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Study of Convective Heat Transfer Enhancement of Nanofluid inside Tube

دراسة تحسين إنتقال الحرارة بالحمل لموائع تحتوى على جزيئات فائقة الدقة داخل انبوب

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فى هذا البحث تم عمل دراسة معملية للسريان وانتقال الحرارة بالحمل داخل انبوب أفقى باستخدام موائع بمقياس النانو (خليط من أكاسيد ذرات متناهية الدقة مع الماء) وهى تعليق مساحيق للمواد المعدنية أو غير المعدنية في قاعدة وسائط يمكن أن تستخدم لزيادة معدل نقل الحرارة في تطبيقات مختلفه.تم استخدام أكاسيد الألومنيوم والنحاس مع الماء داخل أنبوب دائري مع فيض حرارى ثابت. تم الحصول على رقم نسلت لتركيزات الجسيمات فائقة الدقة مختلفة وقد لوحظ زيادة معامل انتقال الحرارة من خلال زيادة تركيز جزيئات فائقة الدقة. الزيادة في معامل انتقال الحرارة بسبب وجود جزيئات فائقة الدقة وهو أعلى بكثير من التوقعات من المائع الأصلى بدون اضافات . وقد لوحظ أن أكسيد النحاس أفضل من أكسيد الألومنيوم وذلك لأن موصلية النحاس وخواصه أفضل من الألومنيوم. تمت مقارنة بين النتائج المعملية ونتائج معملية من دراسات سابقة ووجد توافق الى حد ما. وكذلك العلاقة بين معامل التحسين الحرارى(معامل الاحتكاك ورقم نسلت) فوجد أن أحسن تركيز للمائع هو مابين ٠.٦ الى ٠.٨ % . وكان مدى رقم رينولدز من ٥٠٠ الى ٢٥٠٠ ونسبة التركيز لأكاسيد ذرات متناهية الدقة من ٠.٠ الى ٢.٠% والفيض الحرارى من ١.٢ الى ٧.٦ كيلووات لكل متر مربع من مساحة سطح الانبوب.

Abstract:

Nanofluids are suspensions of metallic or nonmetallic nano-powders in base liquid and can be employed to increase heat transfer rate in various applications. In this work laminar flow forced convection heat transfer of (Al_2O_3 or CuO)/water nanofluid inside a circular tube with constant wall heat flux is investigated experimentally. The Nusselt numbers of nanofluids are obtained for different nano-particle concentrations as well as various Reynolds number. Experimental results emphasize the enhancement of heat transfer due to the nano-particles presence in the fluid. Heat transfer coefficient increases by increasing the concentration of nano-particles in nanofluid. The increase in heat transfer coefficient due to presence of nano-particles is much higher than the prediction of single phase heat transfer correlation used with nanofluid properties. Considering the factors affecting the convective heat transfer coefficient of the nanofluid, a new convective heat transfer correlation for nanofluid under single-phase flows in tube is established. Comparison between the experimental data and the calculated results indicate that the correlation describes correctly the energy transport of the nanofluid. The range of operating parameter is Reynolds number from 500 to 2500 and particle volume concentrations up to 2.0%. Comparison between present and pervious results is carried out.

Keywords: Nanofluid, convective, heat transfer, correlation, friction factor, Thermal–hydraulic performance.

Nomenclatures

A :   Area, m²

Cp   Specific heat, J/kg. K

D   Diameter, **m**

h   Heat transfer coefficient, W/m² K

k   Thermal conductivity, W/m. K

L   Length, m

ṁ   Mass flow rate, kg/s

Nt   Number of thermocouple,-

P   Pressure, N/m²

q″   Heat flux, W/m²

Q   Heat transfer rate, W

T   Temperature, K

U   Mean Velocity, m/s

V   Applied voltage, Volt

v   Volume flow rate, m³/s

Greek Symbols
ϕ Volume fraction of nano-particles,-
μ Dynamic viscosity ,N.s/m²

ρ : Density ,kg/m³

Dimensionless Groups

$$Nu = \frac{h\,d}{k_{nf}}$$ Nu: Nusselt number,

$$Re = \frac{4\,m}{\pi\,d\,\mu_{nf}}$$ Re : Reynolds number,

$$Pr = \frac{Cp\,\mu}{k_{nf}}$$ Pr : Prandtl number,

η : Thermal–hydraulic performance

$\eta = (Nu/Nu_{PL})/(f/f_{PL})^{0.33}$

Subscripts
i Inlet
m : Base fluid
nf: Nanofluid
o : Outlet
P : Particle
w : Wall

1. INTRODUCTION

The conventional fluids, such as water, engine oil and ethylene glycol were normally used as heat transfer fluids. Although various techniques were applied to enhance the heat transfer, the low heat transfer performance of these conventional fluids obstructs the performance enhancement and the compactness of heat exchangers. The use of solid particles as an additive suspended into the base fluid is a technique for the heat transfer enhancement. Improving of the thermal conductivity is the key

idea to improve the heat transfer characteristics of conventional fluids. Since a solid metal has a larger thermal conductivity than the base fluid, suspending metallic solid fine particles into the base fluid is expected to improve the thermal conductivity of the base fluid. The long time stability and large efficient thermal conductivity; the innovative heat transfer fluids-suspended by nanometer-sized solid particles are called 'nanofluids'. These suspended nano-particles can change the transport and thermal properties of the base fluid. Nanofluids are suspensions of metallic or nonmetallic nano-powders in base liquid and can be employed to increase heat transfer rate in various applications.

With increasing heat transfer rate of the heat exchange equipment, the conventional process fluid with low thermal conductivity can no longer meet the requirements of high-intensity heat transfer. Low thermal property of heat transfer fluid is a primary limitation to the development of high compactness and effectiveness of heat exchangers. An effective way of improving the thermal conductivity of fluids is to suspend small solid particles in the fluids [1]. Traditionally, solid particles of micrometer or millimeter magnitudes were mixed in the base liquid. Although the solid additives may improve heat transfer coefficient, practical uses are limited because the micrometer and/or millimeter-sized particles settle rapidly, clog flow channels, erode pipelines and cause severe pressure drops. The concept of nanofluids refers to a new kind of heat transport fluids by suspending nanoscaled metallic or nonmetallic particles in base fluids. Some experimental investigations [2-5] have revealed that the nanofluids have remarkably higher thermal conductivities than those of conventional pure fluids and the nanofluids have great potential for heat transfer enhancement. The nanofluids

were more suits for practical application than the existing techniques for enhancing heat transfer by adding millimeter and/or micrometer-sized particles in fluids. It incurs little or no penalty in pressure drop because the nano-particles are so small that the nanofluid behaves like a pure fluid. To apply the nanofluid to practical heat transfer processes, more studies on its flow and heat transfer feature are needed. **Pak and Cho[6]** performed experiments on turbulent friction and heat transfer behavior of two kinds of the nanofluids. In their study, γ -Al$_2$O$_3$ with mean diameter of 13nm and TiO$_2$ with mean diameter of 27 nm were dispersed in water, and the experimental results showed that the suspended nano-particles increased convective heat transfer coefficient of the fluid. The Nusselt number of the nanofluids was found to increase with the increasing volume fraction as well as Reynolds number. **Lee and Choi[7]** applied the nanofluid as the coolant to a microchannel heat exchanger for

cooling crystal silicon mirrors used in high-intensity X-ray sources and pointed out that the nanofluid dramatically enhanced cooling rates compared with the conventional water-cooled and liquid-nitrogen-cooled microchannel heat exchangers. The cooling capability of 30MW·m^{-2} was achieved. It is expected that the heat transfer enhancement of the nanofluids may result from intensification of turbulence or eddy, suppression of the boundary layer as well as dispersion or back mixing of the suspended nano-particles, besides substantial augmentation of the thermal conductivity of the fluid. Therefore, the convective heat transfer coefficient of the nanofluids is a function of properties, dimension and volume fraction of suspended nano-particles, and the flow velocity. The conventional convective heat transfer correlation of the pure fluid is not applicable to the nanofluid.

Li et al. [8] prepared Cu/water nanofluids with nano-particle sizes

typically of 1-100 nm using the two-step method. Results showed that zeta potential and absorbency are important bases for selecting conditions for dispersing particles.

Furthermore, the observed sediment photographs and particle size distribution showed better dispersion behavior in the suspension with the addition of dispersant. The effect of pH on the stability of the copper suspension was critical.

Hwant et al. [9] prepared various nanofluids (nano-particle: MWCNT, fullerence, copper oxide, and silicon dioxide; base fluid: DI water, ethylene glycol, and oil) and examined their stability using UV-vis spectral analysis. They claimed that the stability of nanofluid is strongly affected by the characteristics of the suspended particle and base fluids such as the particle morphology, the chemical structure of the particles and base fluid. Furthermore, addition of surfactant can improve the stability of the suspensions. In general, methods such as change of pH value, addition of dispersant and ultrasonic vibration aim at changing the surface properties of suspended particles and suppressing formation of particle clusters to obtain stable suspensions. However, the addition of dispersants can affect the heat transfer performance of the nanofluids, especially at high temperature.

Fotukian and Nasr Esfahany [14] studied experimentally the convective heat transfer performance and pressure drop of very dilute (less than 0.24% volume)CuO/water nanofluid flowing through a circular tube. Measurements showed that addition of small amounts of nano-sized CuO particles to the base fluid increased heat transfer coefficients considerably. In average 25% increase in heat transfer coefficient was observed with 20% penalty in pressure drop. Enhancement ratio did not show significant variation with concentration of CuO in nanofluid in the range studied in this work. Flow resistance increased

significantly compared to base fluid even at very low concentrations of CuO. Measured heat transfer coefficients were compared with predictions obtained from different correlations proposed for heat transfer coefficients of nanofluids.

The aim of the present work is to study the convective heat transfer and friction factor of (CuO or Al_2O_3/water) as a nanofluid flow in a circular tube under a constant wall heat flux and different concentrations of nano-particles and pure water. This is made at different values of nanofluid mass flow rates and heat fluxes. The range of Reynolds number from 500 to 2500 is made. The obtained results are correlated compared with the available literature.

2. Experimental Test Loop

The process used to disperse nano-particles in liquid plays a critical role in nanofluid properties. In this study water based nanofluids of different oxide nano-particles including Al_2O_3 ,and CuO with 40-60

nm and 25 nm diameters respectively in different volume concentrations (0.0%− 2.0%) are employed to study the enhancement of convective heat transfer in circular tube with constant wall heat flux. After weighting the required powder, nano-particles are mixed with distilled water in a flask and then vibrated for 8-16 hour in mixer system. No sedimentation is observed for any concentration of nanofluid suspension after 24 hours.

A layout of this test loop is shown in Fig.(1). A test rig is designed and constructed inside the Fluid Mechanics Lab., Mansoura University to study the heat transfer performance and pressure drop of nanofluid flows inside a horizontal tube which is exposed to a uniform heat flux. The loop consists of a circulating pump (2), , test tube (1), water tank (3), heat exchanger (6), U- tube manometer (5), thermocouple (12), and flow meter (13).

The circulating pump of 125 W is used to circulate nanofluid (Al_2O_3+water or CuO +water) through the test loop. Nanofluid is heated in the test section by an electric heater and is passed to tank. Then the nanofluid is cooled in a heat exchanger.

Experiments are designed such that different factors affecting the flow can be studied. Nanofluid is used as a heated medium (of Prandtl number varies from 4 to 10 according to the average temperature and the percent of nanofluid. Mass flow rate is varied from about 10 to 60 kg/hr. This is corresponding to values of Reynolds number ranging from 500 to 2500.

The test section shown in figure (2) is consists of an electrically heated copper tube whose length 1000mm. The outside diameter of tube is 25 mm. The supplied power to the heating coil is changed by using step less variable output power supply. The voltage used during the experiments has the values of 20 to 200 volt. Throughout all experiments, the resistance of heating coil has a constant value of 15 Ω. The effect of impedance on total resistance is very small with compared to the electric resistance.
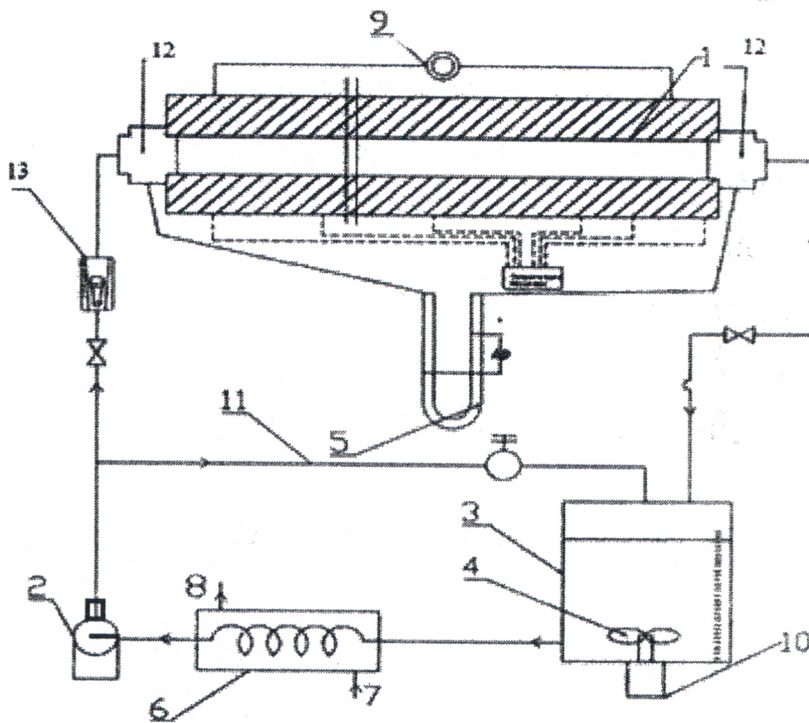
1. Tested tube.   2. Circulating pump.   3. Working fluid tank.
4. Paddle wheel.   5. U Tube manometer.   6. Heat exchanger.
7. Inlet city water. 8. Outlet city water.   9. Variac.
10. Motor   13: Flow meter.   12: Thermocouple

Fig. (1) Experimental test loop
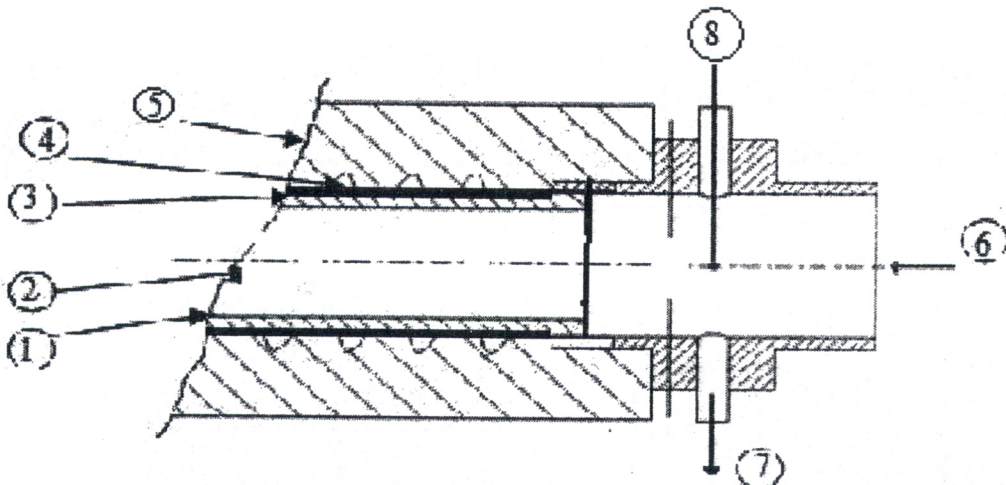
1: Tested tube   2.Nanofluid flow   3: Mica sheet

4: Electric heater coil 5: Insulation   6: Inlet working fluid

7: To manometer   8: Thermocouple

Fig. (2) Detail of the test tube
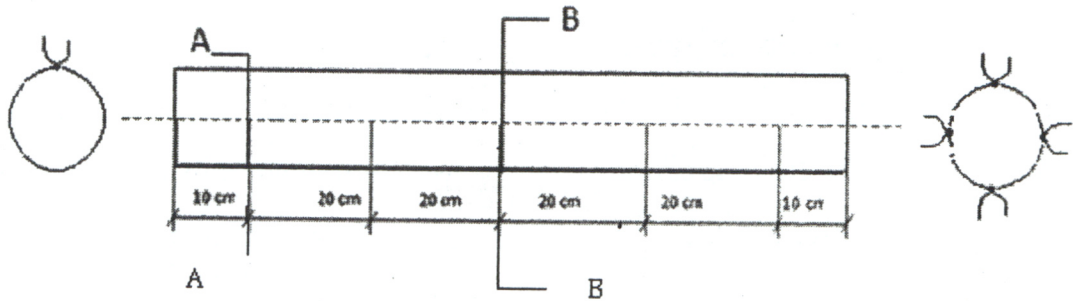
Section At A-A   Section at B-B

Fig.(3) Thermocouples distribution along the test section

The test tube is insulated using Glass wool insulating sheet with thickness of 50 mm with thermal conductivity 0.04 W/m K.

3.2 Experimental Procedure

Before starting a any run, the test loop is checked for leakage of water. The experimental procedure for each run is described in the following:

1.   Switch on the motor pump to circulate the nanofluid. Air is extracted from the U-tube manometer.

2.   Adjust the discharge valve to obtain the desired flow rate for circulating nanofluid. The circulating nanofluid is then heated up through the test tube by the heating coil.

3.   The hot nanofluid is passed through the heat exchanger to remove the heat absorbed by the nanofluid in the test tube using cooling water.

4. The nanofluid is circulated till steady state condition is reached. Before recording any data, each experiment is carried out for about 30 minutes to insure steady state condition.

5.   The following measurements are recorded for each experiment:-

i-   Hot nanofluid temperature at both inlet and outlet of the test tube

ii- Cooling water inlet and outlet temperatures.

iii- Pressure drop across the tube.

iv- Surface temperature of the tested tube at different locations along the tube length is shown in figure (3).

v- These measurements are reported and recorded for each run i.e. for different flow rates, heat flux, and concentrations of (AL_2O_3 or CuO) in water Surface temperature of the tested tube at different location along the tube length see in figure(2).

These measurements are reported and recorded for each run i.e. for every flow rate, heat flux, and concentration of (Al_2O_3 or CuO) in water.

The nanofluid flow rate is measured by rot meter. The pressure drop is measured by using U –tube manometer with color carbon tetrachloride as the measuring fluid.

2.3 Data Reduction

By measuring the temperature distribution along the tube, the nanofluid flow rate, the applied voltage, and resistance to take into account the heat loss from the outer surface of insulating tube, one can estimate the local and average Nusselt number by every value of Reynolds number. The applied power to the electric heating coil is calculated by;

$$Q = \frac{V^2}{R} \quad \dots \dots \dots \dots .(2.1)$$

Where V, Q, and R are the applied voltage, produced heat and electric resistance of the heating coil, respectively;

The net heat transferred to the nanofluid is;

$$Q_{net} = m \, C_p \, (T_o - T_i) \quad \dots \dots .(2.2)$$

Where T_o, T_i and m are the outlet and inlet temperature of fluid and mass flow rate is defined as;

$$m = \rho_{nf} \, v$$

$$Q_{loss} = Q - Q_{net} \quad \dots \dots .(2.3)$$

Where Q_{net} and Q_{loss} are the net heat transfer to nanofluid and heat loss from insulating layer, respectively. The net heat flux transferred to the nanofluid is;

$$q'' = \frac{Q_{net}}{A_s} \dots \dots \dots \dots (2.4)$$

$$A_s = \pi\, D\, L \quad \ldots \ldots \ldots (2.5)$$

Where A_s is the total surface area of the tube and D is the diameter of the tube. The mean temperature of the wall is calculated by the following relation;

$$T_w = \frac{1}{Nt} \sum_{i=1}^{Nt} T_{wi} \quad \ldots \ldots (2.6)$$

The bulk temperature of fluid inside the tube is estimated by the relation;

$$T_b = \frac{T_o + T_i}{2} \quad \ldots \ldots \ldots (2.7)$$

The average heat transfer coefficient, average Nusselt number and average Reynolds number are evaluated using the following relations;

$$h = \frac{q''}{(T_w - T_b)}, \quad h_{av} = \frac{\sum_{i=1}^{6} q_i''}{\sum_{i=1}^{6}(T_o - T_i)}$$

$$Nu = \frac{h_{av}\, D}{k_{nf}}, \quad Re = \frac{4\, m}{\pi\, D\, \mu_{nf}} \quad \ldots \ldots (2.8)$$

Where k_{nf}, m, μ_{nf} and h are the thermal conductivity of nanofluid, mass flow rate of nanofluid, kinematic viscosity of nanofluid and convective heat transfer coefficient.

One can assume that the nano-particles are well dispersed within the base-fluid, so the effective physical properties are described by classical formulas in references [13 and 14] the effective density and specific heat of nanofluid as;

$$\rho_{nf} = (1-\phi)\rho_m + \phi\rho_p \quad \ldots \ldots (2.9)$$

$$\rho_{nf}\, Cp_{nf} = (1-\phi)\rho_m Cp_m + \phi\, \rho_p Cp_p \quad (2.10)$$

The effective dynamic viscosity and thermal conductivity of nanofluids can be calculated using different existing formulas that have been obtained for two-phase mixtures. The following relations are the well-known Einstein's equation for a viscous fluid containing a dilute suspension of small, rigid, spherical particles.

$$\mu_{nf} = \mu_m (1 + 2.5\ \phi)$$

$$(2.11)$$

$$k_{nf} = k_m (1 + 7.4 \times \phi)$$

The relevant thermo-physical properties of the solid nano-particles (Al_2O_3 and CuO) used in the present study are;

Al_2O_3 : Cp_p =773 J/kg.°C, ρ_p =3880 kg/m^3 ,and k_p =36 W/m.°C.

CuO : ρ_p =6350 kg/m^3, k_p = 69 W/m.°C and Cp_p =535.6 J/kg.°C from [14]

Where, ϕ is a ratio of the volume of nano-particle to volume of the base fluid

2.4 Pressure drop

The measured pressure drop includes frictional, entrance and exit components. Therefore, the measured pressure drop (ΔP) for nanofluid flow inside the tested tube is then directly related to the frictional pressure drop. The friction factor (f) is obtained from the pressure drop measurements through the tested tube as;

$$f = \frac{2(\Delta P)d}{\rho_{nf} U^2 L} \quad \ldots \ldots \quad (2.12)$$

Where d, L, U and ρ_{nf} are the tested tube inner diameter and length, mean velocity and density for nanofluid. The mean velocity can be calculated by dividing the measured volume flow rate, measured by rotameter, by cross sectional area of the test tube.

3. RESULTS AND DISCUSSIONS

In this section, the experimental results are investigated. The effect of operating parameters on the coefficient of friction and the heat transfer coefficient and in turns Nusselt number is presented. The experiments for a tube with and without nanofluid are carried out with varying the values of heat source from 100 to 600 W. Nanofluid used as working fluids inside the tube. The range of operating parameters is Reynolds number from 500 to 2500, nanofluid concentration from 0.0 to 2.0%. Finally, the obtained experimental results are compared with the data obtained from available literature.

3.1   Validation of the Present Experimental Data

The present experimental data of the obtained average Nusselt number versus Reynolds number for water are presented and compared with the previous work obtained by **Fotukian and Nasr Esfahany**, 2010, as shown in Fig. (4). It is observed that, there is a good agreement between the present experimental results and the previous results there is a discrepancy of less than10.6%.
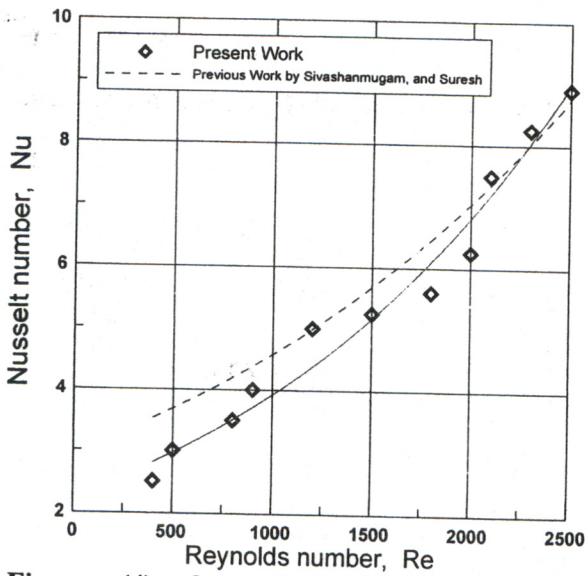
Figure (4) Comparison between average Nusselt number for pure water flow inside the tube versus Reynolds number.

Pressure drop measurements were performed for adiabatic condition to obtain the friction factor for water flow only inside the tube. Figure (5) shows the variation of friction factor (f) versus Reynolds number (Re). It is observed from the figure that, friction factor decreases with increasing Reynolds number for pure water flow inside a tube. The data obtained by the present experiments are agree enough with Bluisus equation cited by **Fotukian and Nasr Esfahany**, 2010, with a discrepancy of less than 4.6%
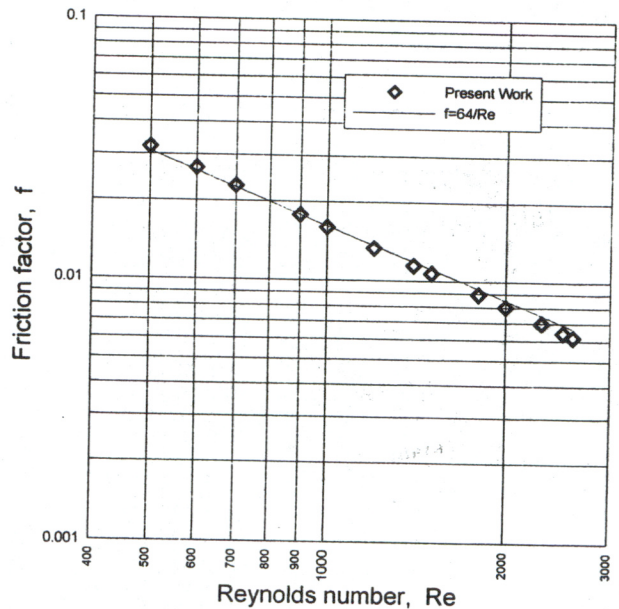

Figure (5) Comparison between average friction factor for water flow inside a tube versus Reynolds number
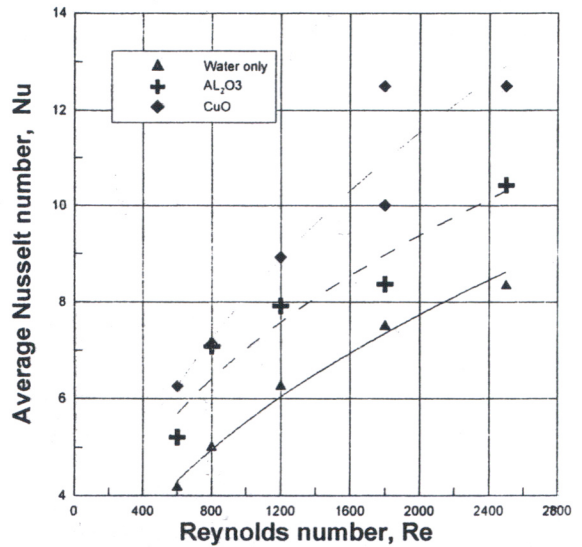
3.2 Performance of Heat Transfer

Nano-particles leads to increase thermal conductivity for nanofluid, therefore convection heat transfer coefficient increases. Also, other factors such as dispersion and chaotic movement of nano-particles, and particle migration, particle fluctuations and interactions may play role in heat transfer augmentation.

Figure (6) shows the variation of the average heat transfer coefficient versus Reynolds number. It is observed from figure that, average heat transfer coefficient increases with increasing Reynolds number and take the higher values for nanofluid compared with water only.
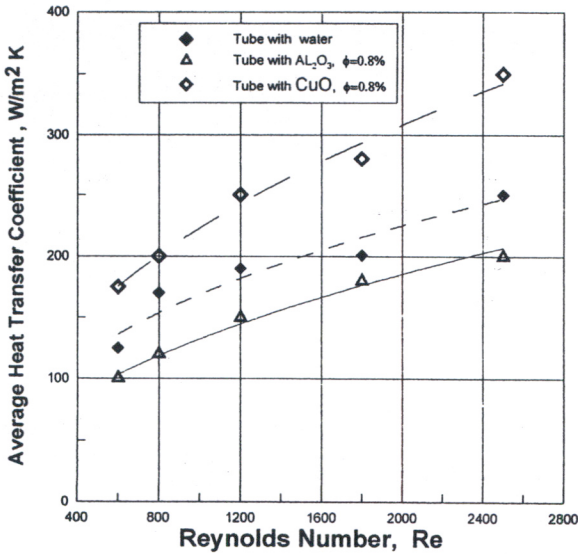
Fig. (6) Average convection heat transfer coefficient for nanofluid (concentration= 0.8 %) and water only flow inside tube

Fig. **(7)** Average Nusselt number for nanofluid (concentration= 0.8 %) and water only flow inside tube

Figure (7) shows the variation of the average Nusselt number versus Reynolds number. It is clear from the figure that, the average Nusselt number takes the same behavior as the average convection heat transfer coefficient and increases with increasing Reynolds number and the higher values were obtained when using the nanofluid compared with water only.

Figure (8) shows the variation of the average Nusselt number versus nanofluid concentrations. Average Nusselt number increases with increasing the concentration of nano-particles and takes the highest value at 0.8%, and then it decreases with increasing the concentration. Increasing the nano-particle concentration intensifies the interaction and collision of nano-particles. In other words, increasing the concentration of nano-particles intensifies the mechanisms responsible for reduced heat transfer. The decreases of Nusselt number is due to the

experiments are performed without cleaning the surface, allowing a nano-particle layer to build up on the surface, to see if the measurement changed at all in the surface of the tube.
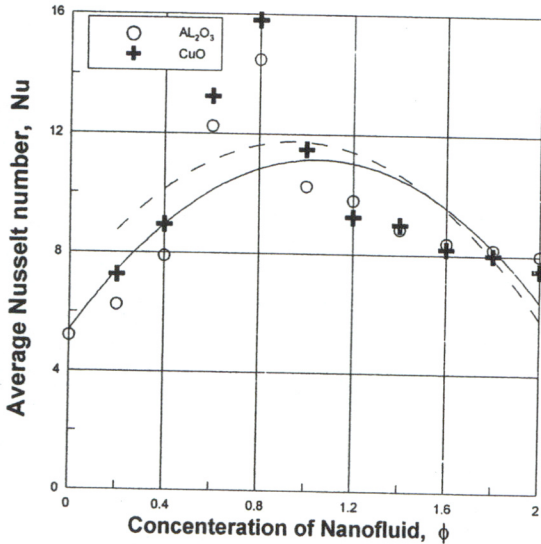

Fig. (8) Variation of average Nusselt number with concentration of nanofluid flows inside tube (at Re=1800).

3.3 Friction factor

Pressure drop experiments are performed for adiabatic condition to obtain the friction factor for the flow of nanofluid and pure water inside tube. Figure (9) shows the variation of friction factor (f) versus Reynolds number (Re) for both pure water and nanofluid flow inside tube. It is observed from the figure that, friction factor decreases with increasing Reynolds number for nanofluid (Al_2O_3+water) and nanofluid (CuO + water) flow inside tube. The increase in the friction can be explained by the swirling flow as a result of the secondary flows of the nano-particle motion inside tube.
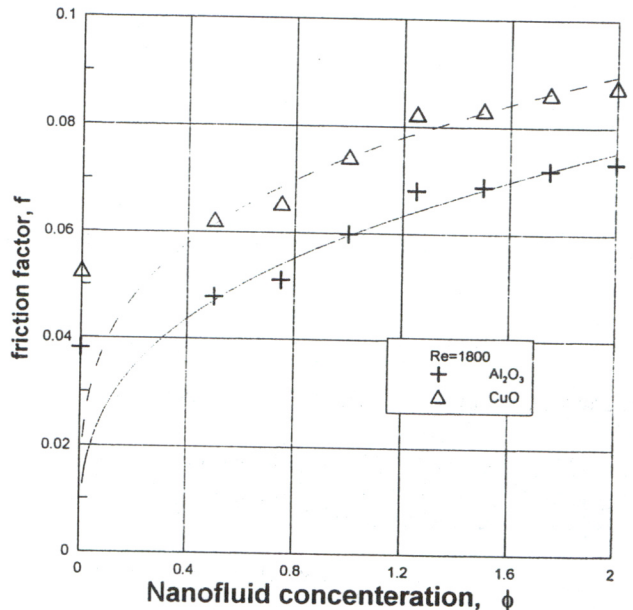

Fig. (9) Variation of average friction factor with concentration of nanofluid flows inside tube (at Re=1800)

Comparison between the values of friction factor for the nanofluid with concentration=0.8 % and pure water flow inside tube with nanofluid is shown also in Fig. (10). It is clear from figure that, friction factor for nanofluid was higher than that for water only. Nano-particles

suspended in the base fluid of nanofluid changes the transport properties than the base fluid and cause an increase for friction factor compared with water only.
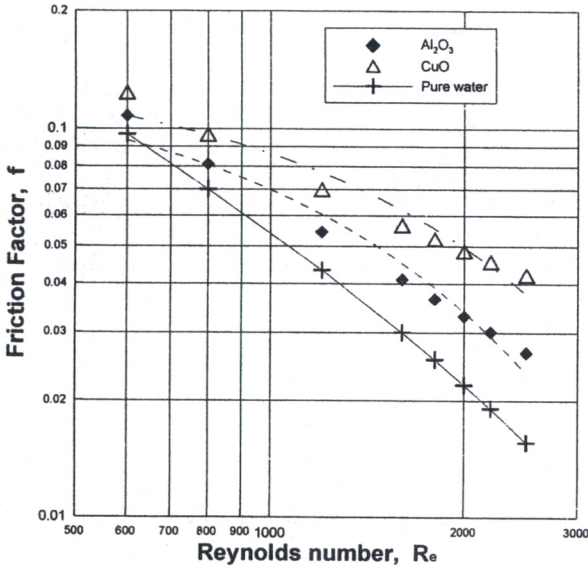

Fig. (10) Coefficient of friction versus Reynolds number for nanofluid (concentration=0.8%) and pure water flow inside tube
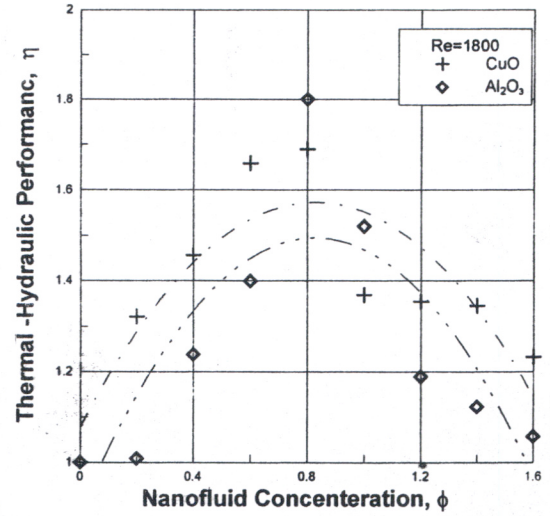

Fig. (11) Coefficient of enhancement versus Reynolds number for nanofluid (concentration=0.8%) and water flow inside tube.
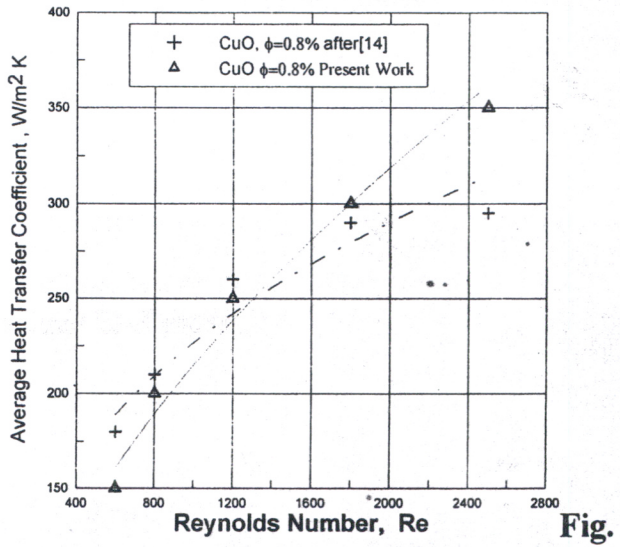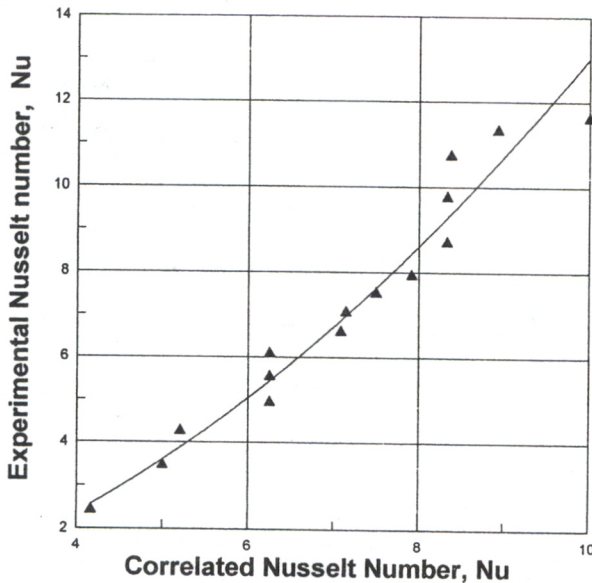

Fig. (12) Comparison with the previous work.

In the present study the thermal–hydraulic performance (η) of the nanofluid flow inside tube compared with water only. The thermal hydraulic performance is defined using the Nusselt numbers and friction factors for a tube as follows [8];

$$\eta = (Nu_{nf}/Nu_m)/(f_{nf}/f_m)^{0.33}. \qquad (2.13)$$

The calculated thermal hydraulic performances versus Reynolds number, for different setups are compared in Fig. (8). The figure shows that the highest values were obtained for nanofluid compared with water. The average value for the thermal hydraulic performance was 1.4 and 1.8 for water only and nanofluid at concentration 0.8% respectively.

The present experimental values of the obtained average heat transfer coefficient versus Reynolds number for 0.6% and 0.8% concentrations are presented and compared with the previous work by **Sivashanmugam, and Suresh, (2007-b)** at 0.7% concentration, as shown in Fig. (9). It is observed that, there is a good agreement between the present experimental results and previous results.

Working fluid and correlations are applicable to laminar region of Reynolds number (Re) between 500 and 2500. The empirical correlations from the experimental results of the nanofluid and water can be writing in term of Reynolds number (Re) and Prandtl number (Pr) as follows:

$$Nu = 0.125\, Re^{\,0.515}\, Pr^{\,0.33}\, (1+\phi)^{-0.415} \qquad (2.14)$$

As shown in Fig.(10) the present results the maximum error is about $\pm 5\%$

CONCLUSIONS

Forced convective heat transfer and friction factor characteristics of circular tube using nanofluid with $\phi = 0.0, 0.20,$

0.40, 0.60, 0.80, 1.0, 1.4, 1.6, 1.8 and 2.0 carried out the enhancement of heat transfer. Average Nusselt number and friction factor increases with increasing the nanofluid concentration compared with water in tube. The performance ratio for all the cases is greater than unity which means that the application of enhancement is reasonable from the point of total energy savings. The experimental results indicate that the single phase correlation is not able to predict heat transfer enhancement by nanofluid. Therefore, increased thermal conductivity is not the only mechanism Responsible for heat transfer enhancement. Addition of nano-particles to fluid changes the flow structure so that besides thermal conductivity increase, chaotic movement, dispersion and fluctuation of nano-particles especially near the tube wall leads to increase in the energy exchange rates and augments heat transfer rate between the fluid and the tube wall. Moreover, at high flow rates the dispersion

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