical properties of Al_2O_3 nanoparticles and water at $T=293\text{ K}$ [19].

Material	ρ (kg/m^3)	c_p (J/kg K)	μ (Pas.)	λ (W/mK)	β ($1/\text{K}$)
Al_2O_3	3880	773	//	36	//
Water	998.2	4182	993×10^{-6}	0.597	2.1×10^{-4}

3. Results and Discussion

An experimental work was presented to study the effect of utilize Al_2O_3 -water nanofluid with volume fractions of 0.01, 0.05, 0.1, and 0.2% flows in closed loop of a smooth and finned bend tube heat exchanger. The water and nanofluid flowed at laminar Reynolds numbers for the range of (450-920) and (6900-10000) for a turbulent flow. In this section, the experimental results are presented as a friction factor and average Nusselt number of air and water side. Firstly, to validate the experimental rig results for the case of water flow only and to compare the air side results Nusselt number that given by Eq. (12) as shown in Figure 4 and found the maximum deviation difference was 9.9%. In addition, the air side results of friction factor from Eq. (19) Blasius equation as shown in Figure 5 whereas the greatest difference obtained was 2.4%.

**Figure 4.** The present results of Nusselt number compared with the Zhukauskas [11] correlation.**Figure 5.** The present results of friction factor outer fluid (air) compared with the Blasius equation [13].

The variation of air side Nusselt number with air Reynolds number for different nanoparticles concentration for smooth and finned bend tube heat exchanger was plotted in Figure 6. The results showed that the air side Nusselt number (Nu_o) increases with increasing of Al_2O_3 nanoparticles volume fraction due to increase in the thermal conductivity of the base fluid which increases the heat transfer rate from the hot nanofluid toward the air stream. Using the Al_2O_3 –water nanofluid instead of water makes a maximum enhancement in the air side Nusselt's number by about (43%) over the water for smooth tube and (54.9%) for finned tube when using nanoparticles concentration at ($\phi=0.2$) and air Reynolds numbers at 22000.

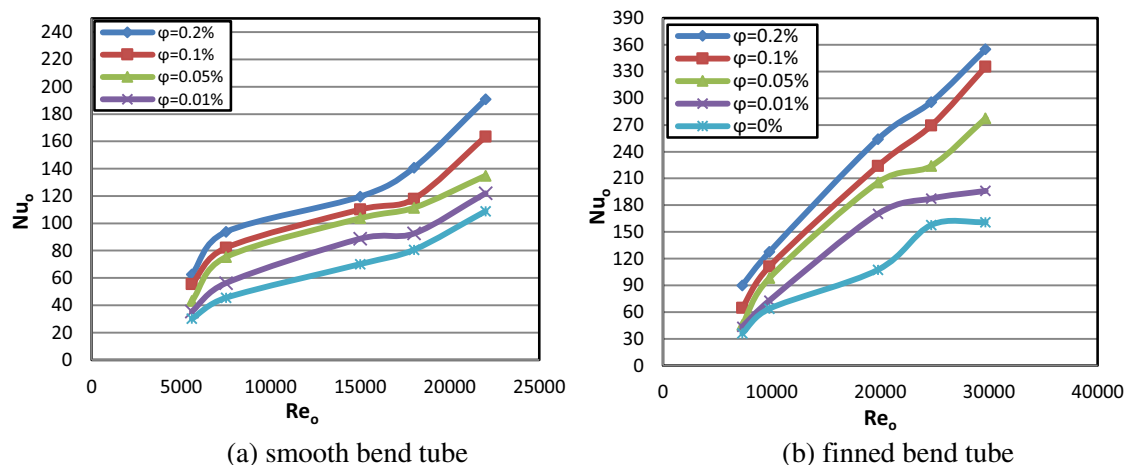


Figure 6. The air side Nusselt number against air Reynolds numbers for different volume fraction at $T_{in}=60^{\circ}C$ and $Q_{water}=8$ L/m.

Moreover, the effect of varying the volume fraction of the nanoparticles on the water side Nusselt number for smooth and finned tube heat exchanger models at different hot fluids flow rates was presented in Figure 7. The results found that the water side Nusselt number (Nu_i) increases with increasing of (Al_2O_3) volume fraction in water at same conditions. Thus, the maximum enhancement of using aluminum oxide nanofluid makes (34.6%) over the water for smooth tube and (44.1%) for finned tube, when using nanoparticles concentration at ($\phi=0.2$) and nanofluids Reynolds numbers at 10000.

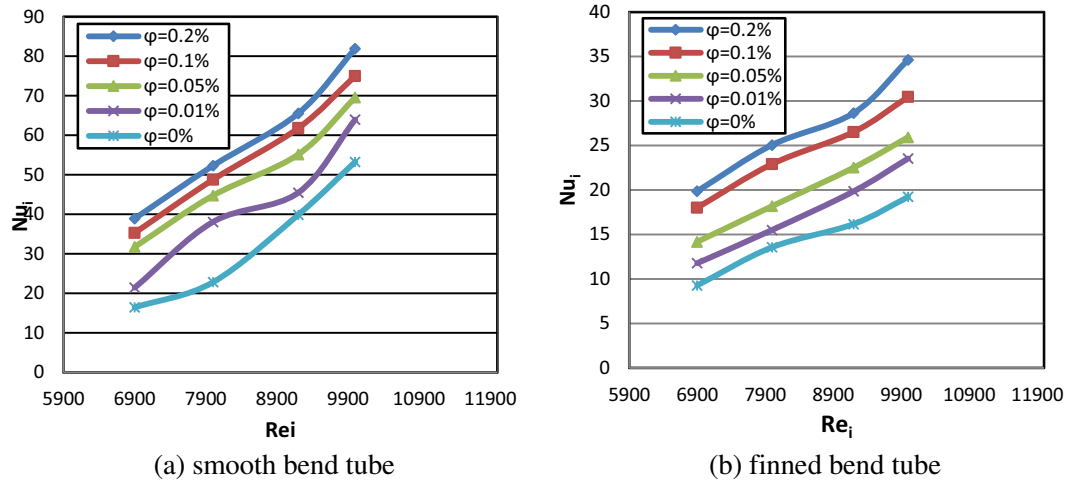


Figure 7. The water side Nusselt number against inner Reynolds numbers with different volume fraction at $T_{in}=70^{\circ}\text{C}$ and $V_{air}=8\text{ m/s}$.

For different nanoparticles volume fractions, the inner friction factor was plotted against the inner Reynolds number of the water and nanofluids was plotted in Figure 8. As can be seen, the inner friction factor of the nanofluids increases with increasing the nanoparticles that was added to the base fluid (water), due to increase the dynamic viscosity of the nanofluid and increasing the friction between the nanofluids and the wall of the tube of the heat exchanger. The percentage of increasing the inner friction factor can be obtain as 1.6, 12.6, 12.6, and 13.9 % for the volume fraction of 0.01, 0.05, 0.1, and 0.2 % respectively for smooth tube. In addition, the inner friction factor decreases with increasing inner Reynolds number for all nanoparticles volume fractions.

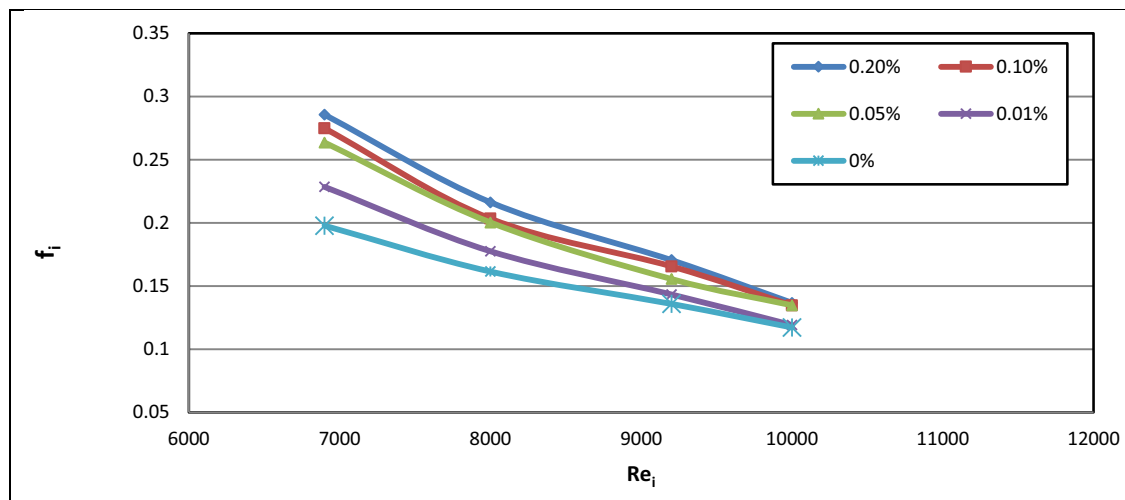


Figure 8. The water side friction factor against inner Reynolds numbers with different nanoparticles concentrations at $T_{in}=70^{\circ}\text{C}$ for smooth bend tube.

Figure 9 shows the effects of the finned tube on the friction factor of air compared to smooth tube. The results showed that the air side finned tube friction factor has higher values as compared with smooth bend tube. Also, nanofluids had better heat transfer characteristics when

they flow in heat exchanger with fins rather than in the heat exchanger without fins. Compared to base fluid flow. Figure 10 shows the comparison of the average Nusselt number of outside (air) which increases in finned model than the smooth model because the fins increase the surface area of heat transfer therefor, fins add to the air side of heat exchanger.

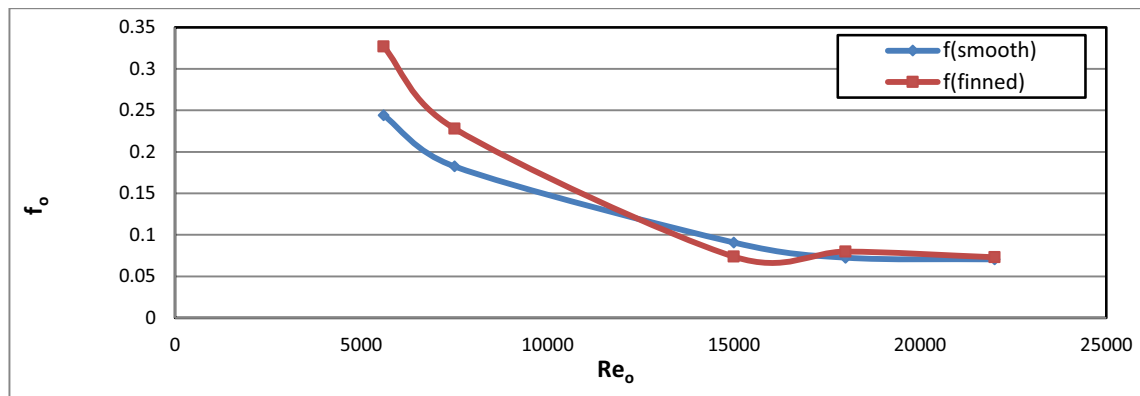


Figure 9. The air side friction factor for smooth and finned bend tube

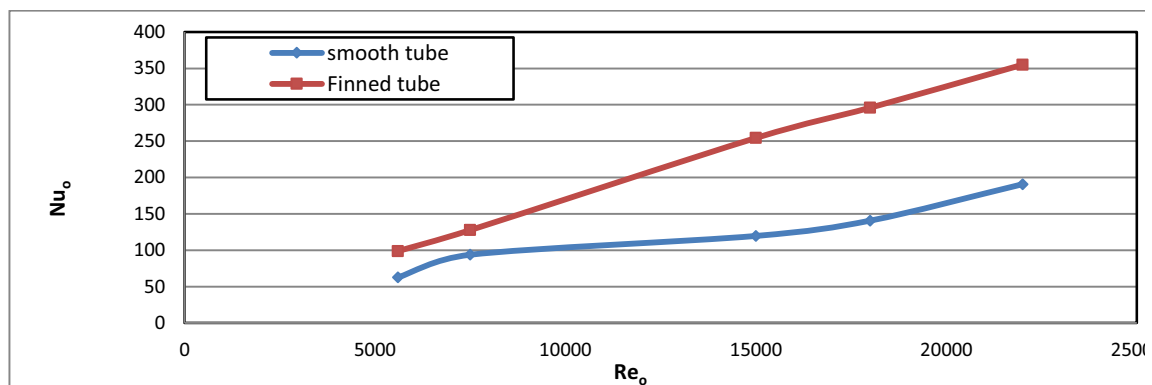


Figure 10. The air side Nusselt number for smooth and finned bend tube for $Q_{\text{water}}=8 \text{ L/m}$ and $T_{\text{in}}=60^\circ\text{C}$

The effect of increasing the inner Reynolds number on the air side Nusselt number was presented in Figure 11. The figure presents the changes in the outer Nusselt number by Reynolds number for nanoparticles concentration of (0.2%) and turbulent region for smooth and finned tube. The results showed that the inner Reynolds number change led to increase in heat transfer rate of the heat exchanger and increase the heat transferred from the hot water toward the air side, also, the higher heat transfer capacity of water compared to air for turbulent condition.

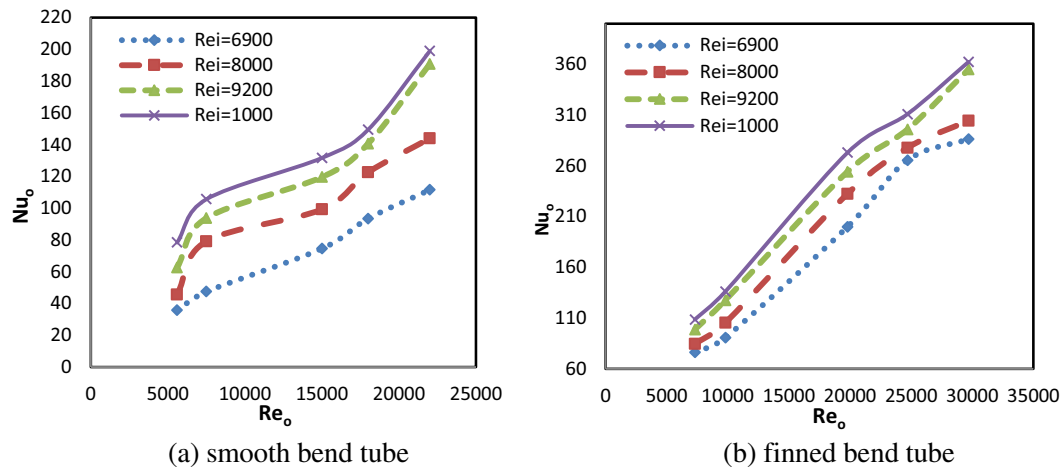


Figure 11. The air-side Nusselt number with different water side Reynolds number for $\phi=0.2\%$ and $T_{in}=60^\circ\text{C}$ for smooth and finned tube.

In addition, the effect of the outer Reynolds number on the variation of the inner Nusselt number of the hot fluids that flow inside the bend tube heat exchanger was plotted in Figure 12. The results showed that the inner Nusselt number increases with increasing the inner and outer Reynolds numbers for smooth and finned tube heat exchanger. Also, it is clear that the inner Nusselt number enhancement of internal flow increases with increase Reynolds number for air, due to increase the cooling rate as increasing the outer Reynolds numbers.

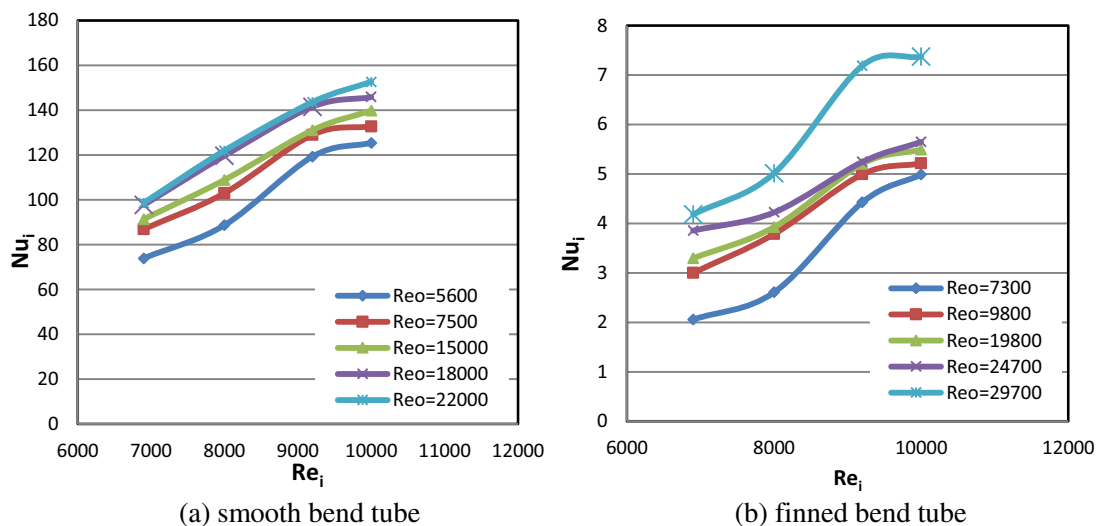


Figure 12. The water-side Nusselt number with different air side Reynolds number for water and $T_{in}=60^\circ\text{C}$ for smooth and finned tube

Figure 13 shows the effectiveness of heat exchanger for smooth and finned bend tube heat exchanger, where the effectiveness of finned heat exchanger was higher than the smooth and is close to one. While figure 14 shows the effectiveness of smooth bend tube heat exchanger for water and $\phi=0.05\%$ nanofluid, the effectiveness of nanofluid concentration was higher than the

water because the nanofluid with suspended nanoparticles increases the thermal conductivity of the mixture and a large energy exchange process resulting from the chaotic movement of nanoparticles.

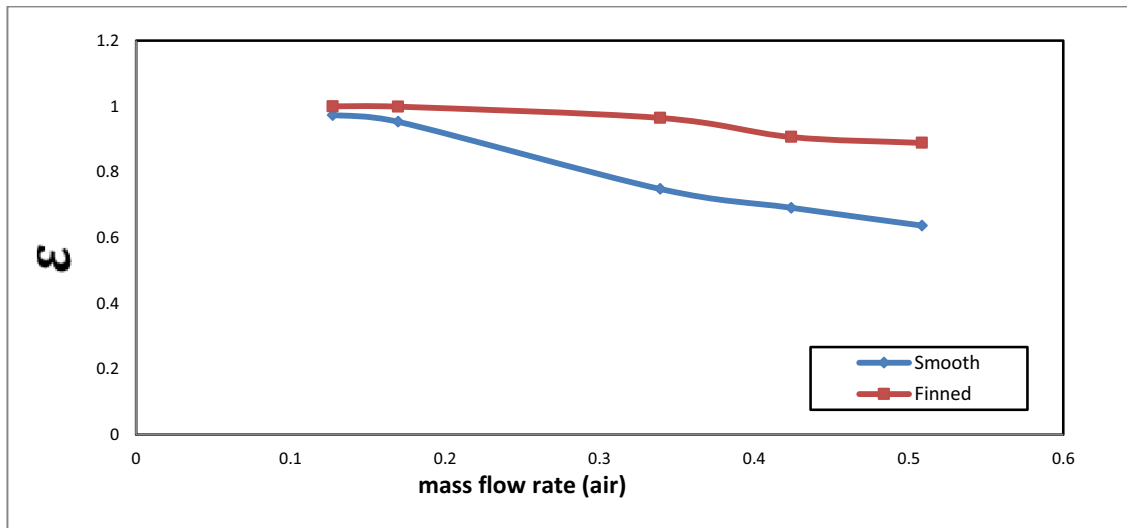


Figure 13. The effectiveness of smooth and finned bend tube heat exchanger for w turbulent flow $Q_{\text{water}}=6 \text{ L/m}$.

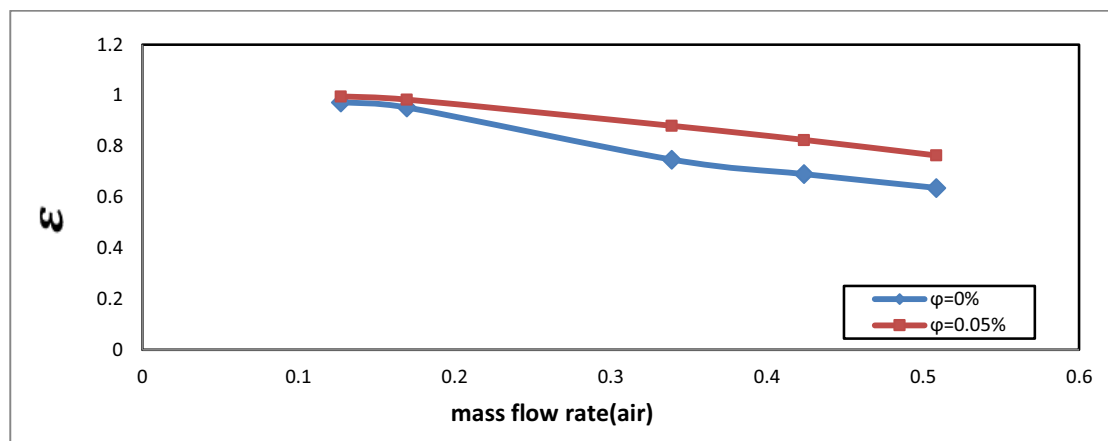


Figure 14. The effectiveness of smooth bend tube heat exchanger for $\phi=0\%$ and $\phi=0.05\%$ nanofluid turbulent flow.

4. Conclusions

The main conclusions of the present study are:

1. The water side Nusselt number increased with increasing nanoparticle concentration with maximum enhancement of (34.6 %) for smooth tube heat exchanger and about (44.1 %) for finned bend tube heat exchanger.
2. Maximum enhancement of the air side Nusselt number was (43%) for smooth tube heat exchanger and (54.9 %) for finned tube heat exchanger because the increasing of nanoparticle concentration.

3. The increasing of volume fraction of Al_2O_3 nanoparticle in water caused an increase in the inner friction factor by (13.9%) for smooth bend tube and (22%) for finned bend tube heat exchanger.
4. Using heat exchanger with fins enhanced the heat transfer rates as compared to that of the heat exchanger without fins, significantly at a constant nanoparticle concentration, and using nanofluids.

Nomenclatures

A_s	Surface area (m)
C_p	Specific heat ($J/kg.K$)
d_f	Outer Fins diameter (m)
d_i	Internal Tube diameter (m)
d_r	External Tube diameter (m)
d_h	Hydraulic diameter (m)
f	Friction factor
h	Convective heat transfer coefficient ($W/m^2.^\circ K$)
k	Thermal conductivity ($W/m.^\circ K$)
\dot{m}	Condensation rate (Kg/s)
N_f	Number of fins
P_f	Fin pitch (m)
Q	Heat transfer (W)
L	Tube length (m)
t_f	Fin thickness (m)
R	Radius of the elbow (m)
ϕ	Volume concentrations
T_{LMT}	Log mean temperature different ($^\circ C$).

Greek Symbols

μ : Dynamic viscosity ($kg/m.s$).
 ρ : Variable density (kg/m^3).
 ε : Heat exchanger effectiveness.

Subscript

av: average
s: surface
nf: nanofluid
f: base fluid.
p: nanoparticles.
o: outer side variables
i: inner side variables

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