EXPERIMENTAL INVESTIGATION OFTHERMAL CONDUCTIVITY ANDPRESSUREDROPFOR WATER–NANOFLUID MIXTURE

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ABSTRACT

This research investigates experimentally the thermal conductivity and the pressure drop of a new kind of engineering materials consisting of nanometer sized particles dispersed in base fluid named nanofluid. The study investigatesnanofluids containing CuO and γ-Al_2O_3 oxide nanoparticles in distilled water as base fluid in different particle sizes and concentrations. The experimental results emphasize the enhancement of the thermal conductivity due to the nanoparticles presence in the fluid.Also the effect of the particle size and concentration on the thermal conductivity. These results show noticeable enhancement in the thermal conductivity especially for the CuO/distilled water nanofluid which reaches to (1.07%), while reaches to (1.05%) for theγ-Al_2O_3/distilled water nanofluidat the concentration of (6 % vol.) and at the room temperature.The experimental results of pressure drop show that the nanofluids in the laminar flow will not cause extra penalty in the pumping power. A good agreement was found between the experimental obtained data for this research and other results from published papers.

اختبار عملي للموصلية الحرارية وهبوط الضغط لخليط ماء وحبيبات متناهي الصغر

الخلاصة

يتضمن البحث الحالي اختبار عملي للموصلية الحرارية وهبوط الضغط لنوع جديد من المواد الهندسية التي تحتوي على حبيباتمتناهية الصغر مخلوطة مع المائع الأساسي تسمى الموائع متناهية الصغر . الدراسة تضمنت سوائل متناهية الصغر مكونة من أوكسيد النحاس CuOوأوكسيد الألمنيوم (الالومينا) γ-Al_2O_3 على شكل حبيبات متناهية الصغرمختلطة مع الماءالنقي كمائع أساسيبكسورحجمية وتراكيز مختلفة. النتائج العملية بينت تحسن ملحوظ في الموصلية الحرارية بسبب الحبيباتمتناهية الصغر المضافة الى المائع. كذلك بينت تأثير الحجم الحبيبي والتركيز على الموصلية الحرارية. تلك النتائج بينت تحسن ملحوظفي الموصلية الحرارية وخصوصاً للمائع متناهي الصغر الذي يحتوي على أوكسيد النحاس CuO مع الماء النقي حيث يصل الى (1.07%)، بينما يصل الى (1.05%) للمائع متناهي الصغر الذي يحتوي على أوكسيد الألمنيوم (الالومينا) γ-Al_2O_3مع الماء النقيبتركيز (6 % vol.) وبدرجة حرارة الغرفة. النتائج العملية لهبوط الضغط بينت ان الموائع متناهية الصغر في حالة الجريان الطباقي لن تتسبب في عواقب إضافية في طاقة الضخ. وجد توافق جيد بين النتائج العملية المستحصلة من هذه الدراسة ونتائج أخرى من بحوث منشورة.

KEYWORDS: nanofluid, γ-Al_2O_3, CuO, nanoparticles, thermal conductivity and pressure drop.

NOMENCLATURE

d	Thickness of the discs	mm
ds	Thickness of the space containing nanofluid	mm
dp	Particle size	nm
e	Heat loss	Watt
f	Friction factor	—
h	Nano-layer thickness	m
I	Electrical current	A
k	Thermal conductivity	W/m k
n	Empirical shape factor	—
r	The radius of the discs	mm
Re	Reynolds number	—
T	Temperature	K
U	Nanofluid velocity	m/s
V	Electrical voltage	V

GREEK SYMBOLS

β	Ratio of nano-layer thickness to the original particle radius	—
ρ	Density	kg/m^3
μ	Viscosity	$N.s/m^2$
Φ	Volume fraction of nanoparticles in suspension	—
Δ p	Pressure drop	Pa

SUBSCRIPT

b	Base fluid
m	Mean
nf	Nanofluid
p	Nanoparticle
s	Nanofluid sample

INTRODUCTION

Fluids heating and cooling play important roles in many industries including power stations, production processes, transportation and electronics. Fluids, such as water, ethylene glycol and engine oil have poor heat transfer performance and therefore high compactness and effectiveness of heat transfer systems are necessary to achieve the required heat transfer. Among the efforts for enhancement of heat transfer the application of additives to liquids is noticeable **[Bergles1973 andAhuja 1975]**. Earlier studies used suspensions of millimeter and micrometer sized particles, which showed some enhancement of heat transfer, experienced problems such as poor suspension stability and channel clogging, extra pressure drop and erosion. The pressure drop occurs in the regions of high velocity flow create a vapor bubble when the pressure at any point in the flow field equals to the vapor pressure of the liquid at that temperature. This phenomenon called cavitations, which lead to shock waves accompanied by high pressure at that point in flow, this phenomenon leads to a significant damage to structural material due to erosion – corrosion effect.

Convective heat transfer can be enhanced passively by changing flow geometry, boundary conditions, or by enhancing thermal conductivity of the fluid. Various techniques have been proposed to enhance the heat transfer performance of fluids. Researchers have also tried to increase the thermal conductivity of base fluids by suspending micro- or larger-sized solid particles in fluids since the thermal conductivity of solid is typicallyhigher than that of liquids**[Xiang and Arun2007].**Numerous theoretical and experimental studies of suspensions containing solid particles have been conducted since Maxwell's theoretical work was published more than 100 years ago**[Maxwell1904]**. However, due to the large size and high density of the particles, there is no good way to prevent the solid particles from settling out of suspension. The lack of stability of such suspensions induces additional flow resistance and possible erosion.The term of nanofluids refers to a new kind of fluids by suspending nanoparticles in base fluids. [**Choi 1995]**was the first to employ the particles of nanometer dimension suspended in solution as nanofluid and showed considerable increase in the nanofluid thermal conductivity.Nanofluids found to possess long time stability and large efficient thermal conductivity**[Khanafer et al. 2003]**.

Many researches are conducted to enhance the thermal conductivity of fluids and also to produce more stable suspensions.Since the theoretical models such as Maxwell and Hamilton–Crosser **[Hamilton and Crosser 1962 and Das et al. 2003]** cannot determine exactly the thermal conductivity of nanofluids, therefore it isnecessary to study about thermal conductivity enhancement mechanisms of this kind of fluids.**[Lee et al. 1999]** reported that suspension of 4% volume CuO 35 nm particles in ethylene glycol shows 20% increase in thermal conductivity.**[Li and Xuan2000]** investigated experimentally for 35 nm Cu/deionizer water nanofluid flowing in a tube with constant wall heat flux and showed that the ratio of the Nusselt number for the nanofluid to that of pure water under the same flow velocity varies from 1.05 to 1.14 by increasing the volume fraction of nanoparticles from 0.5% to 1.2%, respectively.**[Das et al. 2003]** investigated the temperature dependence of thermal conductivity enhancement in nanofluids experimentally,it was observed that a 2–4 fold increased in thermal conductivity of nanofluid can take place over a temperature range of 21–51C^0.**[He et al. 2007]**carried out experimental study on the flow and heattransfer behavior of aqueous TiO_2nanofluids flowing through astraight vertical pipe under both laminar and turbulent flow conditions,it was observed that for a given Reynolds number and particlesize, the convective heat transfer coefficient increased with volumeconcentration in both the laminar and turbulent flow regimes andthe convective heat transfer coefficient was insensitive to thechanges in particle size,the measured pressure drop of nanofluidswas very close to that of the base liquid for a given Reynoldsnumber. **[Hwang et al. 2009]**measured the pressure drop and convectiveheat transfer coefficient of water – basedAl_2O_3nanofluids flowing through a uniformly heated circular tube in the fully developedlaminar flow regime,the experimental results showed that thenanofluid friction factor can be analytically predicted by theDarcy's equation for single-phase flow.**[Xuan and Li 2010]**investigatedexperimentally the convective heat transfer and flow characteristicsfor Cu/water nanofluid flowing through a straight tube witha constant heat flux under laminar and turbulent flow conditions,Cu nanoparticles with diameters below 100 nm were used in theirstudy. The results of the experiment showed that the suspendednanoparticles remarkably enhanced the heat transfer performanceof the conventional base fluid and the friction factor coincidedwell with that of the water, In addition, theyalso proposed new convective heat transfer correlations for theprediction of heat transfer coefficients of the nanofluid for bothlaminar and turbulent flow conditions. As it is necessary to studythe pressure drop of nanofluids besides the heat transfer enhancementin order to apply nanofluid to practical cases, they also conductedpressure drop studies for both the laminar and turbulentflow which revealed no significant augmentation in pressure dropfor the nanofluid.

In the theoretical part, for example**[Palm et al. 2004]**showed numerical investigation of laminar flow heat transfer of Al_2O_3/ethylene glycol and Al_2O_3/water nanofluids in a radial flow system reported considerableimprovement in heat transfer rate, Also they showed that wall shear stress increased with nanoparticles concentration and Reynolds number.**[Xuan and Roetzel2000]** considered two approaches to illustratethe heat transfer enhancement by nanofluids,the first approach was the single phase model in which both the fluid phase and the particles are in thermal equilibrium state and flow with the same velocity,in the second analysis they adopted dispersion model to interpret nanofluid heat transfer enhancement resulting from chaotic movement of nanoparticles in the main flow.

In the present work, the study investigated experimentally the thermal conductivity and the pressure drop for CuO and γ-Al_2O_3oxide nanoparticles in distilled water at different particle sizes and concentrations. The study emphasizes the enhancement of the thermal conductivity due to the nanoparticles presence in the fluid, while the pressure drop investigation indicated that the nanofluids will not cause extra penalty in pumping power in the laminar flow.

RELATED THEORY

Currently, there is no reliable theory to predict the thermal conductivity of nanofluids. From the experimental results of many researchers, it is known that the thermal conductivity of nanofluids depends on parameters including the thermal conductivity of the base fluid and the nanoparticles, the volume fraction, the surface area, and the shape of the nanoparticles, and the temperature. There are no theoretical formulas currently available to predict the thermal conductivity of nanofluids satisfactorily.

[Yu and Choi 2003] proposed a modified Maxwell relation considering to account the effect of the nano-layer by replacing the thermal conductivity of solid particles k_p in Eq. (1) with the modified thermal conductivity of particles k_p, which is based on the so called effective medium theory (i.e. the effect of the liquid nano-layer formed around nanoparticles was taken into account,the nanoparticle and the layer which moves around it considered as a single particle).

$$k_{nf} = \left[\frac{k_{p+}2k_b+2(k_p-k_b)(1+\beta)^3\Phi}{k_{p+}2k_b-2(k_p-k_b)(1+\beta)^3\Phi}\right]k_b \qquad (1)$$

Where: β=h/r is the ratio of the nano- layer thickness to the original particle radius.

The thermal conductivity of the nanofluid is calculated from **[Hamiltonand Crosser 1962]**using the following equation:

$$k_{nf} = \frac{k_p+(n-1)k_b-(n-1)(k_b-k_p)\Phi}{k_p-(n-1)k_b+(k_b-k_p)\Phi} \qquad (2)$$

Where: k_{nf} is the thermal conductivity of the nanofluid, k_p is the thermalConductivity of the nanoparticles, k_b is the thermal conductivity of the base fluid.Furthermore, the thermal conductivity of the nanofluid is calculated from **[Wesley 2006]**.

$$k_{nf} = k_b(T)(4.5503 \times vol\%) + 1 \qquad (3)$$

One well-knownformula for calculating the thermal conductivity of nanofluid is **[Timo et al. 2007]**.

$$k_{nf} = (1 + 3\Phi)k_b \quad (4)$$

There are many analytical models that related to the thermal conductivity of nanofluids, Table (1) shows a summary of some of these models from previous researches.

Also thethermophysical properties of nanofluidcan be calculated at the average bulk temperature of the nanofluid by using the following equations **[Yu and Choi 2003]**.

$$\rho_{nf} = \rho_s \Phi + (1 - \Phi)\rho_b \quad (5)$$

$$\mu_{nf} = (1 + 2.5\Phi)\mu_b \quad (6)$$

EXPERIMENTAL INVESTIGATION

Sample Preparation

Nanofluid samples were prepared by dispersing pre-weighed quantities of dry particles in either distilled water. The pH of each aqueous mixture was measured, the mixtures were then subjected to ultrasonic mixing (Sonics &Materials, Inc. Vibra-Cell VCX 750) for several minutes to break up any particle aggregates. The acidic pH is much higher than the iso electric point of these particles (7 - 9 for aluminum oxide and 6.7 - 8.7 for copper oxide), thus ensuring a positive surface charge on the particles. The surface charge enhanced repulsion between the particles, which resulted in uniform dispersions for the duration of the experiments. Fig.(1) shows an aqueous nanofluids samples containing aluminum oxide and copper oxide.

Thermal ConductivityMeasurement

The thermal conductivity of the nanofluidsCopper oxide/distilled waterand Aluminum oxide/distilled waterwas measured by usingLee's disc method. Fig.(2) shows the test apparatus (Lee's disc apparatus) type (Griffin and George) which contains a heater switch on from the power supply with (V = 6 V and I = 0.2 A) to heat the copper disks and the temperatures of the all disks (1,2 and 3) increases in nonlinear relationships and at different rates with the time according to its position from the heat source, the temperatures were recorded every (5 minutes) until reach to the equilibrium temperature of all disks.

Fig.(3) shows the experimental test cell containing nanofluids, the cell consist of two disks of copper (1 and 2) and the space that contains nanofluid which intended to measure its thermal conductivity was located between these two copper disks, the space that contains the nanofluid is surrounded by insulated material (Perspex pipe) to prevent the effect of convection. The dimensions of the space are (8 mm) in thickness and (42 mm) in diameter exactly the same diameter of the copper disks and the nanofluid is in direct contact with the copper disks. Then the thermal conductivity can be calculated by using the following form**[Murthy et al.2004]**and**[Rondeauzand Bready2001]**:

$$K\left[\frac{T_2 - T_1}{ds}\right] = e\left[T_1 + \frac{2}{r}\left(d_1 + \frac{1}{2}ds\right)T_1 + \frac{1}{2}dsT_2\right] \quad (7)$$

And can calculate the value of e as follows:

$$IV = \pi r^2 e(T_1 + T_3) + 2\pi r e\left[d_1T_1 + \frac{1}{2}ds(T_1 + T_2) + d_2T_2 + d_3T_3\right] \quad (8)$$

$$e = \frac{IV}{\pi r^2(T_1+T_3)+2\pi r\left[d_1T_1+\frac{1}{2}ds(T_1+T_2)+d_2T_2+d_3T_3\right]} \qquad (9)$$

The experimental results for the thermal conductivity were compared with themodels equationsof thermal conductivity developed by many researchers such as**[Yu and Choi model 2003], [Hamilton and Crosser model 1962], [Wesley model 2006] and [Timo et al. model 2007]**. The Hamilton and Crosser model is the closest to the practical by difference does not exceed 1.37%, because that model taking into the consideration the particle shape.

Pressure DropMeasurement

The pressure drop of distilledwater – based γ-Al_2O_3 and CuOnanofluids flowing through a circular tube is experimentally measured to investigate flow characteristics of the nanofluids.

The device shown in fig.(4) was builtto be used in the measurements of pressure difference for the nanofluids passing through a circular tube, which consists of a reservoir used to provide the nanofluid to the system by using a variable speed pump (3- phase pump) controlled by (AC-drive) to change and regulate the speed, the flow rate of the nanofluid was measured by using flow meter, the nanofluid passing through the experimental pipe (Perspex pipe) contains two ports at the inlet and the outlet to measure the pressure variation by using gage pressure (Borden gage).

In order to verify the accuracy and the reliability of this experimental system, the pressure drop is experimentally measured using distilled water before obtaining those of distilled water – based γ-$Al_2O_3$and distilled water – based CuOnanofluids.

Based on the pressure drop of distilled water – basedγ-Al_2O_3 and CuOnanofluids, Darcy friction factor can be expressed **[Kyo et al. 2009]**, which is a dimensionless parameter defined as:

$$f = \frac{-(\frac{dp}{dx})d_{tube}}{\rho U_m^2/2} \qquad (10)$$

Where: $\frac{dp}{dx}$ is the pressure drop.

The friction factor for fully developed laminar flow in circular pipe, it follows that.

$$f = \frac{64}{Re_D} \qquad (11)$$

In order to evaluate the accuracy of nanofluidpressure drop measurements inside the tube, the measured pressure drop from eq. (11) was compared with the Hagen – Poiseuille law **[Heris et al. 2007]**.

$$\Delta p_{th} = 32\frac{u_m \mu L}{d_{tube}^2} \qquad (12)$$

RESULTSAND DISCUSSION

The obtained experimental results emphasize the enhancement of the thermal conductivity due to the nanoparticles presence in the base fluid. In order to verifying the experiments, the experimental cell and thermal conductivity test apparatuswere calibrated to verify the obtained data by measuring the thermal conductivity of standard fluids (distilled water and ethylene glycol).

Figs.(5 and 6) show that the ratio of the thermal conductivity (Knano/Kbase) increases significantly with the increasing of concentration, and the relation between the thermal conductivity with the concentration is a linear relation because the thermal conductivity of the of the nanofluids depending upon the both thermal conductivities of the nanoparticles and base fluid, which means any increase in the concentration means an increment in the nanoparticles leads to increasing the thermal conductivity of the nanofluid. This ratio of increment was (1.07%) for(CuO/distilled water) nanofluid, while for the (γ-Al_2O_3/distilled water) nanofluidthe ratio of the increment was (1.05%) at the concentration of (6% vol.) volume fraction. The results obtained from these figures indicate that the Copper Oxide particles have thermal conductivity higher than that of the Aluminum oxide Particles. The experimental results for this investigation were compared with other data from published papers at the same field, very good agreement was found between the experimental data and (Hamilton and Crosser) model **[Hamilton and Crosser 1962]**.

Thermal conductivity increases for the nanofluid which contains large particle size compared with that contains small particle size, increasing the size of nanoparticles play an important role in the thermal conductivity values and the relation between them is directly proportion as shown in figs. (7 and 8). Thesefigures show the effect of the particle size on the thermal conductivity.

Fig. (9) shows a comparison between the thermal conductivity of (CuO/distilled water) and (γ-Al_2O_3/distilled water) nanofluids at (dp= 25,50 and 75 nm) particle size, this comparison shows the enhancement of the thermal conductivity for the two nanofluids and the effect of the particle size on this enhancement.

The pressure drop investigation apparatus was calibrated, in order to verify the accuracy and the reliability of this experimental system, the pressure drop is experimentally measured using distilled water before obtaining those of distilledwater – based γ-$Al_2O_3$and distilledwater – based CuOnanofluids. The experiments on the pressure drop are conducted within the Reynolds number of 800. Fig.(10)showsthe pressure drop data for distilled water and analytical predictions using Eq. (12) which obtained a good agreement with less than 2.1% error.

Substituting the measured pressure drop into Eq. (10), the Darcyfriction factor can be calculated. Figs. (11 and 12) show that the Darcy frictionfactor of water – basedγ-$Al_2O_3$and CuOnanofluids in laminarflow regime, which has a good agreement with Eq. (11) with less than 1.3% error. This implies that the friction factor correlation for thesingle – phaseflow can be extended to distilledwater – basedCuOand distilled water – basedγ-Al_2O_3nanofluids.

The experimental results of the pressure drop (friction factor) which were obtained show that no significant augmentation in pressure drop for the nanofluidin the laminar flow, which indicates that the nanofluid will not cause extra penalty in pumping power.

CONCLUSIONS

The present work has reached to the following conclusions:-

1. Thermal conductivity increases with the increasing the concentration of nanofluids.
2. Thermal conductivity increases with the increasing of the particle size which presence in the base fluids.

3. Nanoparticle type (material type) plays an important role in the thermal conductivity enhancement.
4. Thermal conductivity of the (CuO/ distilled water) nanofluidis higher than that of the (γ-Al_2O_3/ distilled water) nanofluid, due to the higher thermal conductivity of the Copper Oxide particles compared with aluminum Oxide particles.
5. Nanoparticles shape has a significant effect on theThermal conductivity**.**
6. The pressure drop investigation show that no significant augmentation in pressure drop for the nanofluidin the laminar flow.
7. Using suspensions of nanometer sized particles leads to high mixture stability, exceed the effects of the particles settling.

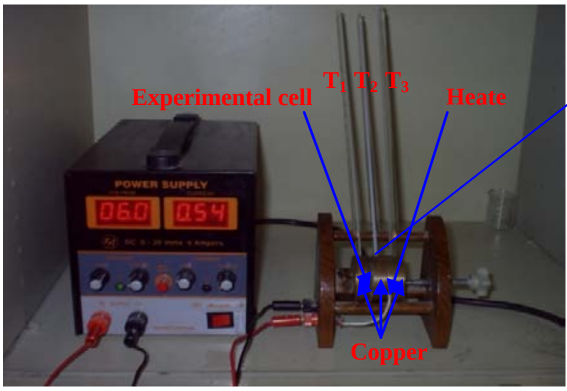
Table1summary ofsome analytical models of the thermal conductivity of nanofluids

Investigator	Formula (k_{eff}/k_b)	Comments
[Maxwell 1904]	$\left[\frac{k_{p+}2k_b + 2(k_p - k_b)(1+\beta)^3\Phi}{k_{p+}2k_b - 2(k_p - k_b)(1+\beta)^3\Phi}\right]k_b$	relates the thermal conductivity of spherical particle, base fluid and solid volume fraction
[Bruggeman1935]	$\frac{1}{4}\left[(3\Phi-1)\frac{k_p}{k_b} + (2-3\Phi) + \frac{1}{4}\sqrt{\Delta}\right]$	$\Delta = [(3\varphi-1)^2(k_p/k_b)^2+(2-3\varphi)^2+2(2+9\varphi-9\varphi^2)(k_p/k_b)]$
[Hamilton and crosser 1962]	$\frac{k_p + (n-1)k_b - (n-1)(k_b - k_p)\Phi}{k_p - (n-1)k_b + (k_b - k_p)\Phi}$	for non – spherical particles, k_p/k_b >100, *n* is an empirical shape factor ($n = 3/\psi$, ψ is the sphericity)
[Wasp et al. 1999]	$\frac{k_p + 2k_b - 2(k_b - k_p)\Phi}{k_p + 2k_b + 2(k_b - k_p)\Phi}$	special case of Hamilton and Crosser's model with $\psi = 1$
[Wang et al. 2003]	$\frac{(1-\Phi) + 3\Phi\int_0^\infty K_{cl}(r)n(r)/[K_{cl}(r)+2k_b]dr}{(1-\Phi) + 3\Phi\int_0^\infty K_b(r)n(r)/[K_{cl}(r)+2k_b]dr}$	a fractal model based on effective medium approximation and fractal theory
[Yu and Choi 2003, 2004]	$\frac{k_{pe} + 2k_b + 2(k_{pe} - k_b)(1-\beta)^3\Phi}{k_{pe} + 2k_b - 2(k_{pe} - k_b)(1+\beta)^3\Phi}, 1 + \frac{n\Phi_{eff}A}{1-\Phi_{eff}A}$	a modified Maxwell and Hamilton–Crosser model, respectively
[Xuan et al. 2003]	$\frac{k_{p+}2k_b - 2(k_b - k_p)\Phi}{k_{p+}2k_b + (k_b - k_p)\Phi} + \frac{\rho p\emptyset c_p}{2k_b}\sqrt{\frac{k_B T}{3\pi r_c}}$	Includes effect of the random motion of the suspended nanoparticles as well as the interfacial interactions
[Xue 2003]	$0 = 9\left(1-\frac{\Phi}{\lambda}\right)\frac{k_{eff} - k_b}{2k_{eff} + k_b} + \frac{\Phi}{\lambda}\left[\frac{k_{eff} - k_{c,x}}{k_{eff} + B_{2,x}(k_{c,x} - k_{eff})}\right]$	Includes the effect of interface between solid particles and base fluid
[Kumar et al. 2004]	$1 + C\frac{2K_BT}{(\pi d_p^2)}\frac{E r_b}{k_b(1-E)r_p}$	Particle size, concentration, and temperature
[Bhattacharya et al. 2004]	$\frac{k_p}{k_p}\Phi + (1-\Phi)$	$k_p = \frac{1}{K_B T^2 V}\sum_{j=0}^{n} Q(0)Q(j\Delta t)\Delta t$
[Jang and choi2004]	$k_b(1-\Phi) + k_p\Phi + 3c\frac{d_b}{d_p}k_b Re_{d_p}^2 pr\Phi$	Four modes: collisions between fluid molecules, thermal diffusion of nanoparticles, collisions between nanoparticles due to Brownian motion and thermal interaction of dynamic nanoparticles with base fluid molecules
[Xie et al. 2005]	$1 + 3\theta\emptyset T + \frac{2\theta^2\emptyset T^2}{1-\theta\emptyset T}$	Includes effect of nano-layer
[Prasheret al. 2005]	$\left(1 + ARe^m pr^{0.33}\emptyset\left[\frac{k_{p+}2k_b + 2(k_p - k_b)\Phi}{k_{p+}2k_b - 2(k_p - k_b)\Phi}\right]\right)$	Effect of convection of the liquid near the particle included

[Xue2005]	$\frac{1-\Phi+2\Phi\frac{k_p}{k_p-k_b}ln\frac{k_p+k_b}{2k_b}}{1-\Phi+2\Phi\frac{k_b}{k_p-k_b}ln\frac{k_p+k_b}{2k_b}}$	for CNTs-based nanofluids and including the axial ratio and the space distribution

(A) **(B)**

Fig. 1 aqueous nanofluids samples(A) containing copper oxide/distilled water and (B) containingaluminumoxide/distilled water



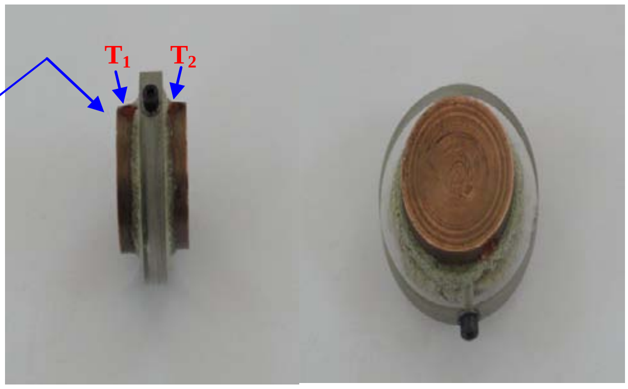


Fig. 2 thermal conductivity test apparatus **Fig. 3 experimental cell**

Fig4Pressure drop investigation apparatus

1. Reservoir
2. Variable speed pump
3. AC- Drive
4. Experimental pipe
5. Borden gages
6. Flow meter
7. Power switch

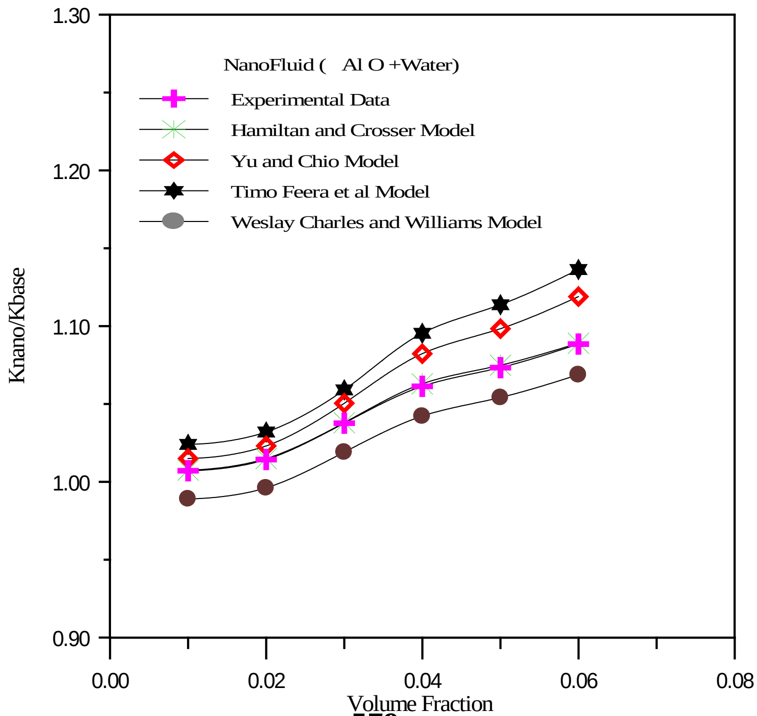


Fig. 5 thermal conductivity ratio of distilled water – based γ-Al_2O_3nanofluid

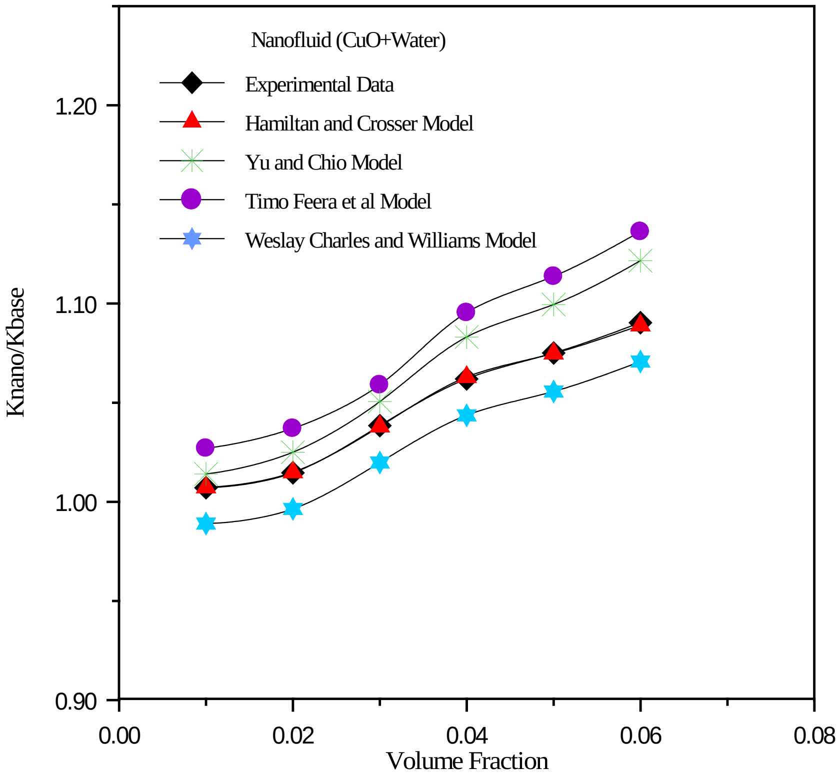


Fig. 6 thermal conductivity ratio of distilled water – based CuOnanofluid

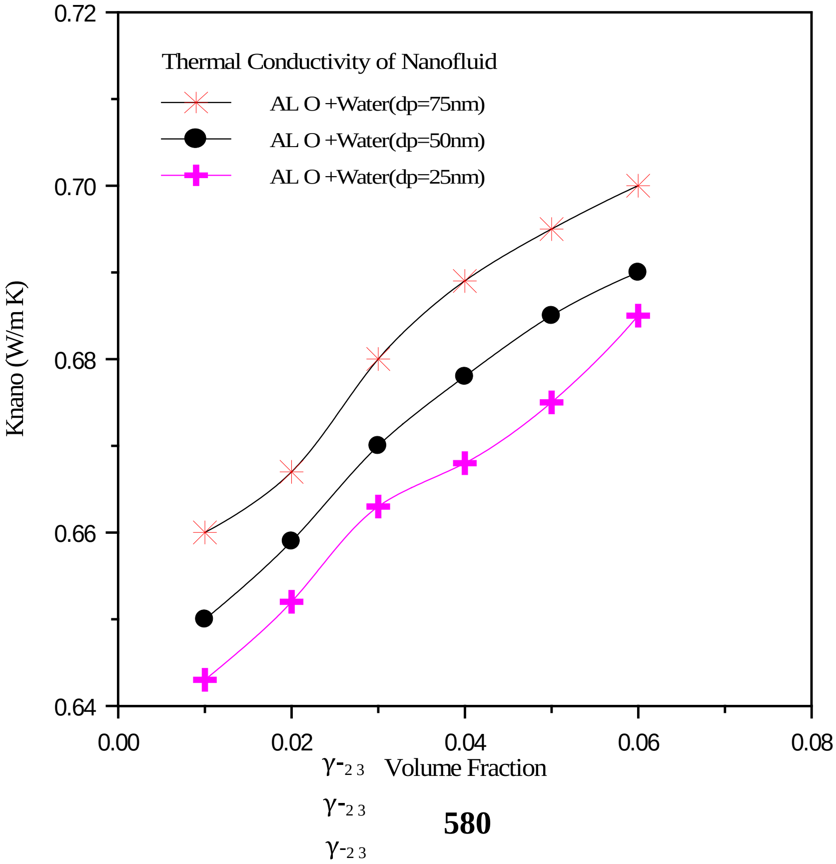


Fig. 7 thermal conductivity of distilled water – based γ-Al_2O_3nanofluid

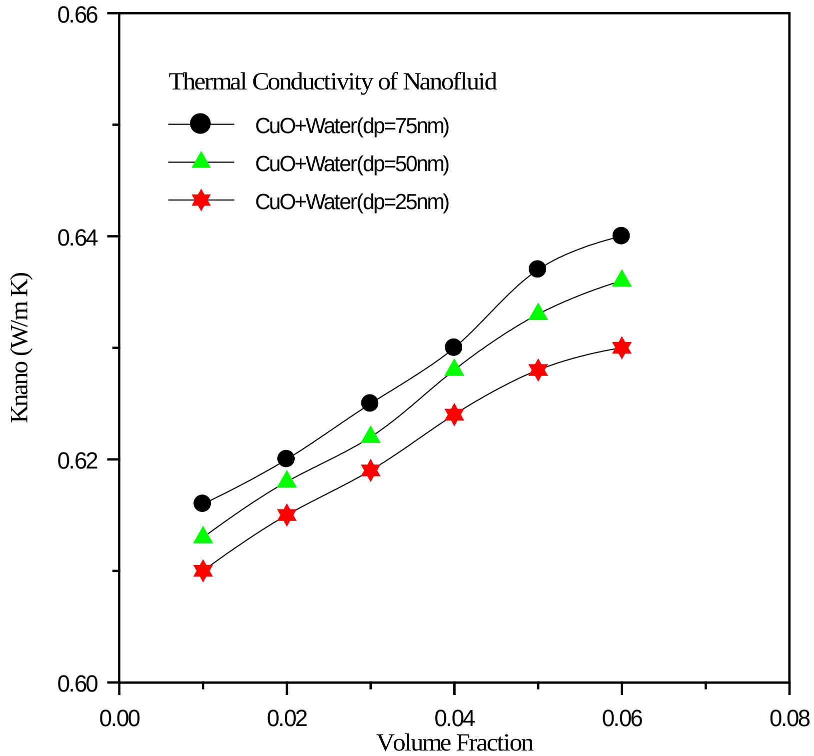


Fig. 8 thermal conductivity of distilled water – based CuOnanofluid

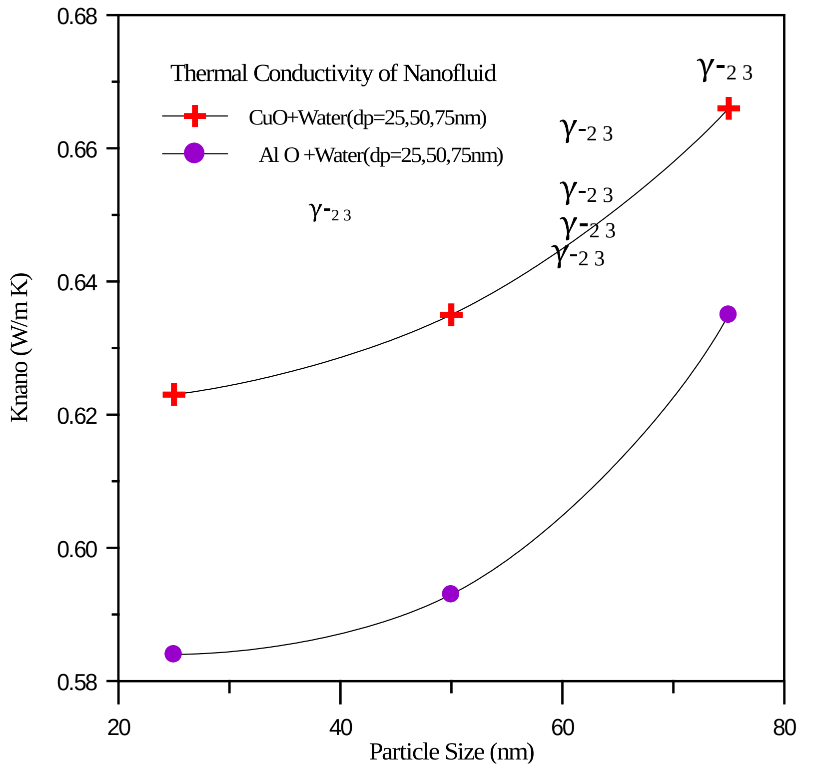


Fig. 9 thermal conductivity of nanofluids versus particle size

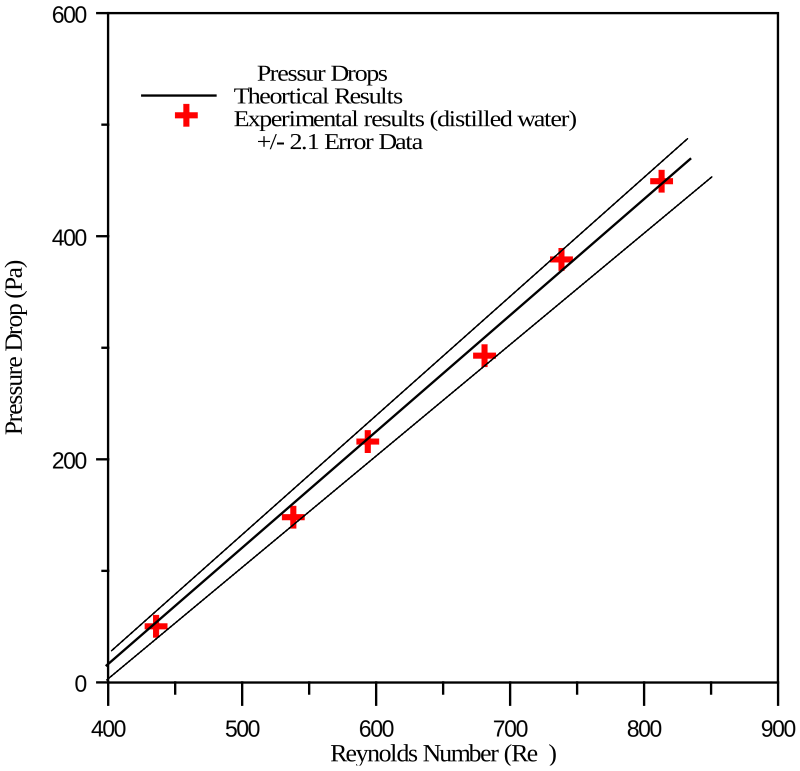


Fig. 10 comparison between theoretical and experimental pressure drop of water

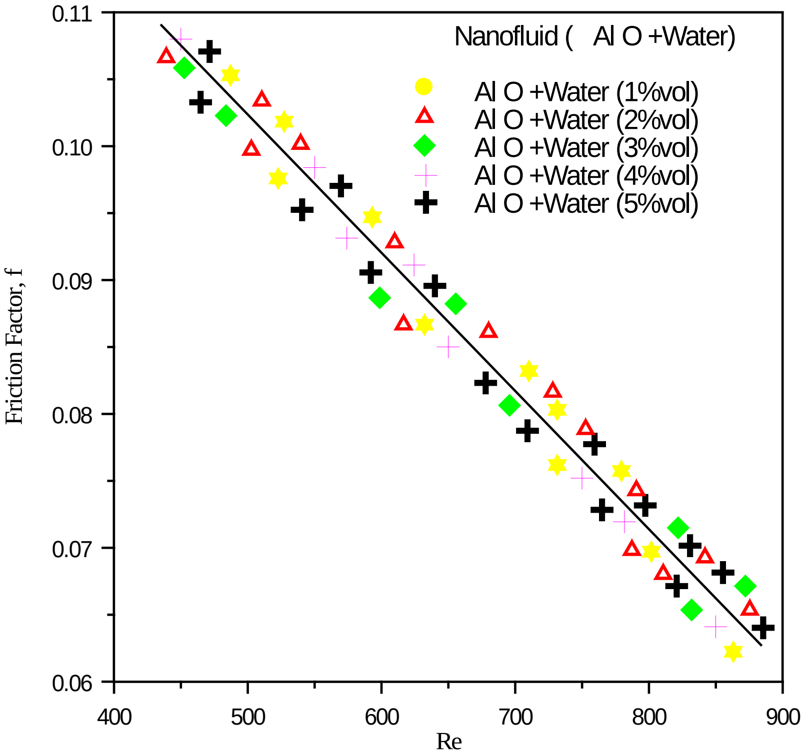


Fig. 11 the frictionfactor of distilled water – based γ-Al_2O_3nanofluid inlaminar flow

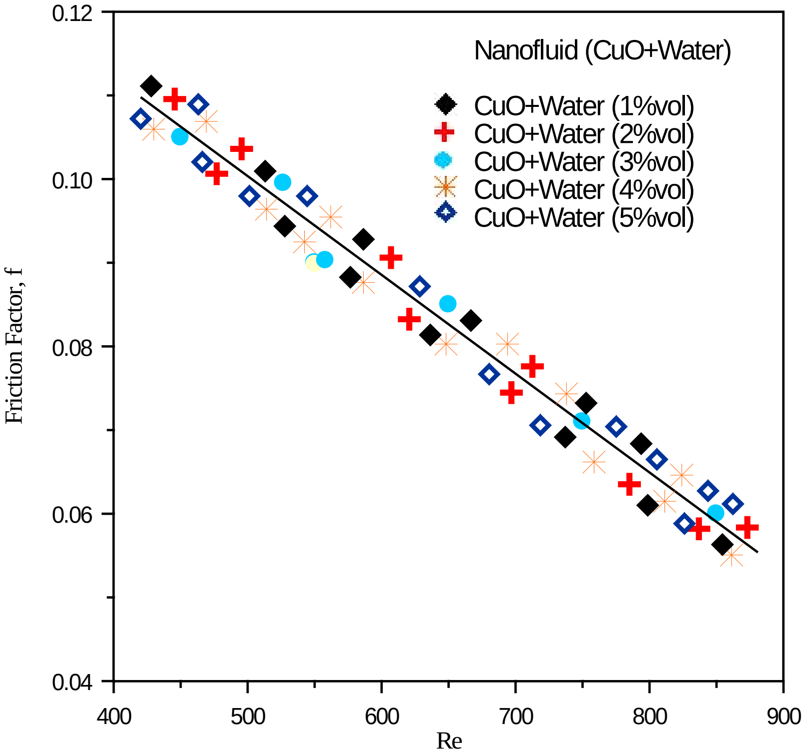


Fig. 12 the frictionfactor of distilled water – based CuOnanofluid in laminarflow

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