Enhancement of Heat Transfer Coefficient Using Fe2O3 –Water Nanofluids

N.I.Zouli[1], S.A.M. Mohammed[2] and M.H. Al-Dahhan[1*]

[1]Multiphase Reactors and Applications Laboratory (m-Real),Chemical and Biological Engineering Department., Missouri University of Science and Technology, Rolla, MO 65409 USA
niz8vb@mst.edu, aldahhanm@mst.edu

[2]Multiphase Reactors and Applications Laboratory (m-Real),Chemical Engineering Department
College of Engineering – University of Baghdad – Iraq ,sawsan.albasri@fulbrightmail.org

ABSTRACT

In this work, we developed a local heat transfer probe that can measure the heat transfer coefficient to study the effect of the nanofluid with various concentrations and size of nanoparticles on the local heat transfer coefficient in a developed separate effect experimental setup.Water with iron (III) oxide (Fe_2O_3) nanoparticles were used as the nanofluids flowing through the test section. The nanoparticle sizes of the Fe_2O_3 were varying between 20 and 40nm. The concentrations for the different nanoparticle sizes were ranged between 0 and 0.09 % in volume fractions. The results show that use of aqueous Fe_2O_3 nanoparticles can significantly enhance heat transfer coefficient in turbulent flow regime, and the enhancement increases with Reynolds and Nusselt number, as well as particle concentration under the conditions of this work, there is an increase of 73.7% at 0.09% volume concentration. The thermal conductivity was measured and compared with the classical model of Maxwell.

Keywords: Fe_2O_3 Nanoparticle, Nanofluid, Thermal Conductivity, Heat Transfer Coefficient

1   INTRODUCTION

Nanofluids, which are the suspensions of nanoparticles in liquids, have received increasing interest for their potential to enhance heat transfer rate in engineering systems while reducing or eliminating the issues of corrosion, sedimentation, and clogging [1].A substantial increments in heat transfer coefficient and liquid thermal conductivity is caused by nanofluids, which makes this its unique feature. According to literature reports on nanofluids, broadly speaking, nanofluids have been studied in two forms of investigations, namely the thermal conductivity and the heat transfer coefficients investigations. Recently, nanofluids have been introduced to enhance thermal conductivity of heat transfer fluids by the addition of a certain concentration of nanoparticles into the heat transfer media [2]. Research has shown that the thermal conductivity and the convection heat transfer coefficient of the fluid can be largely enhanced by suspended nanoparticles [3-5]. Several investigations were carried out to address the effect of nanoparticles on enhancing heat transfer and thermal conductivity properties. According to Masuda et al. [6] , TiO_2/water and γ-Al_2O_3 /water nanofluids with volume fraction 4.3% were both found to have enhanced thermal conductivities, recorded to be 11 and 32% respectively. On the other hand, several theories predict a better heat transfer enhancement for uniformly distributed particles of smaller diameter. Karimi et al.[7] Carried out a comprehensive experimental study on the thermal conductivity of the water-based iron oxide hematite (Fe_2O_3) and magnetite (Fe_3O_4) nanofluids at various volume fractions, temperatures, and magnetic field strengths. The magnetic field was observed to have a greater influence on magnetite than the hematite ferrofluid, and at a volume fraction of 2%, a 175% enhancement was observed for the magnetite ferrofluid, as compared to pure water, which is just 15% while the for the hematite ferrofluid had a 38.5 %.enhancement. This study presents the enhancement in heat transfer coefficient using Fe_2O_3 water based nanofluids. The Fe_2O_3 nanoparticles were used in this research with size of 20-40 nm. In this work a local heat transfer coefficient technique was developed, fabricated and tested. The experiments were conducted at a Re range of 5100 –5600 and at concentrations of (0.01, 0.02, 0.05 and 0.09) vol%.

2   EXPERIMENTAL WORK

The experimental methods mainly consist of nanofluids preparation, Evaluation of thermal and physical properties, and measurement of a local heat transfer coefficient.

2.1   Nanofluid Preparation

Preparation of nanofluids is the main step in the use of nanoparticles for heat transfer coefficient and thermal conductivity sudies. Spherical-shaped Fe_2O_3 nanoparticles with a diameter of 20-40 nm were used with deionized water as basefluid to prepare the nanofluid employed in this study. Two steps method was used for the preparation of Fe2O3/water nanofluids . Different volume fractions (0.01, 0.02, 0.05, and 0.09) of Fe_2O_3 nanoparticles were intimately mixed with the deionized water using IKA ULTRA-TURRAXR T 25 Digital Homogenizer at (5000 rpm) up to 45 min. Then the suspension was further mixed by an intensive ultrasonic technique (Fisher Scientific) for 60

minutes to ensure complete dispersion of the nanoparticles in the base fluid. The prepared nanofluid is stable for experimentation, as no sedimentation was observed.

2.2 Characterization of Fe_2O_3 nanoparticles

The X-ray diffraction (XRD) pattern is displayed in Figure 1 which shows the peaks at 26.103^o, 30.241^o, 35.631^o, 43.285^o, 53.734^o, 57.273^o, and 62.927^o which proves the signatures of the single phase Fe_2O_3 nanoparticles with tetragonal structure. The XRD diffraction can be used to determine which iron oxide compounds are present in nanoparticles and comparing with the reference pattern: Fe_2O_3; Maghemite/TC/RG; syn, 00-039-1346. The sample was put into a solid sample box and set onto the slot of the machine. The 2θ of XRD was scanned from $0o$ to 90°. The pattern obtained from the XRD analysis of the sample was found to match that of the magnetite Fe_2O_3 reference pattern.
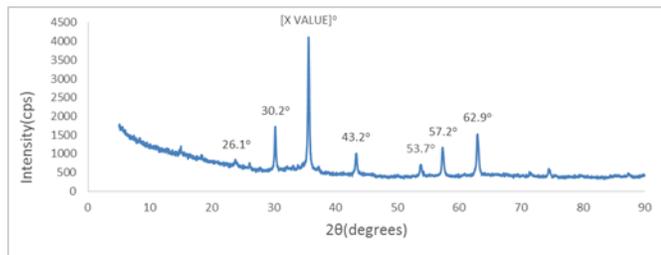

Figure 1:. XRD pattern of Fe_2O_3 nanoparticles.

Figure 2 shows the scanning electron micrograph (SEM) images of Fe_2O_3 nanoparticles. The SEM analysis results indicate that the sample consists of particles with a nearly spherical shape with approximate size of 20-40 nm in diameter. It can be seen in the figure that in all cases, the Fe_2O_3 nanoparticles were observed that some primary particles were aggregated. The level of the aggregation was shown to be dependent of the volume fraction, with 0.02 Fig 2 (A) having least agglomerations. This means that an increase in the volume fraction of the Fe_2O_3 nanoparticles leads to an increase level of aggregation as shown in Fig 2.
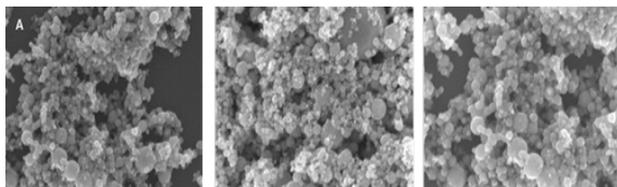

Fig 2: SEM images of Fe_2O_3 nanoparticles samples with different volume fractions: (A) 0.02 (B) 0.04 and (C) 0.09.

2.3 Thermal Conductivity Measurements

The thermal conductivity measurements of the Fe_2O_3/water nanofluids were conducted using Transient Line Source (TLS-100) Probe thermal properties analyser (Thermtest Inc, Canada) based on the transient hot wire method, with an operating range of 0.1 to 5 W/mK. The TLS instrument consists of a digital hand-set controller and needle sensor which is inserted vertically into the nanofluid sample medium. TLS-100 has a single-needle sensor, which is 2.0 mm in diameter, with a height of 100 mm long, connected to a digital hand-set microprocessor for measuring the thermal conductivity of the nanofluids. TLS 100 is easy to use and convenient to handle, with an excellent accuracy of less 5% and reproducibility of less 2%. The measurements were recorded for various samples at different temperatures by inserting the sensor probe into the sample container. The measurements were carried out for different particle volume fractions (0.01- 0.09%). The meter was calibrated prior to the measurements using standard solutions of known thermal conductivity.

2.4 Heat Transfer Coefficient Technique

The heat transfer probe developed and fabricated in Multiphase Reactors Engineering and Applications Laboratory (mReal) to measure the local heat transfer coefficient properly in a single phase flow system by measuring simultaneously the heat flux and surface temperature of the wall. The heat transfer probe comprises of a heat flux sensor (0.15 in x0.08 in) with a fast response time of about 0.02 sec and a thermal resistance of 0.003 °F/BTU/ft²hr. The sensor was placed in a slit mounted inside the test section wall flashed to the wall without disturbing the flow. A photo and schematic diagram of the heat transfer probe are shown in Fig. 3. In this test setup, the two (T-type) thermocouples were purchased from Omega Engineering Inc. USA. Both thermocouples were mounted on the test section at axial positions of 82.55 mm (T_1) and 133.35 mm (T_2) from the inlet of the test section to measure the bulk temperatures of nanofluid. This technique elegantly gives reproducible data under versatile operating conditions. It comprises of the following components: constant heat flux probe, DC power supply, amplifier, thermocouple sensors, data acquisition (DAQ) system and PC. The heat flux as well as the surface temperatures for each experimental run was monitored until the steady-state condition has been reached. The signals from the heat flux as well as the thermocouples were sampled at 50 Hz for about 40 s simultaneously. Equation (1) below describes the relationship between the local instantaneous heat transfer coefficient between the fixed heat flux sensor at surface temperature of (T_{si}) and the bulk fluid (T_{bi});

$$h_i = \frac{q_i}{T_{si} - T_{bi}}; \Delta T_i = T_{si} \quad T_{bi} \tag{1}$$

Where, h_i: local instantaneous heat transfer coefficient ($KW/m^2.k$), q_i: instantaneous heat flux measured by the sensor (KW/m^2), T_{si}: instantaneous surface temperature of the probe (K), T_{bi}: instantaneous bulk temperature of the media (K). The local averaged heat transfer coefficient (h) on the other hand can be obtained from the following expression;

$$h_i = \frac{1}{n}\sum_{i=1}^{n}\frac{q_i}{T_{si}-T_{bi}} = \frac{1}{n}\sum_{i=1}^{n}h_i \qquad (2)$$

Where n is the total number of experimental data points. In the present work, n = 2050 samples were used for all operating conditions, to establish a high stable value of heat transfer coefficients.
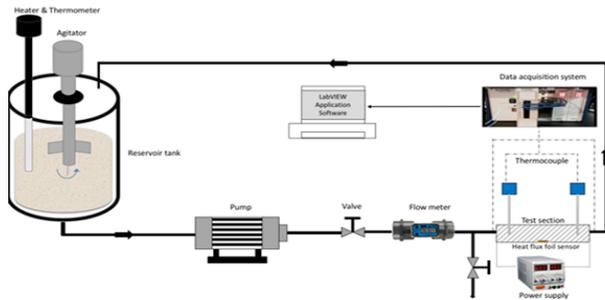

Figure 3: Schematic of Experimental setup.

3 RESULTS AND DISCUSSIONS

3.1 Effect of Particle Volume Fraction on Thermal Conductivity

The results obtained in the current study indicated the thermal conductivity of the nanofluid increases with increasing volume fraction. The relationship between the thermal conductivity ratio and the volume fraction of water-based Fe_2O_3 nanofluids at various experimental temperatures of 25, 45, 55 and 65 °C was presented in Figure 4 shows. It is apparent that even at the lowest volume fraction the thermal conductivity of Fe_2O_3 nanofluid was higher than that of the base fluid and as these volume fractions were increased, enhancements of the thermal conductivity were observed. Thermal conductivity of the base fluid without Fe_2O_3 was found to be 0.595W/m K, however, after the addition of the nanoparticle (Fe_2O_3) at the highest volume fraction, this was found to be enhanced by 23%. This incredible increase in thermal conductivities of Fe_2O_3 nanofluids was attributed to the clustering and alignment of nanoparticle observed. This result was compared with the Maxwell model for the series of the particle volume fraction values employed in the study and was found to be in good agreement with the experimental data.
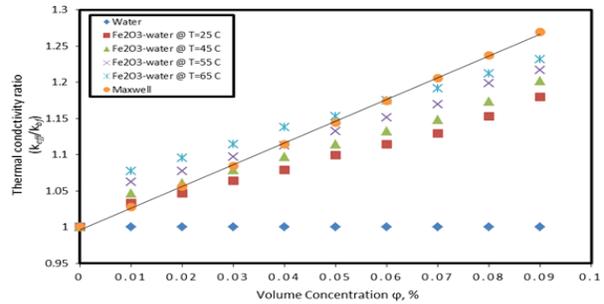

Figure 4: Effects of volume concentration on thermal conductivity of Nanofluids.

3.2 Effect Temperature on Thermal Conductivity

The temperature dependence of the Fe_2O_3-water nanofluid thermal conductivity at various volume fractions were compared to that of water base fluid was shown on Fig. 5.0. It was found that the thermal conductivity of both the nanofluid and the base fluid was generally observed to increase with increasing temperature, although the increase in the case of the nanofluid was found to be more pronounced. Water was found to have the least volume fraction for thermal conductivity at every temperature measurement recorded (25-65oC), and addition of more nanoparticles (0.01-0.09 vol %) enhances the thermal conductivity relative to the water. Thus, the 0.09 vol% volume fraction having the highest thermal conductivity at every temperature measurement recorded.
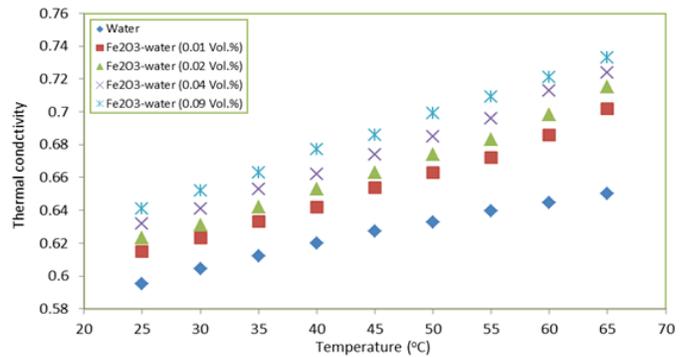

Figure 5: Effects of temperature on thermal conductivity of Nanofluids.

3.3 Effect of Nanoparticle Concentration on Convective Heat Transfer Coefficient

Figure 6 illustrates the enhancement percentage of heat transfer coefficient with the concentration of Fe_2O_3 nanoparticles. It shows that as the Fe_2O_3 concentration increases, the heat transfer coefficient increases. In throught the expriment the enhancement in heat transfer coefficient was linear with the increase in concentration of Fe_2O_3 nanoparticles. The highest enhancement in heat transfer

coefficient of Fe_2O_3 ¬nanofluis was found up to 73.7% at 0.09 vol.%. This substantial enhancement is obtained by adding a very small amount of Fe_2O_3 nanoparticles to the distilled water. It was observed that the enhancement of heat transfer coefficient depends on increasing of the fluid thermal conductivity and decreasing of thermal boundary layer thickness. As suggested by some researchers [8-9] the heat transfer enhancement of nanofluidsIn addition, the convective heat transfer coefficient is largely influenced by the particles' Brownian motion, thermo-physical properties and specific surface area.
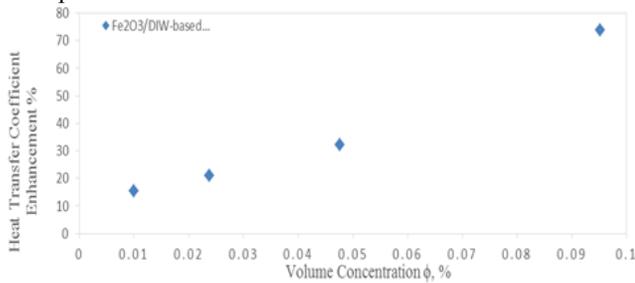

Figure 6: Heat transfer coefficient vs. volume concentration of Fe_2O_3 nanoparticles.

3.4 Effect of of the Nanofluid Reynolds number on Convective Heat Transfer Coefficient

The Reynolds number of Fe_2O_3/water nanofluid for turbulent flow regime studied in this work was taken from 5000 to 5700.Reynolds number of nanofluids can be defined as:

$$ Re = \frac{\rho v d}{\mu} $$

where p is the density (kg/m3), v is the velocity (m/s), d is the tube diameter (m) and μ is the viscosity (kg/m.s). The relationship between the local heat transfer coefficient of the Fe_2O_3/water nanofluid and the nanofluid Reynolds number at different nanoparticle concentrations and temperature (25-65 °C) was graphically shown on Fig. 7.
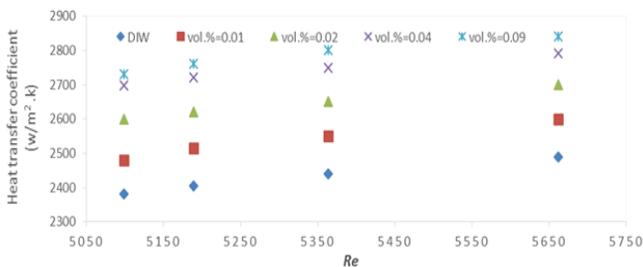

Figure 7: Heat transfer coefficient of water-based Fe_2O_3 nanofluids as a function of Reynolds number at different volume concentration.

The results showed a significantly increase in local heat transfer coefficient of nanofluids with Reynolds number. Also, at a constant Reynolds number, the local heat transfer

coefficient was found to increase with increasing the nanoparticle concentration. The maximum local heat transfer coefficient value was recorded at 0.09 vol.% and Re = 5650 which is 2900 W/m^2 K. The enhancement of about 14.1 % in the heat transfer rate relative to that of the base fluid was observed.

4   CONCLUSIONS

To investigate the effects on convective heat transfer coefficient resulting from suspensions of nanoparticles and thermal conductivity,the convective heat transfer coefficient and thermal conductivity of Fe_2O_3-water nanofluids were measured. The enhancement of the convective heat transfer coefficient and thermal conductivity increased to 73% and 23% at 0.09 vol% ,respectively.

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