International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:10, No:8, 2016

Determination of Thermophysical Properties of Water Based Magnetic Nanofluids

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Abstract**—**In this study, it was aimed to determine the thermophysical properties of two different magnetic nanofluids ($NiFe_2O_4$-water and $CoFe_2O_4$-water). Magnetic nanoparticles were dispersed into the pure water at different volume fractions from 0 vol.% to 4 vol.%. The measurements were performed in the temperature range of 15 ºC-55 ºC. In order to get better idea on the temperature dependent thermophysical properties of magnetic nanofluids (MNFs), viscosity and thermal conductivity measurements were made. SEM images of both $NiFe_2O_4$ and $CoFe_2O_4$ nanoparticles were used in order to confirm the average dimensions. The measurements showed that the thermal conductivity of MNFs increased with an increase in the volume fraction as well as viscosity. Increase in the temperature of both MNFs resulted in an increase in the thermal conductivity and a decrease in the viscosity. Based on the measured data, the correlations for both the viscosity and the thermal conductivity were presented with respect to solid volume ratio and temperature. Effective thermal conductivity of the prepared MNFs was also calculated. The results indicated that water based $NiFe_2O_4$ nanofluid had higher thermal conductivity than that of the $CoFe_2O_4$. Once the viscosity values of both MNFs were compared, almost no difference was observed.

Keywords**—**Magnetic nanofluids, thermal conductivity, Viscosity, $NiFe_2O_4$-water, $CoFe_2O_4$-water.

I. Introduction

THE last technological developments in the electronic and thermal systems made a reference to necessity of increasing heat transfer of thermal systems. It is not possible to answer the increasing cooling load with the present systems, and there are growing needs in high heat transfer performance. Thus, many studies have been carried out on heat transfer enhancement with both active and passive methods. While active methods include the processes that require an additional energy such as twisting, mechanical stirring and vibrating; passive methods consist of processes such as geometrical orientations, enhancement of the thermal properties of the working fluid [1], [2].

Nanofluid applications, which are one of the passive methods, have become a subject that has growing attention in recent years. Choi [3] has become the pioneer in the field of enhancement of thermal properties and application of nanofluids in different thermal systems. Nanofluids prepared by suspending metal and metal-oxide particles in nanometer size into the different base fluids have a great potential concerning heat transfer and cooling of electronic systems [4], [5]. MNFs are new generation of nanofluids and draw attention in recent years. The fluids prepared by the suspension of the magnetic nanoparticles into the nonmagnetic base fluids are called as ferrofluids [6]. The particles used in the production of MNFs mainly consist of Fe, Mn, Zn and their oxide compounds [7]-[9]. This type of fluids is sensitive to the magnetic field like their magnetic solid materials [10], [11]. In view of thermal engineering, adding solid particles into the base fluid has clearly increased thermal conductivity but the viscosity which is another critical thermodynamic property also increases [12], [13]. Thus, the use of MNFs in thermal systems causes not only thermal performance enhancement but also an increase in the pressure drop.

There are numerous study concerning with the thermal properties of the ferrofluids [14]-[16]. Yu et al. [17] considered kerosene based Fe_3O_4 MNFs with a particle size of 155 nm and found more than 30% thermal conductivity enhancement at volume fraction of 1%. Parekh and Lee [8] investigated the thermal conductivity of Fe_3O_4-kerosene MNFs in the temperature range of 25–65 °C at 4.7% volume fraction. They reported that approximately 17% enhancement in thermal conductivity was achieved. Philip et al. [18] studied Fe_3O_4–kerosene MNFs with an average particle size of 6.7 nm. They observed that 23% enhancement in the thermal conductivity was obtained at the particle volume fraction of 7.8%. Djurek et al. [19] studied on $CoFe_2O_4$ nanoparticles with an average particle size of 15 nm, which were suspended into the water chosen as base fluid. They measured the thermal properties of MNFs at the constant temperature. Fertman et al. [20] considered hydrocarbon based MNFs consisting of colloidal Fe_3O_4 particles coated with oleic acid as surfactant. They discussed temperature dependent thermal conductivity in a temperature range of 20 to 80 °C from 0.01 vol. % to 0.2 vol. %. Sundar et al. [21] presented the thermal conductivity correlation for water based Fe_3O_4 nanofluid with an average particle size of 13 nm. The experimental results exhibited a 48% improvement in the thermal conductivity of nanofluid with volume concentration of 2% at 60 °C.

Karimi et al. [22] studied the thermal conductivity of $NiFe_2O_4$. The experiments were carried out at different volume concentrations up to 2 vol. %. The $NiFe_2O_4$ nanoparticles with an average particle size of 8 nm were synthesized using a microemulsion method. The highest enhancement in the thermal conductivity at 2 vol. % was about 17.2% at 55 °C.

In another experimental study, Karimi et al. [6] performed a study in order to investigate the thermal conductivity of water based Fe_3O_4 and $CoFe_2O_4$ MNFs. They reported that the

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thermal conductivity of MNFs increased with increasing particle volume fraction and temperature. The thermal conductivity enhancement was about 22% and 25%for Fe_3O_4 and $CoFe_2O_4$ MNFs at 4.8 vol. % and 60 °C, respectively.

Although studies concerning with the thermal conductivity enhancement of MNFs have been conducted by many researches, further investigations are still needed to explain the effects of various parameters such as the effects of volume fraction and magnetic nanoparticle type on the thermal conductivity and viscosity. There are only few works which refer the temperature dependence and make a comparison between the thermal conductivity of various MNFs to identify the effective parameters on the thermal conductivity and viscosity. The aim of this study is to experimentally investigate the thermophysical properties of water based $NiFe_2O_4$ and $CoFe_2O_4$ MNFs. In the present study, Scanning Electron Microscope (SEM) images of MNFs have been analyzed in terms of stability. Detailed experimental measurements are performed in order to examine the thermal conductivity and viscosity of both MNFs at different volume fractions ranging from 0 vol. % to 4 vol. %.

II. Experimental Setup

A. Synthesis and Dispersion Characteristics of $CoFe_2O_4$-water Nanofluids

Cobalt nitrate, ferrite nitrate, acetone, and sodium hydroxide were purchased from the Sigma Aldrich Corporation. While oleic acid was operated as the surfactant, deionized water was used as the catalase. Firstly, in order to obtain precursors, hydrous dispersions of ferrite nitrate and cobalt nitrate were produced individually for the molar ratio of 1:2. Then, the solutions were blended with each other and mixed for two hours to have a homogeneous mixture. After stirring, pH value of the obtained solution was measured as 2.7. In order to set the pH value to 9, 2 M sodium hydroxide was supplemented drop by drop to the mixture by simultaneously stirring the solution. After black sediment obtained as mentioned above was heated for two hours at boiling temperature. It was exposed to cooling and washed with pure water in order to remove impurities. 200 ml of 2 M aqueous nitric acid was added into the precipitate and blended for two hours. The supernatant mixture was eliminated, and the deposit was washed with acetone. Aqueous ammonia and oleic acid were added in the same amount and mixed at 80 ºC for two hours. Oleic acid was used in order to prevent the agglomeration of cobalt ferrite nanoparticles in the suspension. The chemical reaction is given as;

$$Co^{2+} + 2Fe^{3+} + 8OH^{-} \rightarrow CoFe_2O_1 + 4H_2O$$
$$\sim COOH + NH_4OH \rightarrow \sim COONH_4 + H_2O$$

The volumetric concentration of 1%, 2%, 3% and 4% of cobalt ferrite/water nanofluids were obtained adding proper amount of pure water. After the preparation of the nanofluids, the mixture was sonicated in the ultrasonic homogenizer (UIP 1000S, Hielscher GmbH) for two hours.

The synthesis of $NiFe_2O_4$ was done as given by [22]. The volumetric concentration of 1%, 2% and 3% nickel ferrite/water nanofluids were obtained adding suitable amount of pure water. Likewise, the solution of $NiFe_2O_4$-water nanofluids was sonicated as in $CoFe_2O_4$-water nanofluids.

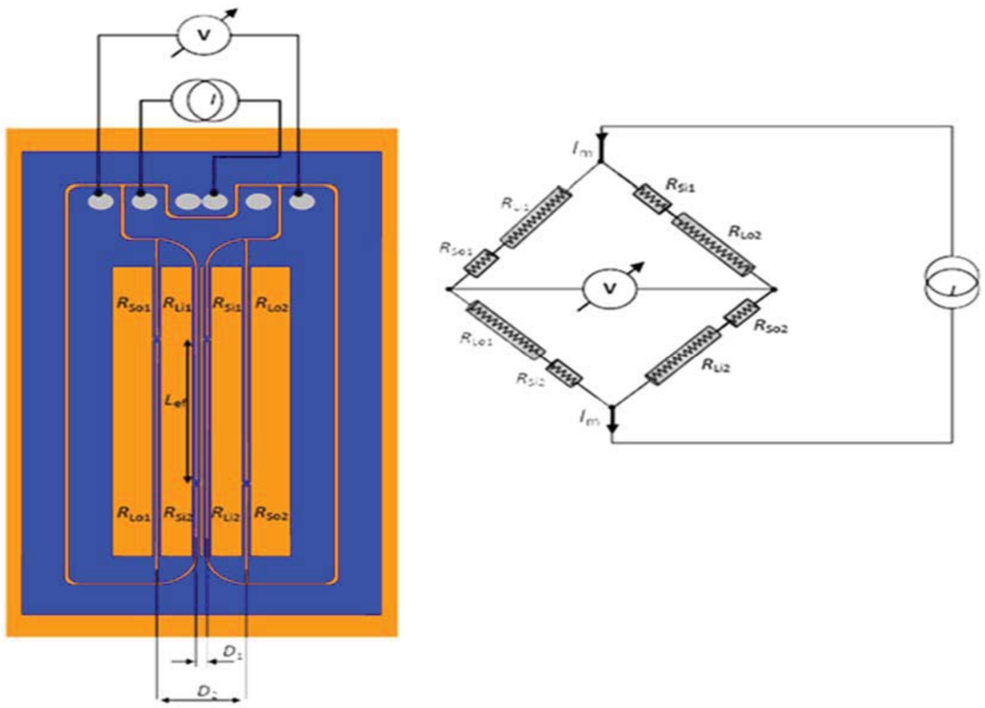

Fig. 1 THB6K sensor and equivalent electrical circuit diagram [24]

B. Measurement of Thermal Conductivity

The thermal conductivity of deionized water and nanofluids were measured with Linseis thb 100 thermal property meter which measures the thermal conductivity based on transient hot bridge (thb) technique. The principle of the transient hot bridge method was given in detail by [23]. Fig. 1 shows the thb6k sensor and equivalent electrical circuit diagram of the sensor. The thb sensor is considered as a printed circuit of nickel foil between two insulating polyimide layers. It consists of the meander strip which is separated into two segments called tandem-strip. In order to enhance the sensitivity of the tandem-strip, a bridge network is built out of four parallel tandem-strips. By using an interconnection of all eight resistor elements, a symmetric bridge circuitis built without zero point adjustment. The bridge voltage corresponds to the temperature difference of the middle parts of the strips (l_{eff}) of which one is inner strip and the other is outer strip [24].

The typical response of THB measurement is given in Fig. 2 The measured voltage U_s is shown as a function of time together with the dimensionless derivation *mln(t)* over *ln(t)*.

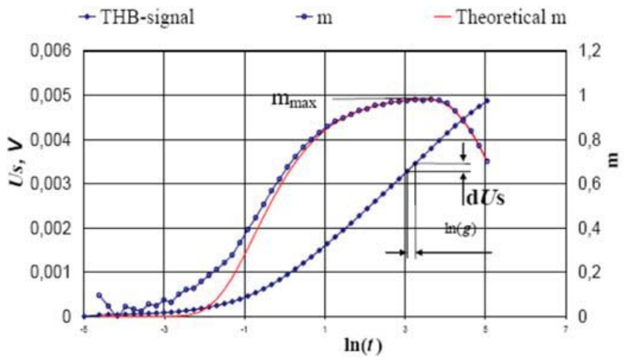

Fig. 2 Typical response of THB sensor [24]

The maximum gradient of the temperature difference ΔT caused by the self-heating of the current I_m or the maximum slope of the signal $d[U_s]$ is proportional to the thermal conductivity. The following equations show the relations [24]:

$$WLF = \frac{\alpha R_{eff}{}^2 \ln(g)}{4\pi L_{eff} \mathrm{d}(U_s)_{max}} \left(\frac{I_m}{2}\right)^3 m_{max} \qquad (1)$$

$$m_{max} = \left(\frac{D_1}{D_2}\right)^{\frac{2D_1^2}{D_2^2-D_1^2}} - \left(\frac{D_1}{D_2}\right)^{\frac{2D_2^2}{D_2^2-D_1^2}} \qquad (2)$$

where WLF represents the thermal conductivity, R_s is electrical resistance, L_{eff} is the effective length, R_{eff} is effective resistance and α is thermal coefficient of the specific resistance of the nickel foil. The terms of $D_1$and D_2 are the distance between the center axis of the inner and outer strips, respectively.

C. Measurement of Viscosity

The experimental setup for the measurement of the dynamic viscosity of pure water and nanofluids consists of a sine–wave viscometer of SV-10 supplied from A&D Corp. and WiseCircu water bath circulator with a sensitivity of 0.1 °C. The schematic diagram of the vibrational viscometer is shown in Fig. 3. In the SV-10 viscometer, two thin sensor plates are immersed in the sample. When the spring plates are vibrated with a uniform frequency, the amplitude varies in response to the quantity of the frictional force generated by the viscidity between the sensor plates and the sample. The vibro viscometer controls the driving electric current for vibrating the spring plates so as to develop uniform amplitude. The driving force required for the viscidity is directly proportional to the product of kinematic viscosity and density [25]. Therefore, on vibrating the spring plates with a constant frequency to develop uniform amplitude for samples with varying viscosities, the driving electric current (driving power) is also directly proportional to the product of viscosity and density of each sample. Using a theoretical formula based on this measurement principle, the physical quantity measured by vibro viscometers is detected as "viscosity × density" in mPa.s unit. The viscosity measurement range of the SV-10 is 0.3 mPa.s to 10000 mPa.s.

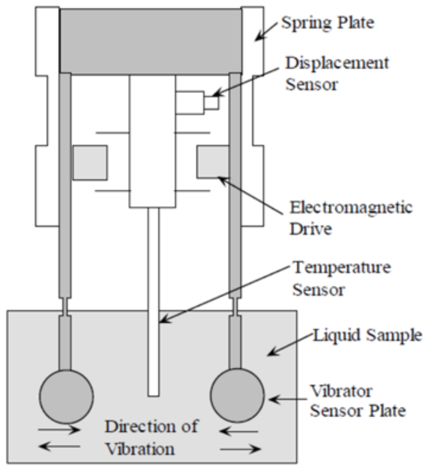

Fig. 3 A schematic diagram of Vibro Viscometer [25]

Dynamic viscosities of pure water and water based $CoFe_2O_4$ and $NiFe_2O_4$ nanofluids with a volume fraction range of 1-4% were measured at the temperature range of 15 °C to 55 °C.

III. Results and Discussion

A. Thermal Conductivity Measurements of $CoFe_2O_4$/Water Nanofluids

The effective thermal conductivity of $CoFe_2O_4$/water nanofluids for volume concentrations of 1, 2, 3 and 4% were measured at the temperature range of 15 °C to 55 °C with 10 °C intervals. Firstly, the experimental measurement device and method of the present study was validated by comparing with the results of [26] for thermal conductivity of pure water as given in Fig. 4. As seen from Fig. 4, the maximum deviation from the results of [26] is about 1.7% at 25°C.

Fig. 5 shows the thermal conductivity ratio k_{nf}/k_{bf} variations of $CoFe_2O_4$ nanofluids versus particle volume concentration. While k_{nf} represents the thermal conductivity of nanofluids, k_{bf} symbolizes the thermal conductivity of the base fluid. As shown in Fig. 5, the thermal conductivity of $CoFe_2O_4$/water nanofluid increases with nanoparticle volume fraction. The enhancement of thermal conductivity for nanofluid is highly apparent at higher volume concentrations. While $CoFe_2O_4$ nanoparticles lead to an increase about 4% in the thermal conductivity at 1% volume fraction, the enhancement is approximately 7% at 4% volume concentration. The variation of the thermal conductivity with temperature is illustrated for different volume concentrations in Fig. 6. It can be seen from the graph that the addition of $CoFe_2O_4$ nanoparticles into the deionized water increases the thermal conductivity. While the increase in thermal conductivity is about 3.5% for ϕ=1% at 15 ^oC, the enhancement becomes approximately 6.5% for ϕ=4% at the same temperature. The slope of the 1% vol. in Fig. 6 is steeper than the slopes of other concentrations. Interestingly, the thermal conductivity values of the nanofluids with 1 vol. % and 3 vol. % have almost the same value 55 ^oC. Moreover, the thermal conductivity of nanofluids with 1 vol. % is higher than that of 2 vol. % at higher temperatures than 35 ^oC. The difference between the slope of the nanofluid with 1 vol. % and other nanofluids can be attributed to the enhanced stability and homogenous distribution of the nanoparticles in the base liquid at low concentrations. Nevertheless, the thermal conductivity increases with increasing temperature at all volume fractions. The increase in the Brownian motion of nanoparticles with increasing temperature results in the enhancement of the thermal conductivity of nanofluids.

The experimental results are compared with different prediction models proposed in the literature (Fig. 7). The Maxwell model [27] computes the thermal conductivity ratio of nanofluids including spherical nanoparticles for low volume fractions.

$$k_{nf} = k_{bf}\left(\frac{k_p+2k_{bf}+2(k_p-k_{bf})\phi}{k_p+2k_{bf}-(k_p-k_{bf})\phi}\right) \quad (3)$$

Bruggeman [28] introduced a model to predict the interactions among homogenous distributed spherical nanoparticles. The model is:

$$k_{eff} = \frac{1}{4}\left[(3\phi-1)k_p + (2-3\phi)k_{bf}\right] + \frac{k_{bf}}{4}\sqrt{\Delta} \quad (4)$$

$$\Delta = \left[(3\phi-2)^2(k_p/k_{bf})^2 + (2-3\phi)^2 + 2(2+9\phi-9\phi^2)(k_p/k_{bf})\right] \quad (5)$$

where ϕ is the nanoparticle volume concentration. The terms of kf and kp represent the thermal conductivity of the base fluid and nanoparticles, respectively. Waps [29] proposed a model in order to predict the thermal conductivity of nanofluids as:

$$k_{nf} = k_{bf}\left(\frac{k_p+2k_{bf}-2(k_{bf}-k_p)\phi}{k_p+2k_{bf}+(k_{bf}-k_p)\phi}\right) \quad (6)$$

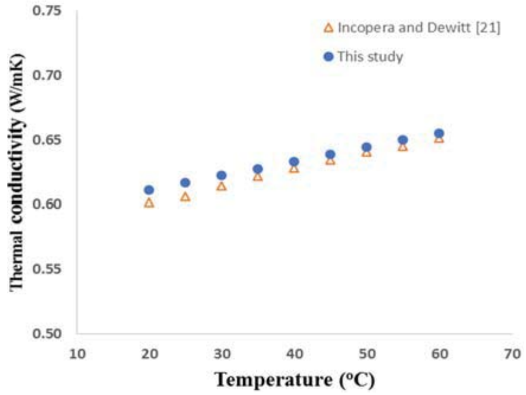

Fig. 4 Comparison of the thermal conductivity data for pure water with [26]

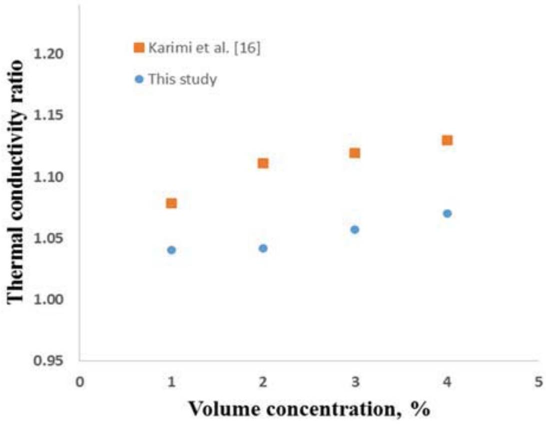

Fig. 5 Comparison of the experimental data with [22]

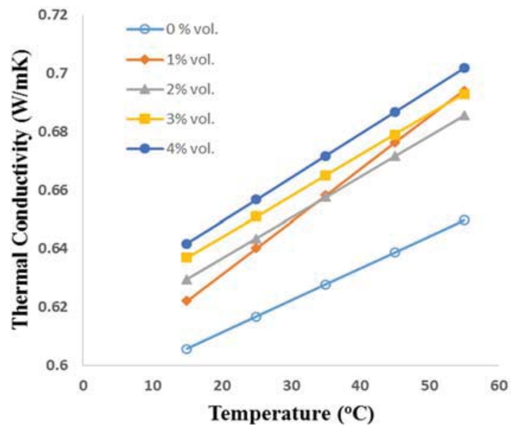

Fig. 6 Thermal conductivity variations of pure water and $CoFe_2O_4$/water nanofluids

As seen from Fig. 7, our experimental data is in a good agreement with Maxwell, Bruggeman and Waps models for whole range of particle volume concentrations. There are small differences between the experimental results and the given three models at low and high temperatures. The Maxwell model seems to give closer predictions to the measured data.

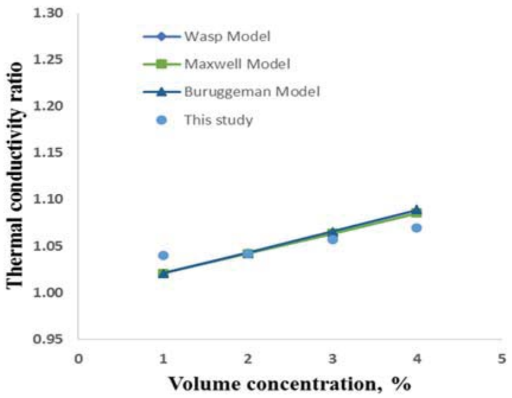

Fig. 7 Comparison of the measured thermal conductivity ratio of the $CoFe_2O_4$/water nanofluids with the well-known correlations

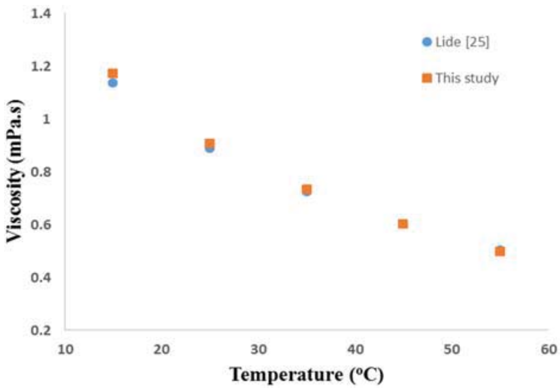

Fig. 8 Comparison of measured viscosity with results of Lide [25]

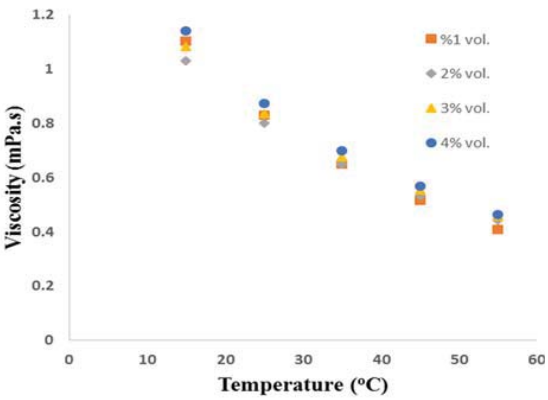

Fig. 9 The variation of viscosity of pure water and $CoFe_2O_4$/water nanofluids with temperature for different volume concentrations

B. Viscosity Measurements of $CoFe_2O_4$/Water Nanofluids

In order to validate our experimental setup, the viscosity of deionized water was measured before each experiment. The measured values were compared with the experimental results of Lide [30]. As seen from Fig. 8, the measured viscosity values are in good agreement with the values of base fluid. After validation, the viscosity values of $CoFe_2O_4$/water nanofluids were obtained for 1, 2, 3 and 4% volume concentrations at the temperature range of 15-55°C.

The variation of viscosity of the nanofluids with the temperature is given for different volume concentrations in Fig. 9. The viscosity of the $CoFe_2O_4$nanofluids decreases with increasing temperature as expected. An increase in the particle volume concentration causes viscosity to increase.

C. Thermal Conductivity of $NiFe_2O_4$/Water Nanofluids

The thermal conductivity of $NiFe_2O_4$/water nanofluid was measured for volume fractions of 1, 2 and 3% for the temperature range between 15 °C and 55 °C with an interval of 10 °C. Fig. 10 shows the distribution of thermal conductivity of nickel ferrite nanofluids with temperature at different volume concentrations. As seen from the figure, the thermal conductivity of the nanofluids highly depends on the particle volume concentration and temperature. Thermal conductivity of the nanofluids is greater than that of the pure water. The addition of nickel ferrite particles into the pure water results in an increase about 6.5% in the thermal conductivity for 1 vol. % at 15 °C. At higher concentrations, much more enhancement in the thermal conductivity is achieved. There is an increase approximately 12.5 % in the thermal conductivity of nanofluids for 4 vol. % at 55 °C. The thermal conductivity increases with increasing temperature for the whole range of particle volume fractions. The trends of the thermal conductivity lines with temperature are almost the same.

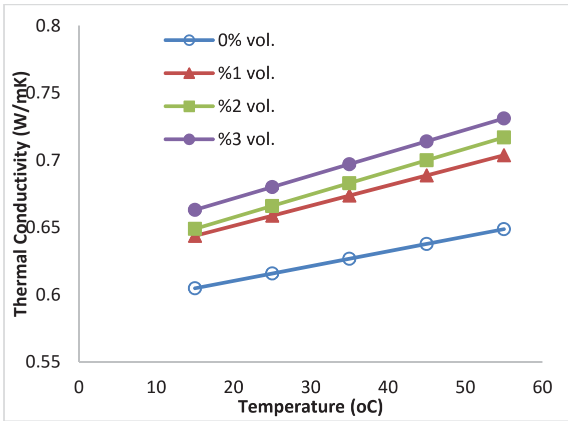

Fig. 10 Thermal conductivity variations of pure water and $NiFe_2O_4$/water nanofluids with temperature for different volume concentrations

Fig. 11 shows the comparison of the thermal conductivity ratio calculated of this study and experimental results of [22]. The thermal conductivity ratio of nickel ferrite/water nanofluid is increased from 6% to 8% at the volume fraction of 1 vol. whereas it grows from 8% to 10% for 2 vol. % within the same temperature range. It is seen from the figure that the present experimental results are close to that of [22] especially at low concentrations.

The experimental results of thermal conductivity ratio of $NiFe_2O_4$/water are compared with different thermal conductivity models in the literature (Fig. 12). As shown in the graph, all three models under predict the enhancement of thermal conductivity ratio as compared with the measured data. While the models underestimate the thermal conductivity of $NiFe_2O_4$/water about 5% at low temperatures, the percentage of under prediction is reduced to 3 at high temperatures.

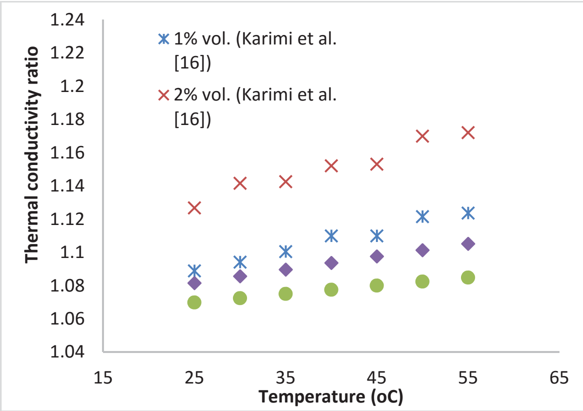

Fig. 11 Thermal conductivity variations of nickel ferrite/water nanofluids with temperature at different volume fractions

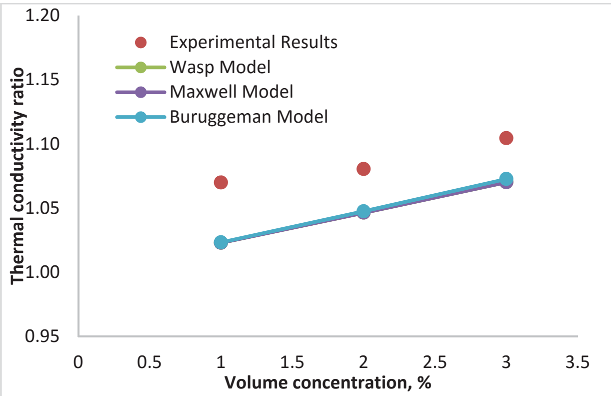

Fig. 12 Comparison of the measured thermal conductivity ratio of the $NiFe_2O_4$/water nanofluids with the well-known correlations

D. Viscosity of $NiFe_2O_4$/water Nanofluids

The variation of the viscosity with temperature at different volume concentrations is given in Fig. 13. The viscosity of nanofluids decreases with increasing temperature for all volume fractions as expected. At lower temperatures, the viscosity of nanofluids generally increases with volume fraction. However, experimental results show that the viscosity of nanofluids with 1 vol. % is higher than the viscosity of nanofluids with 2 vol. %. At higher temperatures, the viscosity of nanofluids converges to one point which is the viscosity value of pure water. The poor stability of nanoparticles within the suspension can be reason of this trend. Though it seems that the viscosity of nanofluids shows less dependency on nanoparticle volume concentrations at higher temperatures.

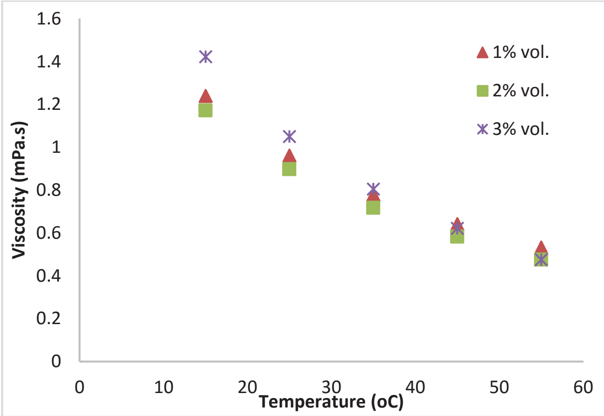

Fig. 13 Viscosity variations of pure water and $NiFe_2O_4$/water nanofluids with temperature for different volume concentrations

IV. Conclusion

The thermophysical properties of water based $NiFe_2O_4$ and $CoFe_2O_4$ MNFs have been investigated experimentally. In the present study, SEM images of MNFs have been analyzed in terms of stability. Detailed experimental measurements have been performed in order to examine the thermal conductivity and viscosity of both MNFs at different volume fractions ranging from 0 vol. % to 4 vol. %. The remarkable conclusions can be summarized as:

- The thermal conductivity of $CoFe_2O_4$/water nanofluid increased with nanoparticle volume fraction. The enhancement of thermal conductivity for nanofluid was highly apparent at higher volume concentrations.
- While $CoFe_2O_4$ nanoparticles lead to an increased about 4% in the thermal conductivity at 1% volume fraction, the enhancement was approximately 7% at 4% volume concentration.
- The thermal conductivity of $CoFe_2O_4$/water nanofluid increased with increasing temperature at all volume fractions.
- There were small differences between the experimental results and the given three models at low and high temperatures. The Maxwell model seemed to give closer predictions to the measured data.
- An increase in the particle volume concentration caused viscosity of $CoFe_2O_4$/water nanofluid to increase.
- The thermal conductivity of the nanofluids highly depended on the particle volume concentration and temperature.
- The addition of $NiFe_2O_4$ particles into the pure water resulted in an increase about 6.5% in the thermal conductivity for 1 vol. % at 15 °C. At higher concentrations, much more enhancement in the thermal conductivity was achieved. There was an increase approximately 12.5% in the thermal conductivity of nanofluids for 4 vol. % at 55°C.

- The thermal conductivity models under predicted the enhancement of thermal conductivity ratio of $NiFe_2O_4$/ water nanofluid as compared with the measured data.

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