Experimental analysis of Heat Transfer and Flow in Two Types of Tubes by Using Oil – Based Nanofluids

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Abstract

This article presents an experimental study on enhancement of heat transfer and pressure drop of nanofluid flow. In this study the two methods using to enhancement of heat transfer and pressure drop, the first method by used the helically coiled tube instead of the straight tube, while second method by used the nanofluids instead of the base fluid (oil). The concentrations of nanofluid used are ranging from (4.27 – 31.88 wt%). Two types of nanoparticles used in this paper copper (Cu(50nm)) and zirconium oxide (ZrO_2 (80nm)) as well as the base fluid (oil).The effect of different parameters such as flow Reynolds number, nanofluid temperature, concentration and type of nanoparticle on heat transfer coefficient and pressure drop of the flow are studied. The obtained results show an increase in heat transfer coefficient of 34.65% for Cu + oil and 25.72% for ZrO_2 + oil at concentration of 5%vol compared with base fluid (oil). The heat transfer coefficient and pressure drop is increased by using nanofluids (Cu, ZrO_2 – oil) instead of the base fluid (oil). In addition the results indicated that by using helically coiled tube instead of the straight tube, the heat transfer performance is improved as well as the pressure drop enhancement due to the curvature of the tube. Furthermore, the first method indicated that used helical tube instead of the straight tube is a more effective way to enhance convective heat transfer coefficient compared with the second method which is using nanofluid instead of the base fluid (oil). The highest heat transfer coefficient ratios are obtained for the helical tube. For instance, a maximum increase of 27.77% (Cu+ Oil) and 19.23% (ZrO_2+ Oil) in Nusselt number ratio for a range of Reynolds numbers between ٢0 and 200 is obtained for the straight tube, while, the increase of 32.5% (Cu+ Oil) and 24.13% (ZrO_2+ Oil) is obtained for the helical tube, respectively at the same Reynolds numbers' range. This paper decided that the nanofluid behaviors are close to the typical Newtonian fluids through the relationship between viscosity and shear rate. Moreover to performance index are used to present the corresponding flow and heat transfer technique.

Keywords: Nanofluids, Straight tube, Spiral tube, Convective heat transfer, Pressure drop**.**

الخلاصة

تقدّمُ هذه المقالةِ دراسةَ تجريبيةَ على تحسينِ نقلِ الحرارةِ وهبوطِ الضغطِ للموائع الفائقة الدقةحيث في هذه الدراسةِ توجد طريقتانِ عَلى تحسينَ نقلِ الحرارةِ وهبوطِ الضغطِ, الطريقة الأولى باستعمالِ انبوب بشكل حلزوني بدلاً مِنْ الأنبوب المستقيم، بينما الطريقة الثانية استخدام الموائع النانوية بدلا من مائع الأساس الزيت إنّ تراكيز الموائع النانوية المستعملة تَتراوحُ مِنْ(4.27 -31.88 wt%). أثنان مِنْ أنواعِ الجزئيات النانوية استعملت في هذه الدراسة وهي النحاسِ ((Cu(50nm) وأوكسيد الزركونيوم ((ZrO_2 (80nm) بالإضافة إلى مائع الأساس (زيت).أنّ تأثيرَ العوامل المختلفةِ مثل عدد رينولدز للتدفقِ , درجة حرارةِ المائع النانوية ونوع وتركيز الجزئيات النانوية على معاملِ نقلِ الحرارةِ وهبوطِ ضغطِ التدفقِ قد درسه. وأوضحت الدراسة الزيادةً في معاملِ انتقال الحرارةِ وكانت كالتالي (Cu + oil) 34.65%,(Cu + oil) 25.72% (ZrO_2 + oil) عند تركيزِ ٥ % بمقَارنَة مع مائع الأساس (زيت). إنّ معاملَ انتقال الحرارةَ وهبوطَ الضغطِ يزدادُ باستعمال الموائع النانوية(Cu, ZrO_2 – oil) بدلاً مِنْ السائلِ الأساس (زيت). علاوة على ذلك اشارت النتائج ان استعمالِ انبوب بشكل حلزوني بدلاً مِنْ الأنبوب المستقيم يؤدي الى تحسين نقل الحرارة بالإضافة الى تحسين انحدار الضغط بسب التقوس بالأنبوب . كما ان الطريقةُ الأولى اوضحت بأنّ استعمال الأنبوب الحلزونيَ بدلاً مِنْ الأنبوب المستقيمِ هي طريقة أكثر فعّالية لتَحسين معاملِ انتقال الحرارةِ الحملي مقَارنَة بالطريقةِ الثانيةِ التي تَستعملُ الموائع النانوية بدلاً مِنْ مائعِ الأساسِ

(زيت). على سبيل المثال , اقصى زيادة كانت الى(Cu+ Oil)21.33%,(ZrO2+ Oil)16.86%, في معاملِ انتقال الحرارةِ ولمدى عدد رينولدز(٢٠ –٢٠٠) وللأنبوب المستقيمِ، بينما الزيادة ٤٠,٥٦% (Cu+ Oil), ٢٤,٣٦%(ZrO2+ Oil)للأنبوب الحلزونيِ، ولنفس مدى أعدادِ رينولدز . قرّرتْ هذه الدراسة بأنّ سلوك الموائع النانوية هي موائع نيوتونيةِ من خلال العلاقةِ بين معدل القصَّ واللزوجةَ للموائع النانوية علاوة على ذلك إلى معامل الأداءِ يُستَعملُ لإظهار الجريان وتقنيةَ انتقال الحرارة.

الكلمات المفتاحية: المواد النانوية، أنبوب مستقيم، أنبوب حلزوني، انتقال حراري للحرارة، انخفاض الضغط

Nomenclature

Symbol	Quantity	units
$\bar{\bar{q}}$	Heat flux	W/m^2
CHF	Constant heat flux	—
Cp	Specific heat	J/kg k
ΔP	Pressure drop	pa
D	Tube diameter	m
d	Diameter of the coil	m
$\bar{\bar{h}}$	Mean heat transfer coefficient	W/m^2 K
L	Length of the tube	m
$\dot{m}$	Mass flow rate	kg/s
Nu	Nusselt number	—
P	Tube cross section perimeter	m
Pr	Prandtl number	—
Re	Reynolds number	—
T	Temperature	°C
X	Distance from entrance of tube	m
	Greek Symbol	
μ_n	Dynamic viscosity Nano fluid	$N.s/m^2$
η	Performance Index	—
Φ	Volume concentration	—
	Subscripts	
bf	Base fluid (base oil)	—
nf	Nanofluid	—
m	Mean fluid bulk temperature	—
ST	Straight Tube	—

1. Introduction

Thermal load removal is a great concern in many industries including power plants, production and chemical processes, transportation and electronics. In order to meet the ever increasing need for cooling the high heat flux surfaces, different enhanced heat transfer techniques have been suggested. Most of these methods are based on structure variation, vibration of heated surface, injection or suction of fluid and applying electrical or magnetic fields which are well documented in literature[Bergles,1973; Thome, 2006]. However, applying these enhanced heat transfer techniques is nolonger feasible for cooling requirement of future generation of microelectronic systems, since the ywould result in undesirable cooling systemsize and low efficiency of heat exchangers. To obviate this problem, nano fluids with enhanced thermo-fluidic properties have been proposedsince the past decade. Nanofluid is a uniform dispersion of nanometersized particles inside a liquid which was first pioneered by [Choi,1995]. Excellent characteristics of nanofluids such as enhanced thermal conductivity, long time stability and little penalty in pressure drop increasing and tube wall abrasion have motivated many researchers to study on thermal and flow behavior of nanofluids. These studies are mainly focused on effective thermal conductivity, phase change behavior, tribological properties, flow and convective heat transfer of nanofluids. A wide range of experimental and theoretical studies has been performed on effective thermal conductivity of nanofluids within past decade. In these studies, the effect of different parameters such as particle concentration, particle size, mixture temperature and Brownian motion on thermal conductivity of nanofluids was investigated. The results showed an increase in thermal conductivity of nanofluid with the increase of nanoparticles concentration and mixture temperature [Chandrasekar *et al*., 2010;Yu *et al*., 2010; Mintsa *et al*., 2009 and Vajjha and Das, 2009]. Also it was shown that larger enhancement in thermal conductivity is attributed to the finer particle size [Karthikeyan *et al*., 2008].Due to the enhanced thermal properties of nanofluids, majority of recent studies are focused on convective heat transfer behavior of nanofluids in laminar and turbulent flows. Almost all of these works report the enhancement of nanofluid convective heat transfer. Several numerical and experimental studies have considered nanofluid convective heat transfer in turbulent flow [Fotukian and Nasr , 2010; Pak and Cho, 1998; Williams *et al*., 2008 and He *et al*., 2007]. Some other studies have investigated the convective heat transfer of nanofluids in laminar flow. Wen and Ding [Wen and Ding, 2004]have studied Al_2O_3/water nanofluid heat transfer in laminar flow under constant wall heat flux and reported an increase in nanofluid heat transfer coefficient with the increase in Reynolds number and nanoparticles concentration particularlyat the entrance region. Convective heat transfer of CNT nanofluids in laminar regime with a constant heat flux wall boundary condition was investigated by [Ding *et al*., 2006]. They observed a maximum enhancement of 350% in convective heat transfer coefficient of 0.5 wt. % CNT/water nanofluid at Re=800.In addition, a few works have studied friction factor characteristics of nanofluids flow besides the convective heat transfer. Xuan and Li[Xuan and Li, 2003] investigated the flow and convective heat transfer characteristics for Cu/water nanofluids inside a straight tube with a constant heat flux at the wall, experimentally. Results showed that nanofluids give substantial enhancement of heat transfer rate compared to pure water. They also claimed that the friction factor for the nanofluids at low volume fraction did not produce extra penalty in pumping power. In laminar flow, [Chandrasekar *et al*., 2010]investigated the fully developed flow convective heat transfer and friction factor characteristics of Al_2O_3/water nanofluid flowing through a uniformly heated horizontal tube with and without wire coil inserts. They concluded that for the nanofluid with a volume concentration of 0.1%, the Nusselt number increased up to 12.24% compared to that of distilled water. However, the friction factors of the same nanofluid were almost equal to those of water under the same Reynolds numbers. Another technique which is employed for heat transfer augmentation is using helical tubes instead of straight tubes. Due to their compact structure and high heat transfer coefficient, helical tubes have been introduced as one of the passive heat transfer enhancement techniques and are widely used in various industrial applications such as heat recovery processes, air conditioning and refrigeration systems, chemical reactors, food and dairy processes. Single-phase heat transfer characteristics in the helical tubes have been widely studied by researchers both experimentally and theoretically. The heat transfer rates between a helically coiled heat exchanger and a straight tube heat exchanger were compared by [Prabhanjan *et al*., 2002].

Results showed that the geometry of the heat exchanger and the temperature of the water bath surrounding the heat exchanger affected the heat transfer coefficient.[Xin *et al*., 1997] studied the effects of coil geometries and the flow rates of air and water on pressure drop in both annular vertical and horizontal helical pipes. The test sections with three different diameters of inner and outer tubes were tested. The results showed that the transition from laminar to turbulent flow covers a wide Reynolds number range. On the basis of the experimental data, a correlation of the friction factor was developed. The maximum deviation of the friction factor from experiments and the correlation was found to be 15%.Choi and colleagues [Choi *et al*., 2008] used spherical and rod shape Al_20_3 and spherical AIN nanoparticles dispersed in transformer oil to make nanofluids. All three types of nanofluids showed a small enhancement in the heat transfer coefficient at a Reynolds number range of 100 to 500. A maximum of 20% increase was observed for the AIN/transformer oil based nanoparticles at a volume fraction of 0.5%. The object of this article, examine the various factors that could potentially impact the enhancement of heat transfer coefficient of oil – based nanofluid including nanoparticle size, volume fraction, Reynolds number and nanofluid temperature.

2. Nanofluid preparation

The studied nanofluid is formed by cupper (Cu (50nm)) and zirconium oxide(ZrO_2) (80nm) nanoparticles and the two – step method was used to prepare nanofluids. Nanofluid samples were prepared by dispersing pre – weighed quantities of dry Particles in base fluid (oil). In a typical procedure, the pH of each nanofluids a mixture was measured (pH = 4.3 – 4.5).The mixtures were then subjected to ultrasonic mixing [100 kHz, 300 W at 25 – 30C^0, Toshiba, England] for one hour to break up any particle aggregates. The nanofluid of this study was included 20W50 engine oil (Castrol Company) (GTX) and nanoparticles (US Research Nano materials, Inc). Their properties are shown in table 1, 2 and 3 respectively.

Table1: The properties of engine oil [US Research]Table2: The properties of Nano powder Cu

Name	SAE 20W50
Density at 15.6°C (kg/m^3)	893
Viscosity at 100°C (cSt)	17
Viscosity index	115
Total alkalinity (mgKOH/g)	6
Minimum ignition point	214
Minimum Pour point (°C)	– 24

Cupper Nano powder Cu, 99%, 50 nm	
Purity	>99%
crystal phases	Monoclinic
APS	50nm
SSA	20– 40 m^2/g
Color	Red
Morphology	Nearly spherical
True density	8.893 g/cm^3

Table3: The properties of Nano powder ZrO_2

Zirconium oxide Nano powder ZrO_2, 99%, 80 nm	
Purity	>99%
crystal phases	Monoclinic
APS	80nm
SSA	20– 40 m^2/g
Color	White
Morphology	spherical
True density	5.89 g/cm^3

An image nanofluids containing (Cu (50 nm)) and oxide zirconium (ZrO_2) (80 nm) is display in Fig .1.Nanofluids with different weight percent (Φ= 4.29, 8.27, 21.64, and 31.99 wt %).

Fig.1 Show nanofluids for Cu+Oil, ZrO2+Oil and Oil

3. Experimental setup

The experimental set up is divided for two experimental. The experimental loop was designed for convective heat transfer in laminar flow domain. The horizontal test section was Pyrex tube with an inner diameter (ID) of 4mm and length of 2.5m. The tube surface is electrically heated by coil made from tungsten matter connecting to an AC power supply to generate heat flux. To measure the wall temperature of the Pyrex tube and the bulk mean temperature of the fluids at the inlet and out let of the tube eight thermocouples (T – types) are soldered at place along the test section and two thermocouple (T – types) are inserted at the inlet and out let of the test section. The pressure drop is measured by two gauge pressure. To preserve a constant temperature at the inlet of the test section the heated fluid returns to reservoir tank passing spiral Pyrex heat exchanger to a cooler fluid. The flow meter was positioned just after the pump discharge.

The second experimental set up consist of the heat exchanger is made of Pyrex (soft glass) and test section has the helically tube10 mm inner, 12 mm outer diameters, 34 turns and length of coil is 750 mm shell has 70 mm inner, 80 mm outer diameters and 1000 mm length. The set – up has helically coiled tube side loop and shell side loop. The helically coiled tube side loop handles two types of nanofluids used copper – oil, and zirconium oxide. Shell side loop handles hot water. Shell side loop consist of storage vessel of 20 L capacity with heater of 4.5 Kw, control valve, pump and thermostat. The helically coiled tube side loop consists of test section containing shell and spiral tube, pump [Bosch 1046 – AE], needle valve , flow meter (Dwyer series MMA mini – master flow meter) having a range of (0.01 – 3.5 LPM), cooling unit and storage vessel of 10 L capacity. The temperature of hot water in the shell side storage vessel is maintained by thermostat. Four T – type thermocouples of 0.15 ^{0}C accuracy are used to measure inlet and outlet temperatures of shell and tube side**.** Eight T– type thermocouple were placed at equal interval on the outer surface of coiled tube to measure the wall temperatures. The thermocouples are placed and glued with epoxy to avoid leakage. The pressure gauges are placed across the helical tube to measure the pressure drop. The shell is insulated with Acrylic resin coated fiberglass sleeping to minimize the heat loss from shell to the ambient. Distilled water was tested prior to nanofluid after completion of construction and calibration of the flow loop, testing of the loop's functionality for measuring Nusselt number and viscous pressure loss. The numbers of the total tests were 200. Hot water and cold water were passed to shell side and tube side to check the leakages in the circuit and tested the thermocouples and thermostat. Hot water was circulated to the shell side. The nanofluids (Cu + Oil and ZrO_2+Oil) at (Φ= 4.27, 8.24, 21.57, and 31.88wt %). weight concentration was circulated through the tube side. Shell side pump is switched on when water reaching to a prescribed temperature. This done by thermostat attached in distilled water storage system. The flow configuration was made parallel flow condition. The corresponding temperatures were recorded after attaining the steady state. The same procedure was done for nanofluid at 4.27wt % weight concentration. The flow configuration is changed from parallel to counter flow. The same procedure is followed and the temperatures are recorded. Flow rate on shell side (2.25 LPM) and coiled tube pitch are maintained constant throughout the test. The flow rate on tube side is varied. The flow in tube side is in the range of 0.75 – 2LPM. A photograph and schematic diagram of the first and second experimental rig are shown Figs. (2), (3) for convective heat transfer and flow characteristics of the nanofluid. As well as the test section for first and second experiment set up as shown in Figs. (4), (5).

Fig .2.The experimental system of the convective heat transfer and flow characteristics For nanofluids

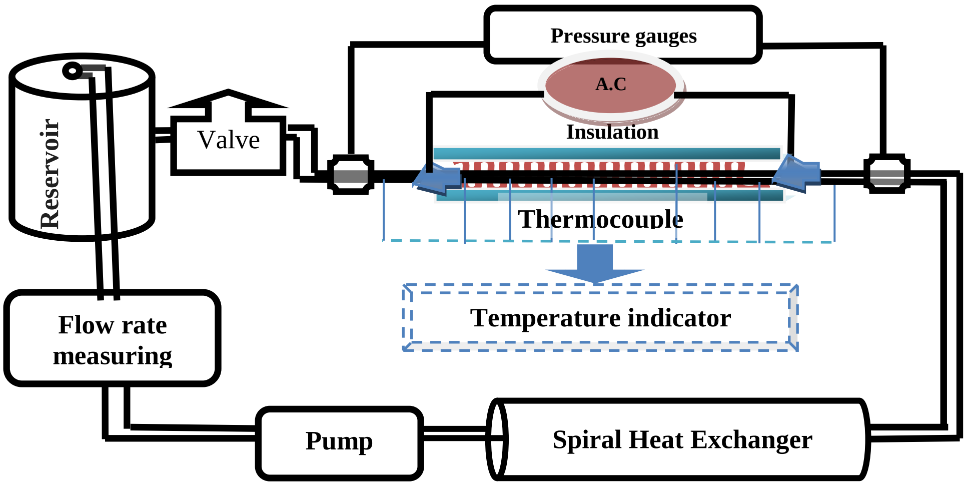

Fig .3.Schematic of heat transfer test rig.

Fig (4).The test section for first experiment set up

Fig (5).The test section for second experiment set up

4. Measurement of Thermal Properties Nanofluid

All physical properties of the nanofluids (Cu, ZrO_2 + oil) and oil needed to calculate the pressure drop and the convective heat transfer are measured. The dynamic viscosity (μ) is measured using brook field digital viscometer model DV – E. The thermal conductivity, specific heat and density are measured by Hot Disk Thermal Constants Analyzer(6.1), specific heat apparatus (ESD – 201) as well as the measurement of density was carried out by weighing a sample and volume. The thermal properties of nanofluidsdynamic viscosity (μ), thermal conductivity, specific heat and density are measured with different weight concentrations at (Φ= 4.27, 8.24,21.57, and 31.88wt %). The empirical relation used in this study to comparison with the practical measurements for nanofluid properties. The thermo physical properties of nanofluid were calculated at the average bulk temperature of the nanofluid by the following equations. The figures (6–9) reveal density, viscosity, specific heat,and thermal conductivity for the two types of nanofluid(Cu+ oil) and (ZrO_2 +oil).

The volume fraction (Φ) of the nanoparticles is defined by.

$$\varphi = \frac{v_p}{v_p + v_f} = m\frac{\pi}{6}d_p^{-3} \qquad (1)$$

Density[21]

$$\rho_{nf} = \Phi\,\rho_s + (1-\Phi)\,\rho_{oil} \qquad (2)$$

Viscosity [Das et al., 2007]

$$\mu_{nf} = (1 + 2.5\Phi)\,\mu_{oil} \qquad (3)$$

Specific heat [Das *et al.*, 2007]

$$Cp_{nf}\,\rho_{nf} = \Phi(\rho_s\,Cp_s) + (1-\Phi)(\rho_{oil}Cp_{oil}) \qquad (4)$$

Recently [Chandrasekar *et al.*, 2008] presented an effective thermal conductivity model (Eq.5)

$$\frac{k_{nf}}{k_{oil}} = \left[\frac{Cp_{nf}}{Cp_{oil}}\right]^{-0.023}\left[\frac{\rho_{nf}}{\rho_{oil}}\right]^{1.358}\left[\frac{\mu_{oil}}{\mu_{nf}}\right]^{0.126} \qquad (5)$$

To evaluate the local convective heat transfer coefficient, the following equation is used,.

$$\bar{\bar{q}} = h(T_S - Tm) \qquad (6)$$

Where :$\bar{\bar{q}}$ is the heat flux; h, Ts and Tm are the local heat transfer coefficient, the wall temperature, and the bulk fluid temperature at the distance of x from the test tube inlet, respectively.

Tm (x) is calculated by the following equation,

$$\mathbf{Tm\ (x) = T_i + \frac{\bar{\bar{q}}\,P}{\dot{m}C_P}x} \quad (7)$$

Where: T_i, p, $\dot{m}$ and Cp are the fluid temperature at the inlet of test section, the surface perimeter, the mass flow rate and the heat capacity, respectively.
Finally, the following expressions are used to calculate the mean heat transfer coefficient and Nusselt number,

$$\bar{\mathbf{h}} = \frac{\mathbf{1}}{\mathbf{L}}\int_0^L \mathbf{h(x)dx} \quad (8)$$

$$\bar{N}\mathbf{u}_{nf} = \frac{\mathbf{hD}}{\mathbf{k}} \quad (9)$$

5. Results and discussion

In order to verify the accuracy and the reliability of the experimental system, the heat transfer coefficients are experimentally measured using base oil as the working fluid before obtaining those of oil based Cu and ZrO_2nanofluids

Figures.(10) exhibit the change in temperature of the nanofluids with uniform heat flux along the tube, for the nanofluids at different Rayleigh numbers, Reynolds numbers and volume fractions. The temperature of the nanofluids was calculated from equation (7), after the measurement of the inlet temperature to the nanofluid in the test section. The temperature of the nanofluids increased with the length of the tube and linear relationship between nanofluid temperature and dimensionless axial distance. Figure .(11) depict the variation of the internal surface temperature with uniform heat flux along the tube with a dimensionless axial distance (Z^*) using of nanofluids at different Rayleigh numbers, and volume fractions . The temperature increases along the tube heated by uniform heat flux (600 W/m^2) . The temperatures difference in the tube surface between the maximum and minimum value at high concentration is smaller than temperatures difference at low concentration**.** Addition nanoparticles of Cu (50nm), and ZrO2 (80 nm) to oil does not effect on the progressive shape to temperature distribution. Experimentally measured Nusselt numbers are compared against the values obtained by the theoretical solution presented in [Wu *et al.*, 2007].Fig.12shows the variation of theoretical values with experimental values for average Nusselt number. As it is seen from this figure, the deviation of the experimental data from the theoretical one is within −13% and +7%.Also, the measured pressure drop is compared with the pressure drop obtained from the following theoretical equation.

$$\Delta p = 32\frac{u_m \mu L}{D_{tube}^2} \quad (10)$$

In which, μ is measured at the average of inlet and outlet temperatures. Fig. 13shows the variations of the theoretical values for pressure drop along the test section versus measured pressure drop. The experiments are done at the same condition explained in the heat transfer validation. As it can be seen from Fig. 13, the deviation of the experimental data from the theoretical one is within −8% and +11%.Having established confidence in the experimental system, the heat transfer and pressure drop characteristics of oil – based Cu, ZrO_2nanofluids flowing inside the straight and helical tube are investigated experimentally for laminar flow conditions under constant heat flux. Note that in the following results, heat transfer and pressure drop data for each two specific cases are not achieved under exactly the same Reynolds numbers. This is because the viscosity of oil based nanofluid is so dependent on fluid temperature and particle volume fraction.

Figs. (14,15, 16 and 17). exhibit the variation of mean Nusselt number versus Reynolds number for the flow of base oil and the nanofluids (Cu + oil ,ZrO_2+ oil) with different nanoparticle volume concentrations inside the straight tube and the helical tube. The addition nanoparticles of copper and zirconium oxide to the base oil has led to an increase in mean Nusselt number for flow inside both the straight tube and the helicaltube. In general the addition of nanoparticles enhances the thermal conductivity of the base fluid. This enhancement in thermal conductivity would increase the convective heat transfer coefficient. As well as, chaotic movement of the nanoparticles in flow will disturb the thermal boundary layer formation on the tube wall surface. As a result of this disturbance, the development of the thermal boundary layer is delayed. Since, higher Nusselt number of nanofluid flow in a tube are obtained at the thermal entrance region, the delay in thermal boundary layer formation resulted by adding nanoparticles will increase the mean Nusselt number. At higher volume concentrations of the nanofluids, both the thermal conductivity of the Cu, ZrO_2 – base oil mixture and the disturbance effect of the nanoparticles will increase. Therefore, as it is expected, nanofluids with higher volume concentrations have generally higher mean Nusselt number.
(Φ= 4.27, 8.24,21.57, and 31.88wt %).

Figs. 18 and 19reveal the ratios of mean Nusselt number of nanofluids with 31.99 wt %to that of base oil as a function of Reynolds number for straight and helical tubes. It is observed that nanofluids (Cu + oil, ZrO_2+ oil) have better heat transfer performance when they flow inside helical tube instead of flowing inside the straight tube. The results clearly show that at nearly the same range of Reynolds numbers, the highest Nusselt number ratios are obtained for the helical tube. For instance, a maximum increase of 27.77% (Cu+ Oil) and 19.23% (ZrO_2+ Oil) in Nusselt number ratio for a range of Reynolds numbers between 20 and 200 is obtained for the straight tube, while, the increase of 32.5% (Cu+ Oil) and 24.13% (ZrO_2+ Oil) is obtained for the helical tube, respectively at the same Reynolds numbers' range. This phenomenon could be due to the intensified chaotic motion of the nanoparticles inside helical tube. Since, the shear rate near the wall of the helical tube is high, the non-uniformity of the shear rate across the cross section will increase and therefore, the particles are more motivated by the variation of the shear rate. The latter point suggests that applying nanofluids instead of the base fluid would enhance the convective heat transfer more effectively in the helical tube.

Figs.20 and 21depicted the variation of mean Nusslet number versus Reynolds number for straight and helical tubes. This comparison is made for base oil and 31.88wt %nanofluids (Cu + oil ,ZrO_2+ oil) flow at constant heat flux of 2500 W/m^2, in order to have a close examination in the behavior of helical tube. Obtained results show that helical tube has increased heat transfer rates significantly compared to those of straight tube. The possible mechanisms which are responsible for heat transfer enhancement in helical tube could be attributed to the change in temperature and velocity distributions along the tube cross section. As fluid flows within a helical tube, it experiences a centrifugal is generated. A secondary flow induced by the centrifugeal force has significant ability to enhance the heat transfer rate by increasing the velocity gradient across the section of the tube. As a result, heat is transferred more rapidly in the helical tube.

The measured pressure drop for the flow of base oil and Cu,ZrO_2 + base oil nanofluids with different volume fractions as a function of Reynolds number along the straight tube and the helical tube is given in Figs. (22, 23, 24 and 25), respectively. The results exhibit that there is a noticeable increase in pressure drop of nanofluidwith4.27wt% nanoparticle concentration compared to the oil value. This enhancement trend tends to continue for the nanofluids with higher volume fractions. This is because of the fact that suspending solid particles in a fluid generally increases dynamic viscosity relative to the base fluid. Since, the viscosity is in direct relation with pressure drop, the higher value of viscosity leads to increased amount of pressure drop. Another reason which can be responsible for pressure drop increasing of nanofluids may be attributed to the chaotic motion and migration of nanoparticles in the base fluid. This reason explains why at higher flow rates, the rate of increase in pressure drop has gone up while at very low Reynolds numbers, the pressure drops of base oil and nanofluids are almost the same. However, the rate of pressure drop increasing achieved for nanofluids with concentration ranges from 4.27wt% to 31.88wt %is less than that obtained when nanofluid with 4.27wt% is used instead of oil. One reason for this behavior may be due to the anti – friction properties of Cu, ZrO_2 nanoparticles. Cu, ZrO_2 nanoparticles are basically spherical.

The spherical shape of nanoparticles may result in rolling effect between the rubbing surfaces and the situation of friction is changed from sliding to rolling, thus the lubricant with nanoparticles achieves a good friction reduction performance. The rolling effect of nanoparticles was also reported by Battez et.al. and Wu et.al.. As well as it is concluded that for straight tube, the maximum pressure drop increasing of about 16.3% (Cu + oil) and 12.1% (ZrO_2+oil) are achieved when nanofluid with 5 % vol concentration is used instead of base fluid. However, for the helical tube, the maximum pressure drop enhancement of 23.2 % (Cu + oil) and 18.2 % (ZrO_2+oil) are obtained. It means that, the rate of pressure drop increasing due to the using of nanofluid is more prominent in the helical tube.

When applying helical tube instead of the straight tube and using nanofluid flow inside the test sections instead of the base liquid flow, enhanced the convective heat transfer coefficient. However, these enhanced heat transfer techniques were both accompanied with increase in pressure drop which can limit the use of them in practical applications. Therefore, in order to find the optimum work conditions, a further study on the overall performance of these techniques should be carried out to consider pressure drop enhancement besides heat transfer augmentation, simultaneously. To do so, a new parameter called performance index, η, is defined as follows:

$$\eta = \frac{\left(\dfrac{Nu_{nf}}{Nu_{ST,\,bf}}\right)}{\left(\dfrac{\Delta p_{nf}}{\Delta p_{ST,\,bf}}\right)} \qquad (11)$$

In which, Nu and ΔP represent mean Nusselt number and pressure drop of the flow resulted by applying enhanced heat transfer techniques, respectively. In addition, $Nu_{ST,\ bf}$ and $\Delta P_{ST,\ bf}$ are the mean Nusselt number and pressure drop of the base oil flow inside the straight tube, respectively. Apparently, when the performance index is greater than 1, it implies that the heat transfer technique is more in the favor of heat transfer enhancement rather than in the favor of pressure drop increasing. Therefore, the heat transfer methods with performance indexes greater than 1 would be feasible choices in practical applications.

Figs. (26,27,28 and 29)reveal the variation of performance index versus Reynolds number for nanofluids(Cu + oil) and (ZrO_2+oil) with different volume concentrations flowing inside the straight tube at constant heat flux of 2500 W/m^2. Here, Nu_{nf} and ΔP_{nf}in Eq. (10) are the mean Nusselt number and pressure drop of the nanofluid flow inside the straight tube, respectively.

Figs (26,and 27) it is seen that the performance index is greater than 1 just for nanofluids with 8.24,21.57, and 31.88wt %concentrations. The maximum performance index of 1.1 and 1.02 are obtained for the nanofluids(Cu + oil) and (ZrO2+oil) with 31.88 wt %concentration at Reynolds number of 190 at the straight tube. While figures (28,and 29) in the helical tube 1.5 and 1.32 respectively for the same nanofluids. Also It is seen from these figures that the, all concentration for the helical tube has performance indexes greater than 1. It means that for base flow along the helical tube, the rate of increasing in pressure drop is lower than increasing in heat transfer coefficient. In addition, it is evident from Figs. (26,27,28 and 29) that applying helical tube instead of the straight tube is a more effective way to enhance the convective heat transfer compared to using nanofluids instead of the base fluid. This relatively high performance index suggests that applying both of the heat transfer enhancement techniques studied in this investigation is a good choice in practical application

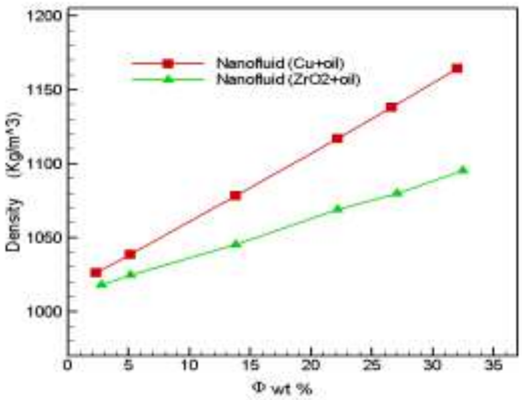

Fig 6.Density of nanofluids for (Cu+ oil) and (ZrO_2+oil)at different volume fraction

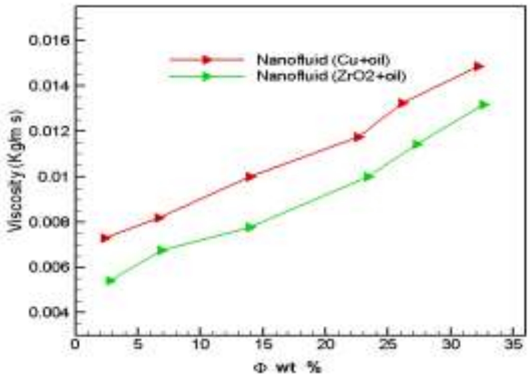

Fig 7.Vicosity of nanofluids for (Cu+ oil) and (ZrO_2+oil)at different volume fraction

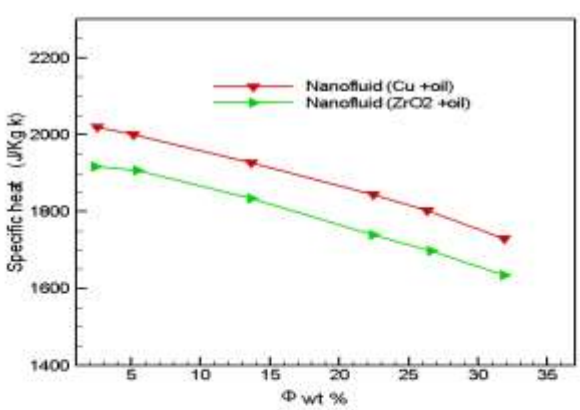

Fig 8.of nanofluids for (Cu+ oil) and (ZrO_2+oil) at different volume fraction

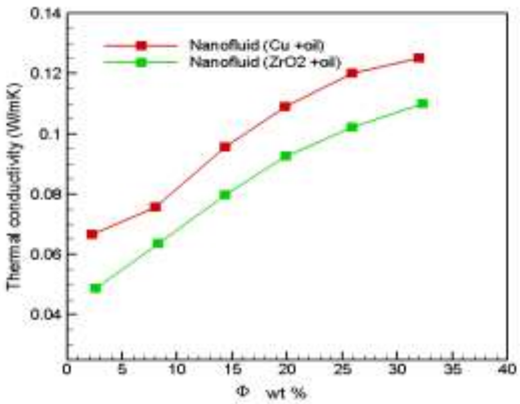

Fig 9.Thermal conductivity of nanofluids for (Cu+oil) and (ZrO_2+oil)at different volume fraction

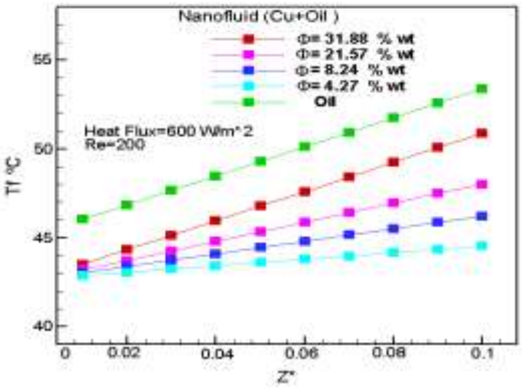

Fig 10. Temperature distribution of the nanofluid (Cu +oil) in tube at CHF and different Φ

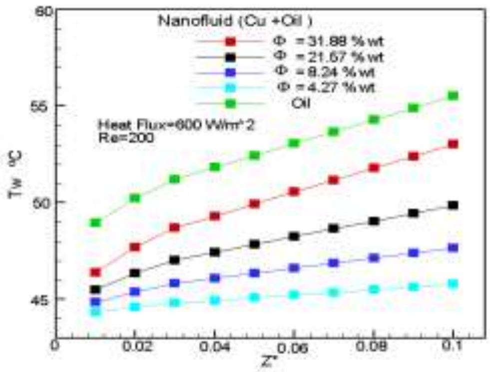

Fig 11.Wall temperature distribution of the nanofluid (Cu + oil) in tube at CHFand different Φ

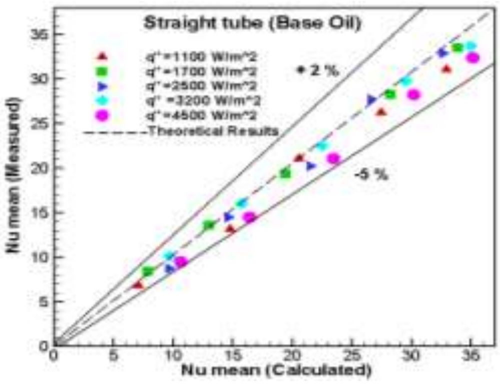

Fig 12.Comparison between theoretical and experimental Mean Nusselt number of base oil at CHF=2500W/m^2

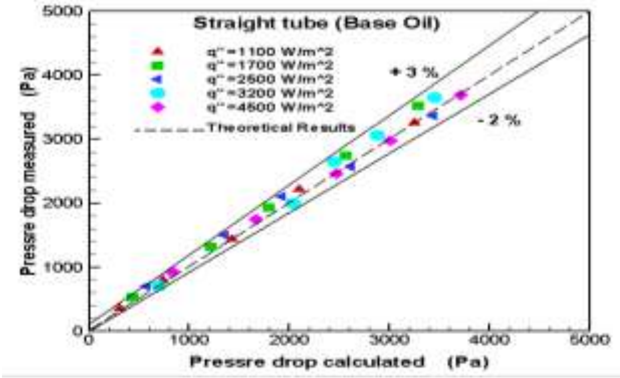

Fig 13.Comparison between theoretical and experimental Pressure drop of base oil at CHF=2500W/m^2

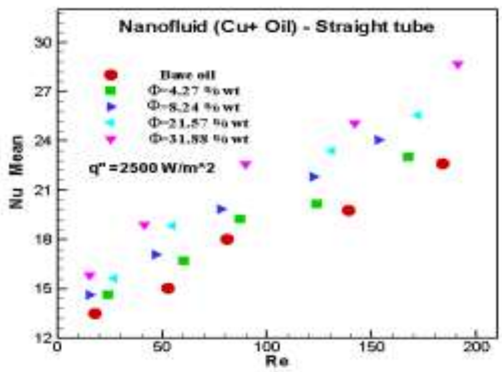

Fig 14. Variation of mean Nu with Re tonanofluid (Cu+oil)in straight tube at CHF and different Φ

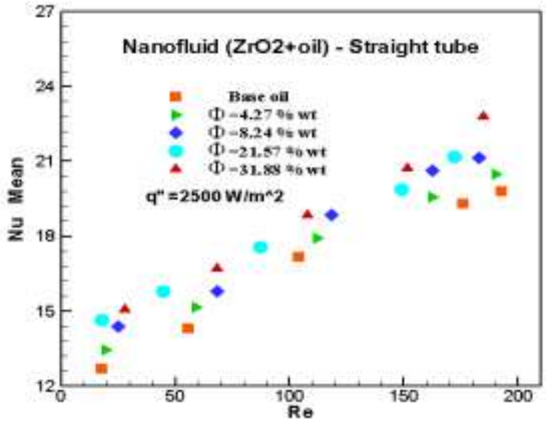

Fig 15.Variation of mean Nu with Retonanofluid (ZrO_2+oil) in straight tube at CHFand different Φ

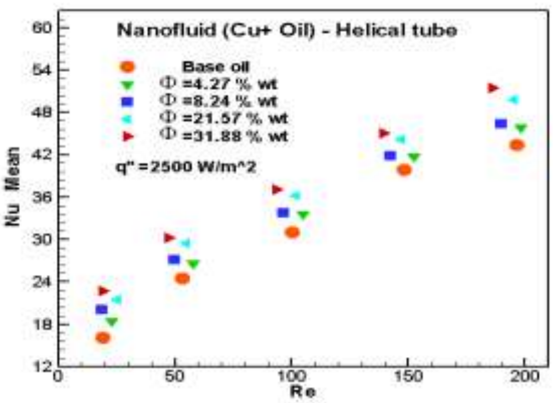

Fig 16. Variation of mean Nu with Re tonanofluid (Cu + oil) in helical tube at CHF and different Φ

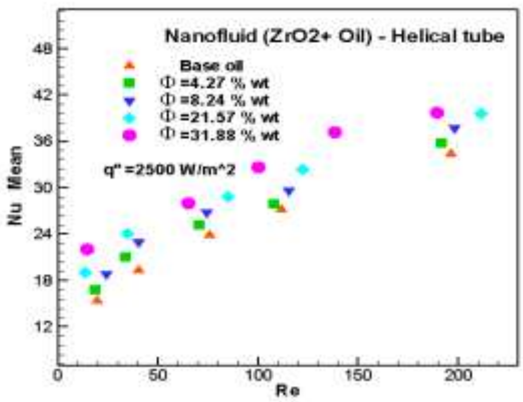

Fig 17.Variation of mean Nu with Retonanofluid (ZrO_2+ oil) in helical tube at CHFand different Φ

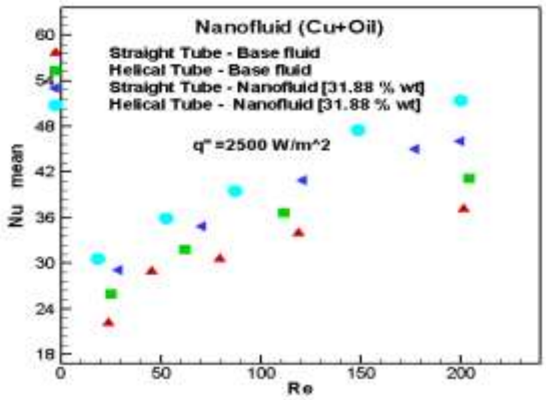

Fig 18. Variation of mean Nu versus Retonanofluid (Cu + oil) instraight tube and helical tube at Φ=31.88%wt

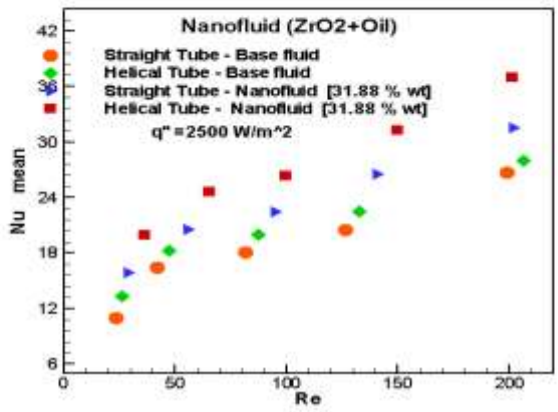

Fig 19. Variation of mean Nu versus Retonanofluid(ZrO_2 +oil)in straight tube and helical tube at Φ=31.88%wt

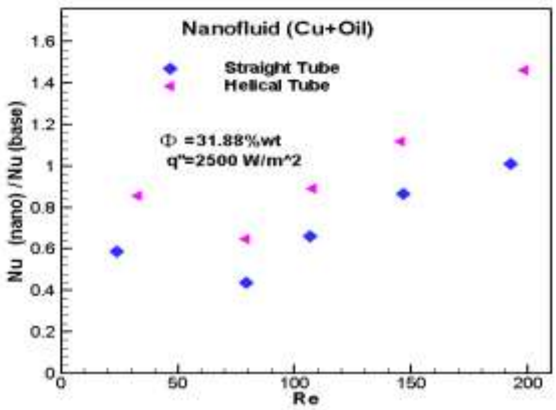

Fig 20. The Nu ratio versus Retonanofluid(Cu + oil) in straighttube and helical tube at CHF andΦ=31.88%wt

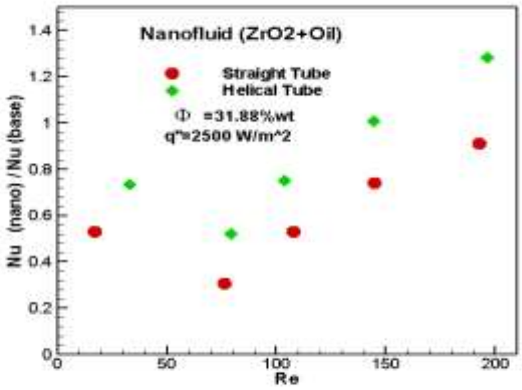

Fig 21. The Nu ratio versus Re tonanofluid(ZrO_2+ oil) in straighttube and helical tube at CHF andΦ=31.88%wt

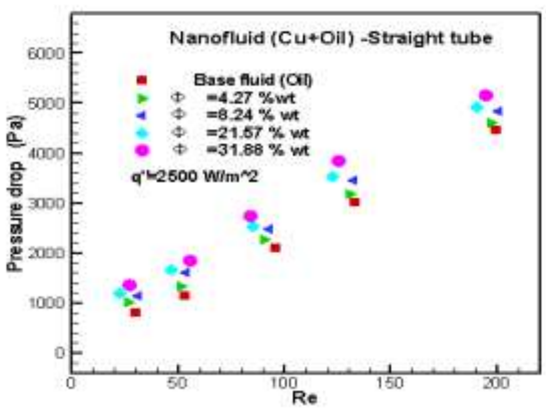

Fig 22. Pressure dropversus Re tonanofluid (Cu + oil)in straight tube at different Φ and CHF

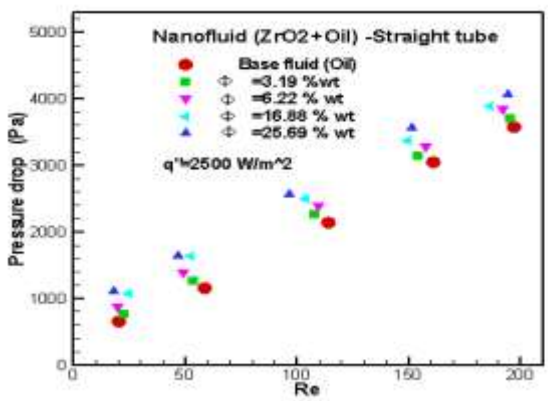

Fig 23. Pressure dropversus Re tonanofluid (ZrO_2 + oil)in straight tube at different Φ and CHF

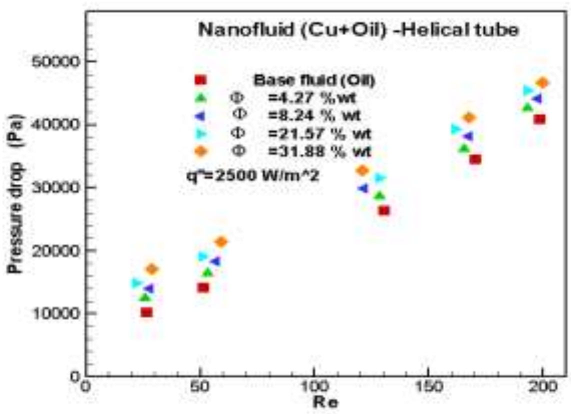

Fig 24. Pressure dropversus Re tonanofluid (Cu + oil)in helical tube at different Φ and CHF

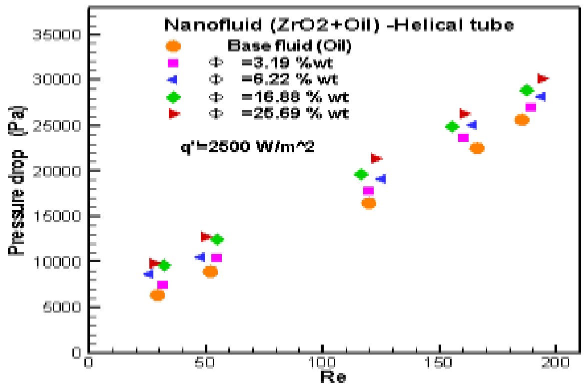

Fig 25. Pressure dropversus Re tonanofluid (ZrO_2 + oil)in helical tube at different Φ and CHF

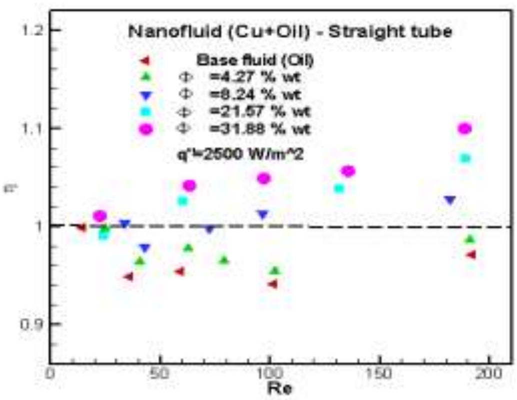

Fig 26. The performance index versus Reto nanofluid (Cu + oil)in straight tube at different Φ and CHF

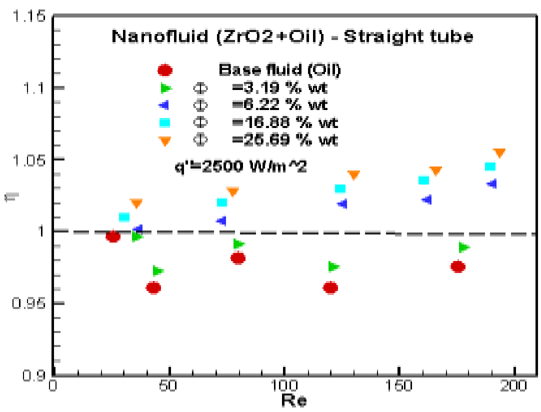

Fig 27.The performance index versus Reto nanofluid (ZrO_2 + oil)in straight tube at different Φ and CHF

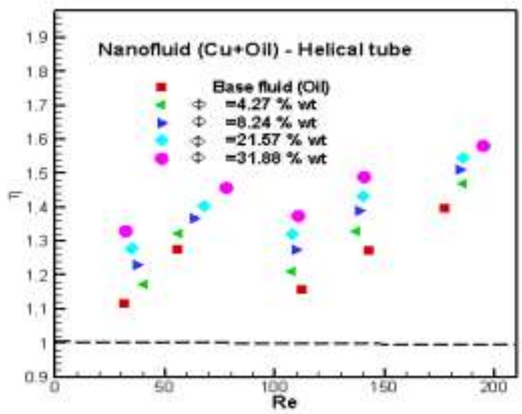

Fig 28. The performance index versus Reto nanofluid (Cu + oil)in helical tube at different Φ and CHF

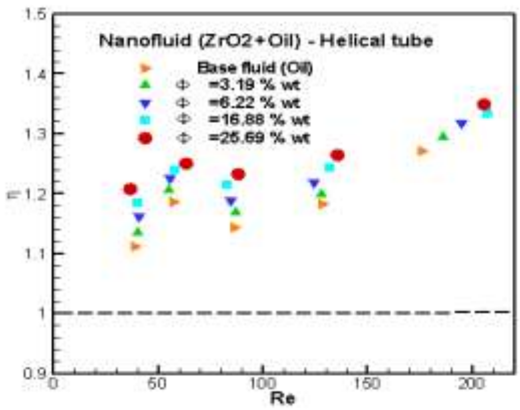

Fig29.The performance index versus Reto nanofluid (ZrO_2 + oil)in helical tube at different Φ and CHF

6. Conclusion

The following conclusions are drawn from this study:

1. The type and size nanoparticles play an important role in enhancement of heat transfer rate.
2. Theheat transfer characteristics in helical tube is better than straight tube by using Nanofluids and compared with oil flow
3. Metal nanofluid (Cu + oil) have better mean Nusselt number and pressure drop in helical tube rather than oxide nanofluid (ZrO_2+ oil) in the straight tube and compared with oil flow.
4. The performance index for the nanofluid flow inside the helical tube is greater than the performance index for the nanofluid flow inside the straight tube comparing with the base oil flow. This relatively high performance index suggests that applying both of the heat transfer enhancement techniques studied in this investigation is a good choice in practical application.
5. The pressure drop of nanofluids in helical tube is greater than pressure drop of nanofluids in the straight tube and compared with the oil flow.

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