American Journal of Materials Synthesis and Processing
2016; 1(4): 47-55
http://www.sciencepublishinggroup.com/j/ajmsp
doi: 10.11648/j.ajmsp.20160104.13

Science Publishing Group

Physical, Chemical Properties and Applications of Transformer Oil Based Ferrofluid/Dielectric Fluid

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To cite this article:
S. R. Chitra, V. Gayathri. Physical, Chemical Properties and Applications of Transformer Oil Based Ferrofluid/Dielectric Fluid. *American Journal of Materials Synthesis and Processing.* Vol. 1, No. 4, 2016, pp. 47-55. doi: 10.11648/j.ajmsp.20160104.13

Received: September 19, 2016; **Accepted**: October 9, 2016; **Published**: January 12, 2017

Abstract: Ferrofluid is colloidal system poised of single domain of nanoparticles dispersed in a carrier liquid. Ferrofluid bargain incredible new potentials to improve heat transfer performance compared with pure liquids and can be watchful to be the next-generation of heat transfer fluids. In the present work Fe_3O_4 nanoparticles were synthesized by co-precipitation chemical synthesis, and were coated with oleic acid as surfactant agent. Owing to their excellent characteristics, ferrofluid find varied applications in enhancing heat transfer. Research work on the concept, heat transfer enhancement mechanism, and application of the ferrofluid is still in its primary stage. This study affords an investigation in this field with focus on applications of ferrofluid due to their thermophysical and electrical properties.

Keywords: Ferrofluid, Nanoparticles, Co-precipitation route, Thermal Conductivity, Density, Specific Heat Capacity, Viscosity, Electrical Conductivity, Dielectric Fluid

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1. Introduction

In ferrofluid, the thermal management and heat treatment process are important in industrial applications such as power, manufacturing, transportation, and electronics. Many researchers are reconnoitering enhanced ways to improve the thermal performance of ferrofluid. One of the methods used is to add nanoparticles of high thermal conductivity materials like metal and metal oxides into ferrofluid to enhance the complete thermal conductivity of the ferrofluid. The thermal conductivity of ferrofluids including metal particles or metal oxide particles has been studied by numerous researchers [1, 2 and 3]. Xuan and Li [4] have revealed that the heat transfer properties of transformer oil can be improved using nanoparticle additives. Generally, the thermal conductivity of ferrofluids increases with an increase of volume fraction and some researchers have observed anomalous thermal conductivity enhancement for dilute suspensions (< 1% by volume) of metallic nanoparticles [5, 6]. The focus of this present work was on ferrofluid containing nano-sized particles dispersed in transformer oil. The precise objectives were determination of the effects of temperature and nanoparticles concentration on the thermal conductivity of ferrofluid and explication of the mechanism of conduction. Thermal conductivity measurements were performed using KD2 Pro technique. The ferrofluid samples consisted of $MgMnNiFe_2O_4$ nanoparticles dispersed in water. Thermal conductivity measurements were performed at wide range of temperature (35°C to 45°C). In addition, a comparison was made amongst the experimental results of thermal conductivity and the results calculated using various models presented for predicting them and discuss their applications.

2. Synthesis for Transformer Oil Based Ferrofluid

Synthesis for transformer oil based ferrofluid for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ $(0.00 \leq x \leq 0.60)$ nanoparticles was prepared by co-precipitation route (Figure 1). Aqueous solution of the compounds and $FeCl_3$ were prepared in separate beakers. After that solutions were mixed at the room temperature and the resulting solution was mixed into the $FeCl_3$ solution.

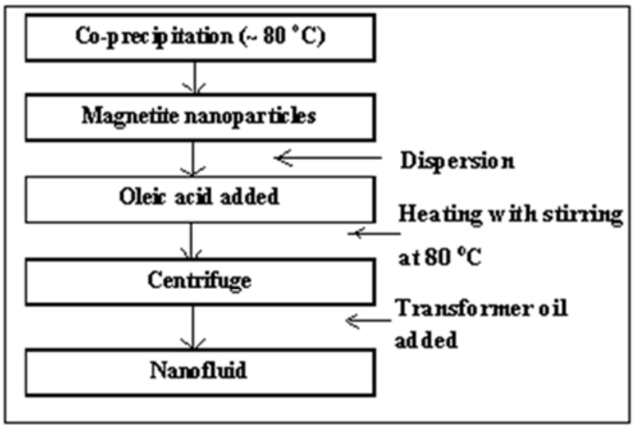

Figure 1. *Flow chart for the preparation technique of transformer oil based ferrofluid.*

Now the solution with sodium hydroxide was allowed to heat until the temperature reached to 85°C. The resulting solution of these was added into the boiling solution of NaOH and temperature of the resulting solution was maintained at 85°C followed by continuous stirring. The pH of the final solution is maintained at 12 and stirring was continued for 3 to 4 hours. Precipitation and formation of nanoferrites takes place by the conversion of metal salts into hydroxides that occurs immediately followed by transformation of hydroxides into ferrites. After completion of the reaction the solution was filtered and washed many times with the distilled water for the elimination of excess of NaOH and then the oleic acid was added to the solution and heated with stirring for 2½ hours. Then the solution was decanted to remove the excess of water and oleic acid and the particles are centrifuged and dried [7].

3. Results and Discussions for Transformer Oil Based Ferrofluid

The particle analysis was done by using zeta potential analysis (Malvern Instrument). A Thermophysical property of the prepared ferrofluid is measured using KD2 pro thermal properties analyzer and DE-V Brookfield viscometer. The electrical conductivity values were measured using a 4-cell conductivity electrode meter (CYBERSCAN CON 11).

3.1. Zeta Potential Analysis

The zeta potential is most often used as an indicator of the dispersion stability for transformer oil based ferrofluid using $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ nanoparticles. Large zeta potentials predict a more stable dispersion [8].

The synthesized MgMnNi-transformer oil based ferrofluidhas high negative zeta potential values and thus they are stable under a wide pH range. The maximum zeta potential value of nickel content (x=0.40) was found to be -18.8 mV, so that the particles are highly stable even at a pH 10 (Figure 2). Table 1 show that zeta potential parameters for all the concentrations of transformer oil based ferrofluid.

Table 1. *Measurements using zeta analysis for transformer oil based ferrofluid for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ with various compositions (x).*

Compositions (x)	Zeta Potential (mV)	Electrical conductivity (mS/cm)	Viscosity (Pa.s)
0.00	-20.2	0.0613	0.881
0.10	-21.4	0.0599	0.812
0.20	-20.3	0.0576	0.886
0.30	-19.7	0.0225	0.874
0.40	-18.8	0.0209	0.834
0.50	-19.5	0.0201	0.879

Dispersant name: Transformer oil; Temperature (°C): 25; Zeta runs: 13; Dispersant Dielectric Constant: 78.5

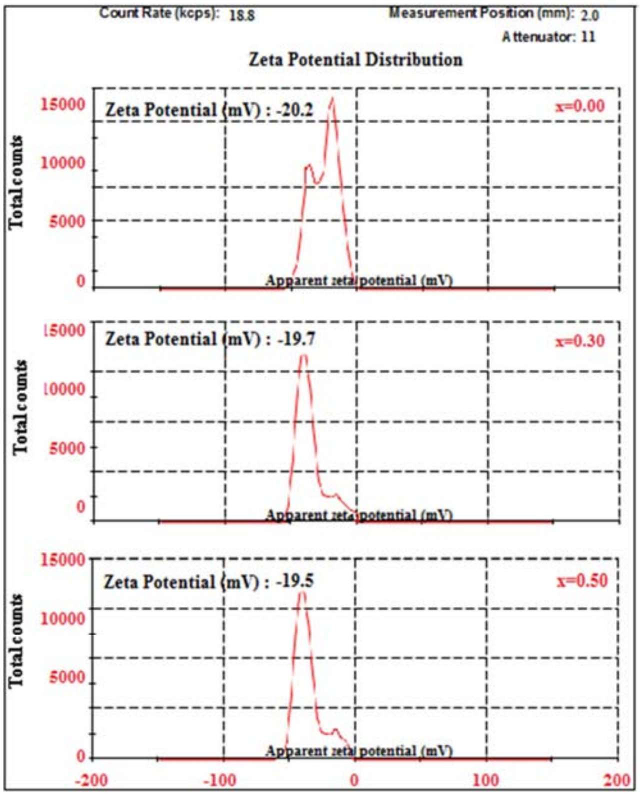

Figure 2. *Zeta potential for transformer oil based ferrofluid for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ nanoparticles with x=0.00, x=0.30 and x=0.50.*

3.2. Thermal Conductivity Measurement

In the present research thermal conductivity measurements were measured for transformer oil based ferrofluid using KD2 Pro method. Experiments performed with KS-1 sensor needle at different temperature for different concentrations of nanoparticles such as 1%, 2% and 4% (Table 2).

Experimental results of thermal conductivity values for transformer oil based ferrofluid at various concentrations with different temperature are shown in Figure 3(a), Figure 3(b) and Figure 3(c). From this we observed that the effective thermal conductivity enhancement of the transformer oil based ferrofluid increases 58% at 4% volume concentration.

Table 2. Thermal conductivity for transformer oil based ferrofluidfor $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ with various volume fractions for Ni=0.00, Ni=0.20 and Ni=0.40.

S. No.	Temperature (°C)	Thermal conductivity ($Wm^{-1}K^{-1}$)								
		$Mg_{0.40}Mn_{0.60}Ni_{0.00}$/ transformer oil based ferrofluid			$Mg_{0.40}Mn_{0.40}Ni_{0.20}$/ transformer oil based ferrofluid			$Mg_{0.40}Mn_{0.20}Ni_{0.40}$/ transformer oil based ferrofluid		
		1%	2%	4%	1%	2%	4%	1%	2%	4%
1	35°C	0.612	0.613	0.618	0.639	0.642	0.646	0.641	0.643	0.646
2	50°C	0.614	0.615	0.619	0.641	0.645	0.648	0.643	0.646	0.650
3	65°C	0.615	0.617	0.622	0.644	0.649	0.651	0.645	0.650	0.652
4	80°C	0.617	0.619	0.624	0.647	0.652	0.653	0.648	0.653	0.655

Figure 4. illustrated the comparison between experimental results and predicted values of thermal conductivity for transformer oil based ferrofluid. It has been shown that the effective thermal conductivity of the present model is much higher than that of the Maxwell prediction. We also observed that the experimental results of Mg-Mn-Ni transformer oil based ferrofluid have more enhancements in thermal conductivities, when compared with the other theoretical models like Maxwell, Hamiltonian and Wasp models [9, 10 and 11].

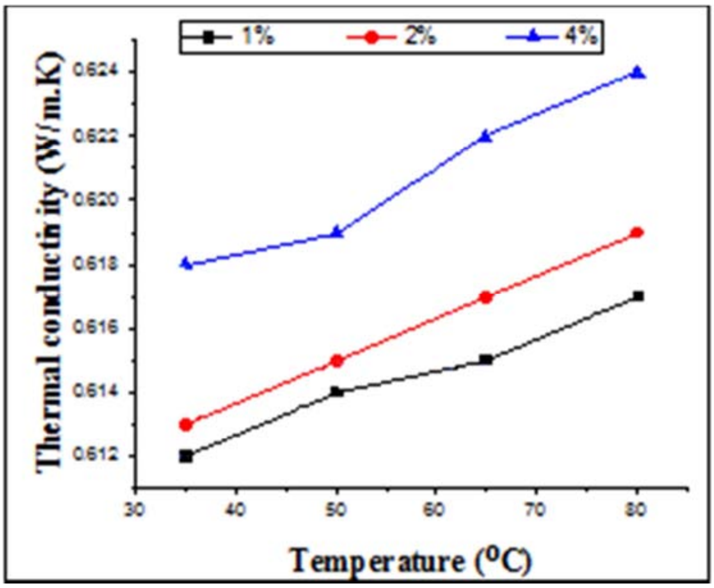

Figure 3(a). *Experimental results of thermal conductivity for transformer oil based ferrofluid for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ with x=0.00 at various volume fractions.*

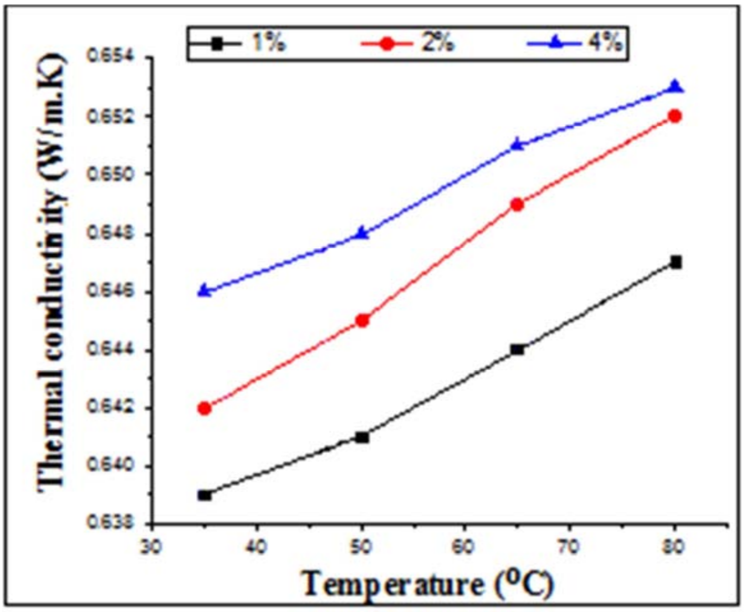

Figure 3(b). *Experimental results of thermal conductivity for transformer oil based ferrofluid for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ with x=0.20 at various volume fractions.*

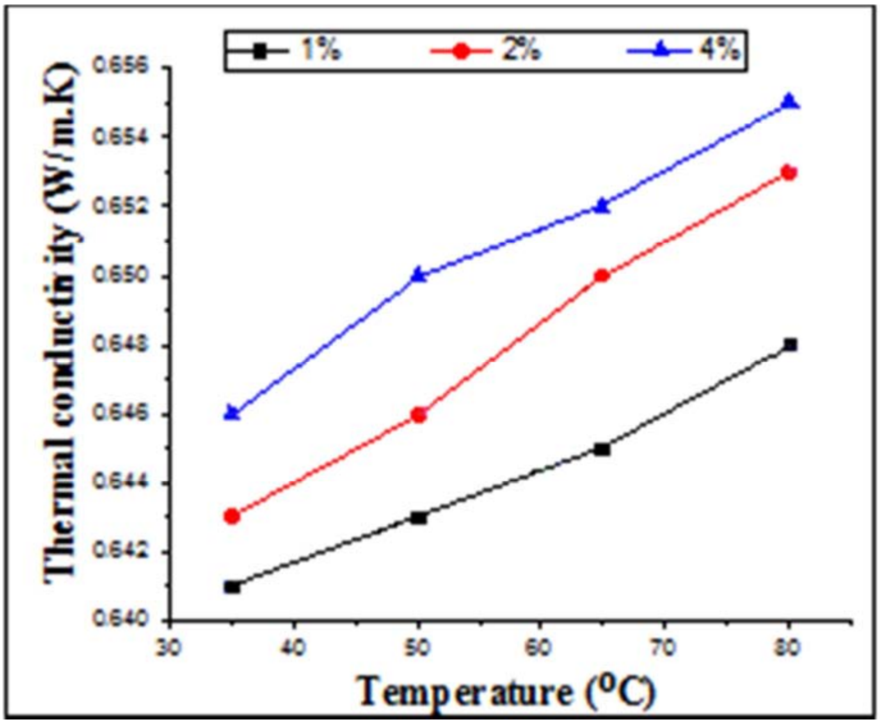

Figure 3(c). *Experimental results of thermal conductivity for transformer oil based ferrofluid for* $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ *with x=0.40 at various volume fractions.*

It can be observed that thermal conductivity for transformer oil based ferrofluid increases with increase in temperature and also with increase in concentrations of the nanoparticles. The effective thermal conductivity enhancement increases 58% by suspending 4% volume of nanoferrite spherical particles for transformer oil based ferrofluid.

Figure 4. shows that the measured thermal conductivity of the present model is much higher than that of the Maxwell prediction [12]. From this we observed that the measured thermal conductivity ratio of the present model is much higher than that of the other theoretical models.

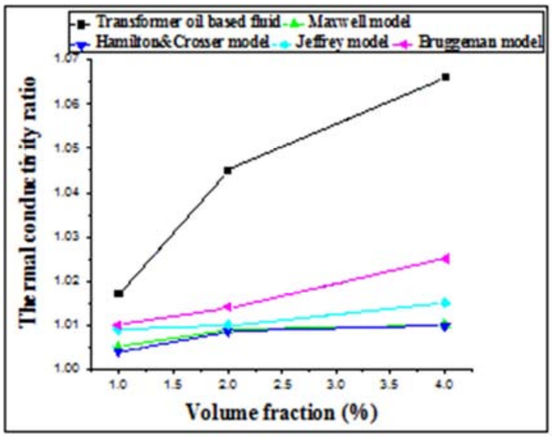

Figure 4. *Comparison between experimental results of thermal conductivity enhancement ratio* (K_{nf} / K_{bf}) *at various volume fractions with x=0.40 for* $Mg_{0.40}Mn_{0.60-x}$ $Ni_xFe_2O_4$ *transformer oil based ferrofluid and the predicted values.*

3.3. Density

The density of $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluid for 1%, 2% and 4% volume fractions with x=0.40 at different temperature increases with volume fractions indicated that the volumetric specific heat for transformer oil based ferrofluid decreases gradually with increasing in volume fractions (Figure 5).

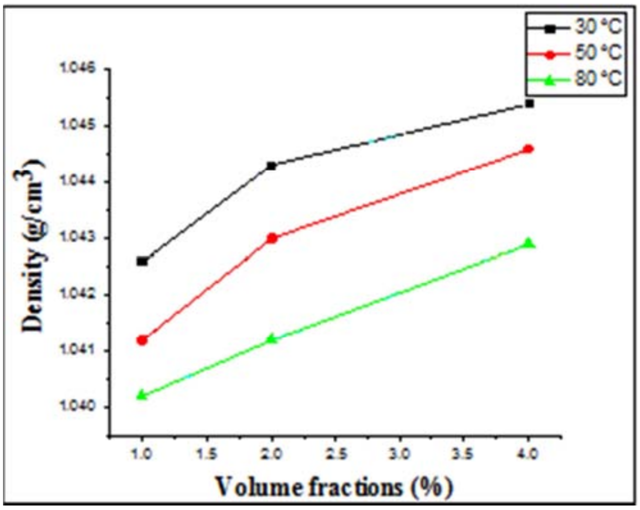

Figure 5. *Variation of experimental density values of* $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ *transformer oil based ferrofluid for 1%, 2% and 4% volume fractions with x=0.40 at different temperature.*

Table 3. *Experimental density values of* $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ *transformer oil based ferrofluid for 1%, 2% and 4% volume fractions with x=0.40 at different temperature.*

Volume fraction (%)	**Density(g/cm^3) of $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluid for x=0.40 at 30°C**	**Density(g/cm^3) of $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluid for x=0.40 at 50°C**	**Density(g/cm^3) of $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluid for x=0.40 at 80°C**
	Experimental results	**Experimental results**	**Experimental results**
1	1.0426	1.0412	1.0402
2	1.0443	1.0430	1.0412
4	1.0454	1.0446	1.0429

3.4. Volumetric Specific Heat

The volumetric specific heat can be measured by KD2 Pro using SH-1 sensor needle. Figure 6 shows the specific heat for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluid for 1%, 2% and 4% volume fractions with x=0.40 at different temperature.

Table 4. *Volumetric specific heat measurements of* $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ *transformer oil based ferrofluid for various volume fractions with x=0.40 at different temperature.*

T (°C)	**Volumetric Specific heat (MJ / m^3.K) of transformer oil based ferrofluid for x=0.40 at 1%**	**Volumetric Specific heat (MJ / m^3.K) of transformer oil based ferrofluid for x=0.40 at 2%**	**Volumetric Specific heat (MJ / m^3.K) of transformer oil based ferrofluid for x=0.40 at 4%**
	Experimental results	**Experimental results**	**Experimental results**
10	3.67	3.66	3.62
25	3.78	3.73	3.67
35	3.81	3.78	3.71
50	3.95	3.89	3.80
65	3.97	3.95	3.87
90	4.12	4.10	4.09

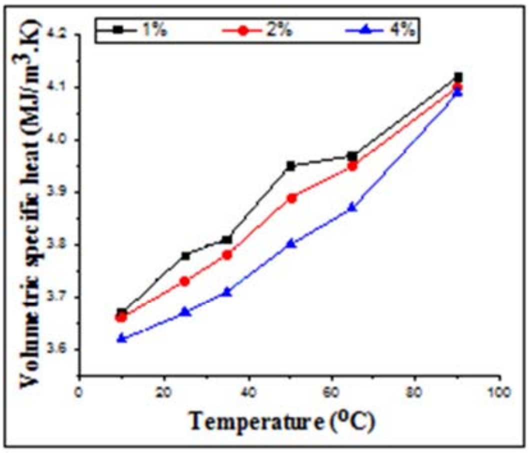

Figure 6. *Volumetric specific heat values of* $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ *transformer oil based ferrofluids for 1%, 2% and 4% volume fractions with x=0.40 at different temperature.*

The experimental data measured at different temperature ranges from 30°C to 90°C for 1%, 2% and 4% volume fractions of $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluid with x=0.40 is shown in Table 4. It depends on the prepared nanoparticles, volume concentration of nanoparticles and temperature of the fluids [13, 14]. From the present work the volumetric specific heat values for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluid for 1%, 2% and 4% volume fractions with x=0.40 at different temperature decreases gradually with increasing volume fractions of nanoparticles and increases with increase in temperature.

3.5. Viscosity

For the measurement of viscosity of $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ ($0.00 \leq x \leq 0.60$) transformer oil based ferrofluid Brookfield DV-E viscometer is used with temperature from 30°C to 90°C at 1%, 2%, 4% volume fractions[15].

The viscositymeasurementsof the prepared ferrofluid with an influence of temperature as well as shear rate are tabulated in Table 5 and Table 6. From Figure 7(a), Figure 7(b) and Figure 7(c) we have shown that the viscosity values of $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ ($0.00 \leq x \leq 0.60$) transformer oil based ferrofluid decreases with increase in temperature. As shown in Figure 7(a), 7(b) and 7(c) the shear viscosities of the $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ ($0.00 \leq x \leq 0.60$) transformer oil based ferrofluid mainly decrease for a higher shear rate. Experimental results also indicated that nanoparticle size decreases, the viscosity decrease and it becomes much more dependent on the volume fractions. From Figure 7(a), Figure 7(b) and Figure 7(c) and also Figure 8(a), Figure 8(b) and Figure 8(c) we observed that the prepared fluids have Non-Newtonian behavior with shear thinning since the relation between the shear stress and the shear rate is not linear.

Table 5. *Viscosity measurements for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluids for 1%, 2% and 4% volume fractions at different temperature.*

Temperature (°C)	Viscosity (Pa.s)								
	$Mg_{0.40}Mn_{0.60}Ni_{0.00}$/ transformer oil based ferrofluid			$Mg_{0.40}Mn_{0.40}Ni_{0.20}$/ transformer oil based ferrofluid			$Mg_{0.40}Mn_{0.20}Ni_{0.40}$/ transformer oil based ferrofluid		
	1%	**2%**	**4%**	**1%**	**2%**	**4%**	**1%**	**2%**	**4%**
10°C	0.71	0.76	0.79	0.73	0.79	0.81	0.75	0.81	0.83
40°C	0.56	0.59	0.62	0.54	0.61	0.64	0.59	0.63	0.65
80°C	0.44	0.46	0.51	0.41	0.47	0.53	0.46	0.49	0.54
100 °C	0.41	0.43	0.49	0.39	0.45	0.52	0.43	0.47	0.54

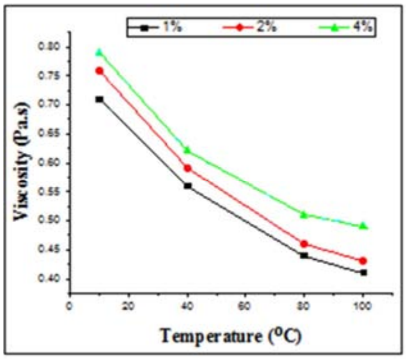

Figure 7(a). *Volume fraction dependent viscosities for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluids at different temperature for 1%, 2% and 4% volume fractions with x=0.00.*

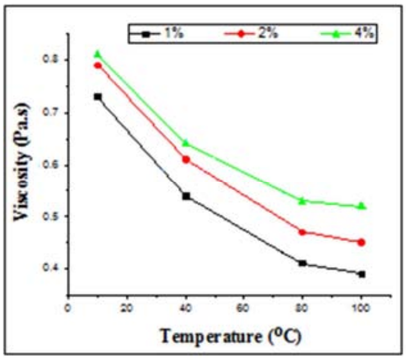

Figure 7(b). *Volume fraction dependent viscosities for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluids at different temperature for 1%, 2% and 4%volume fractions with x=0.20.*

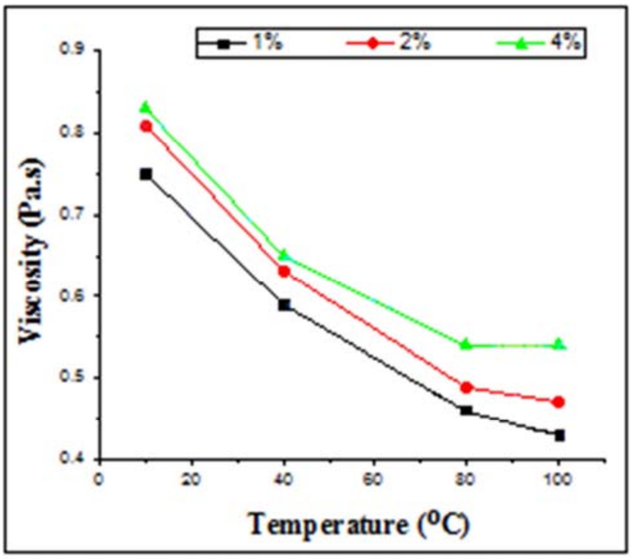

Figure 7(c). *Volume fraction dependent viscosities for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluids at different temperature for 1%, 2% and 4%volume fractions with x=0.40.*

From the experimental results we observed that the shear viscosity of transformer oil based ferrofluid mainly decreases for a higher shear rate. The viscosity and flow curve as a function of shear rate, showing that the transformer oil based ferrofluid has Non-Newtonian behavior and shear thinning. The experimental results indicated that the viscosity decrease with the decrement of particle size so that it is much more dependent on the volume fractions of the prepared ferrofluid.

Table 6. *Viscosity measurements for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluid for various shear rate values at different temperature with x=0.40 for 4% volume fraction.*

Shear Rate (1/s)	Viscosity (Pa.s)								
	$Mg_{0.40}Mn_{0.60}Ni_{0.00}$/ transformer oil based ferrofluid for 4% volume fraction			$Mg_{0.40}Mn_{0.40}Ni_{0.20}$/ transformer oil based ferrofluid for 4% volume fraction			$Mg_{0.40}Mn_{0.20}Ni_{0.40}$/ transformer oil based ferrofluid for 4% volume fraction		
	35°C	**40°C**	**45°C**	**35°C**	**40°C**	**45°C**	**35°C**	**40°C**	**45°C**
5	0.79	0.72	0.69	0.81	0.73	0.70	0.83	0.74	0.71
10	0.71	0.68	0.66	0.73	0.70	0.69	0.75	0.70	0.70
20	0.65	0.61	0.57	0.68	0.64	0.59	0.67	0.65	0.61
40	0.60	0.56	0.55	0.62	0.59	0.58	0.63	0.60	0.60
80	0.58	0.55	0.50	0.60	0.58	0.53	0.61	0.59	0.57
100	0.57	0.52	0.49	0.59	0.55	0.51	0.59	0.56	0.55
500	0.50	0.46	0.44	0.53	0.49	0.47	0.54	0.51	0.49
1000	0.47	0.44	0.43	0.49	0.47	0.45	0.50	0.49	0.48
2000	0.42	0.41	0.40	0.45	0.45	0.42	0.47	0.46	0.42

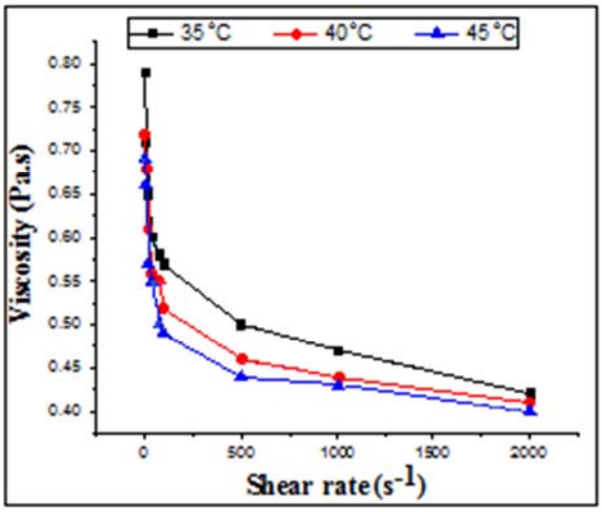

Figure 8(a). *Shear dependent viscosities for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$transformer oil based ferrofluids at different temperature values with x=0.00 for 4% volume fraction.*

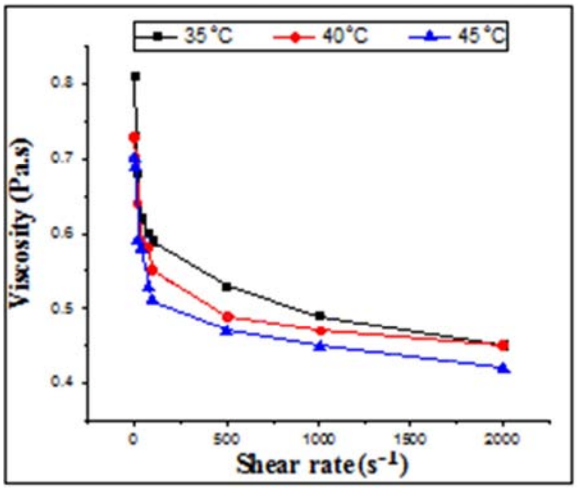

Figure 8(b). *Shear dependent viscosities for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluids at different temperature values with x=0.20 for 4% volume fraction.*

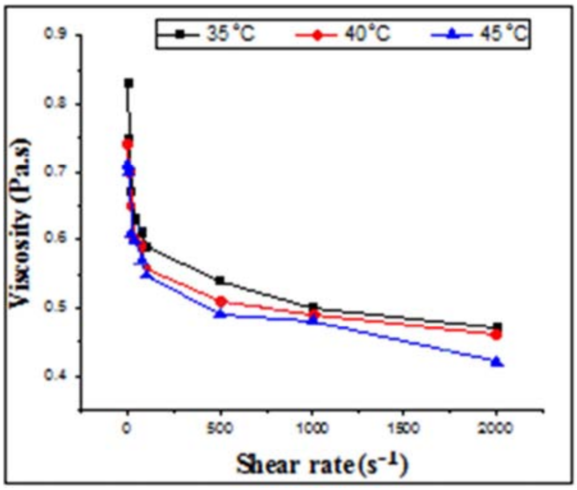

Figure 8(c). *Shear dependent viscosities for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluids at different temperature values with x=0.40 for 4% volume fraction.*

3.6. Heat Transfer Characteristics

The Nusselt number can also be determined from the existing correlations and discussed the local Nusselt number/heat transfer co-efficient and Reynolds number for transformer oil based ferrofluid [16].

Mathematical model for heat transfer co-efficient for transformer oil based ferrofluids

Ferrofluid is higher conductive and convective heat transfer fluids compared to their base fluids [17]. The local Nusselt number is calculated from below Eq. as [17]

$$N_u = \frac{h_x D_i}{k_f} \tag{1}$$

where k_f is the thermal conductivity of fluids and D_i is the inner diameter value of the nanoparticles. The Nusselt number for a flow over spherical particles with a diameter, d_{np}, is modified from the above model as:

$$N_u = \frac{h d_{np}}{k_{nf}} \tag{2}$$

where 'h' is heat transfer coefficient.

Rearranging the above equation (1 and 2) and defining d_{np} as the average nanoparticle size, the heat transfer coefficient can be defined by

$$h = \frac{N_u k_{nf}}{d_{np}} \tag{3}$$

By definition, Reynold number is given as

$$R_e = \frac{4m}{\pi d_{np} \mu_{nf}} \tag{4}$$

where 'μ_{nf}' is the dynamic viscosity of the fluid. From Figure 4, we observed a close agreement between the present experimental results of Nusselt number with the Dittus–Boelter and Shah's models [18]. From Figure 9 we observed a close agreement between the present experimental results of Nusselt number for transformer oil based ferrofluid with the Einstein's model [19].

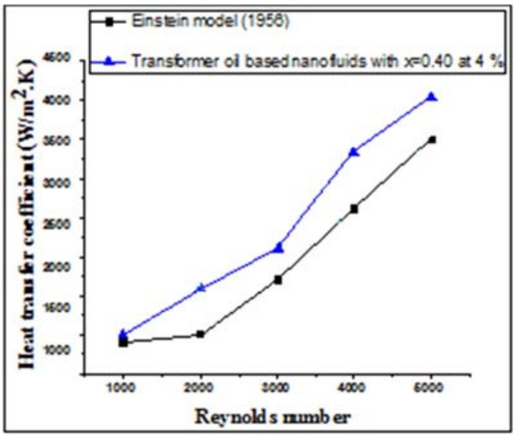

Figure 9. *Change of heat transfer co-efficient with Reynolds number for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ transformer oil based ferrofluid with x=0.40 for 4% volume fraction with different temperature.*

3.7. Electrical Measurement

The electrical conductivity values of the ferrofluid were measured using a Cyberscancon 11conductivity electrode meter. The electrode meter provides both temperature and conductivity values concurrently for the specified instant. The conductivity of a solution is directly proportional to its ion concentration owing to the charge on ions in solution assists the conductance of electrical current. The accuracy for conductivity and temperature measurement is ± 1% and the conductivity ranges from 20 μS/cm to 200 mS/cm.

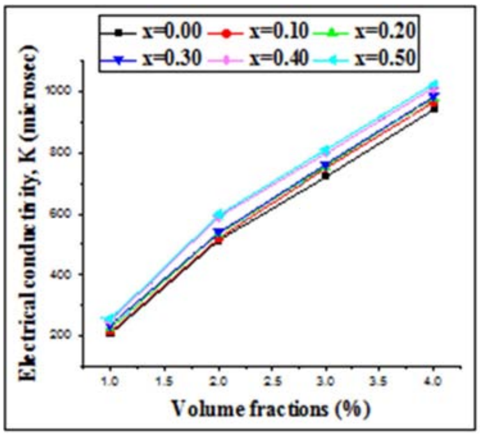

Figure 10. *Electrical conductivity values for transformer oil based ferrofluid for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ (0.00 ≤ x ≤ 0.60) with various volume fractions for various compositions.*

From this we observed that the electrical conductivity of prepared ferrofluid increases linearly with volume fractions (shown in Figure 10). The highest value of electrical conductivity, 1025 μS/cm, was recorded for a volume fraction of 4% at a temperature of 70°C.

3.8. Results and Discussion on Application of Dielectric Fluid/Ferrofluid

The transformer oil based ferrofluid can be used for increasing the dielectric strength or breakdown voltage in power transformers. Usually oil transformers trusted on highly refined mineral oil as a cooling medium. The cooling medium in power transformers undertake two topmost functions–insulating and cooling. That means they avoid the flow of electric current between conductive components, and also conduct the heat out of active transformer devices (i.e. out of both electric windings and transformer core) [20, 21]. Thus there is need to improve the effect of enhanced temperature on the physical and insulating properties of ferrofluid. The prepared ferrofluid has better thermal management and they can be applicable for the use as an insulation and cooling fluid in electrical power transformers.

The dielectric strength of transformer oil based ferrofluid has more enhancement than the mineral oil and exhibit improvement in both electrical and thermal properties. The ferrofluid has nanoferrite particles which have higher resistivity and low dielectric loss. The oil based ferrofluid is considered to be substitutions to change conventional transformer oil because transformer oil based ferrofluid show improvement in both electrical and thermal properties.

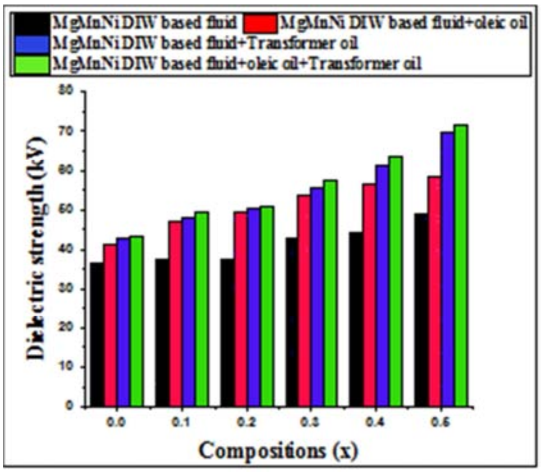

Figure 11. *Dielectric strength or dielectric breakdown voltage of $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ (0.00 ≤ x ≤ 0.60) transformer oil based ferrofluid.*

There are particular basic factors to reveal the electrical properties of the transformer oil such as breakdown voltage parameters, dielectric dissipation factor, dielectric constant and resistivity. The breakdown voltage is a significant factor to estimate the transformer oil's capacity of acceptance to electrical stress. The dielectric loss factor and resistivity typically has a good correlation at high temperature; the dielectric dissipation factor increases as the resistance diminishes. It has been showed experimentally that the transformer based ferrofluid of suitable composition and nanoparticle concentration not only increases the heat transfer by thermal and magnetic convection, but it also has higher dielectric strength than ordinary insulation ferrofluid.

From Figure 11 shows that the addition of $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ (0.00 ≤ x ≤ 0.60) with oleic acid and transformer oil would improve the dielectric behavior of the fluid. Since the carbon particles in oleic acid have a high attraction to dissolved water in the oil. The result of AC breakdown test results for $Mg_{0.40}Mn_{0.60-x}Ni_xFe_2O_4$ (0.00 ≤ x ≤ 0.60) transformer oil based ferrofluid showed that these ferrofluid shown improved breakdown strength.

4. Conclusions

Thus, the ferrofluid has more enhancements in thermal conductivity than other models and the increase was found to be 58%. Hence from the study, it can be concluded that this ferrofluid can be used for heat transfer applications due to their enhancement in thermal conductivity. The prepared transformer oil-based ferrofluid can be used as insulation fluids in electrical applications. It has been showed experimentally that the transformer based ferrofluid of suitable composition and nanoparticle concentration not only increases the heat transfer by thermal and magnetic convection, but it also has higher dielectric strength than ordinary insulation fluids. This is the objective of future works.

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