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An Investigation on Stability, Electrical and Thermal Characteristics of Transformer Insulting Oil Nanofluids

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ABSTRACT

Transformer insulating oil nanofluid is made to improve dielectric and thermal properties of oil by employing nanoparticles with proper properties. In the current work, nanofluids based on transformer mineral oil were prepared by three procedures using diamond nanoparticles with high thermal conductivity, as well as high dielectric properties. It was tried to consider the impacts of use of surfactants and ball milling process in the preparation procedures. The effects of a variety of stabilizers (the amount and type) and also the ultrasonic time on diamond nanoparticles' stability in the oil were investigated and optimized experimentally. Using the optimized nanofluids, thermal conductivity and viscosity of the oil nanofluids were compared and discussed. In addition, the consistency of the thermal conductivity results with Maxwell and also Hamilton and Crosser theoretical models was examined. It was revealed that, the nanofluid preparation procedure, temperature and nanoparticles' concentration had effects on thermal conductivity of the transformer oil nanofluid, while the presence of nanoparticles had a slight impact on the viscosity of the fluid. Also the effect of presence of diamond nanoparticles on the electrical properties of transformer oil was studied. Based on the experimental results, adding diamond nanoparticles could lead to an increase in the transformer oil breakdown voltage, while it had nearly no effect on dielectric loss at low concentrations.

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1. INTRODUCTION[1]

Oil is used in transformers as an electrical insulating and also a cooling material. However, having a low thermal conductivity, transformer oil has a poor effect on cooling. Considering the fact that the excessive increase in temperature raises the probability of dielectric breakdown [1], it is desired to improve the cooling power of the oil while its dielectric properties are preserved. By increasing the thermal conductivity of the transformer oil, lifetime and load capacity of the equipment enhance significantly.

It has been proved that, the particles with higher thermal conductivity compared to the base fluid can increase the thermal conductivity of the compound. Therefore, in early researches, the particles with the size in the range of micrometer and millimeter were employed in heat transfer fluids [2]. However, adding these particles to the base fluid caused several problems such as aggregating, sedimentation and blocking the channels, as well as an increment in the required power of the pump.

After introducing nanofluids by Choi et al. [3], lots of studies with promising results have been conducted on their heat transfer applications. Considering the important role of transformers in the electrical grid, a new type of transformer oil-based nanofluid has attracted the attention of many researchers in the recent years. Transformer oil nanofluid is a colloidal suspension composed of nanoparticles with the average size of less than 100 nm in the oil [4, 5]. This new fluid, without mentioned drawbacks of fluids containing

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bigger particles, is expected to improve the heat transfer effects and also dielectric properties of the oil [6].

There are several researches on different properties of the transformer oil nanofluids, including electrical properties and thermal conductivity. Yuzhen et al. [7] studied the effect of nanoparticles on the dielectric strength of mineral oils. They examined three types of nanoparticles with different electrical conductivities: insulating metal oxide nanoparticles, semi-conductive metal oxide nanoparticles and conductive metal oxide nanoparticles. The research showed that, the breakdown voltages of all nanofluids were much greater than that of pure transformer oil. However, the greatest breakdown voltage was achieved using insulating meal oxide nanoparticles. Yue-Fan et al. [8] studied the effect of presence of titanium oxide nanoparticles on the breakdown voltage of transformer which led to increase in breakdown voltage value. In another study, Karthik et al. [9] examined the effects of adding different nanoparticles, including Al, Al_2O_3, Cu and CuO, on the important properties of transformer oil. They showed that, by adding the nanoparticles, the flash and the pouring temperatures increased significantly. In addition, before heating the nanofluid, adding nanoparticles led to a decrease in the breakdown voltage of the transformer oil, while after heating (decreasing the humidity of the oil), reverse results were obtained.

In another research, Chiesa and Das [10] studied the dielectric strength and thermal conductivity of several mineral oil nanofluids. Based on the results, thermal conductivity enhancements of 1.1, 1.08 and 1.03 for nanofluids containing 1% of SiC, Al_2O_3, and SiO_2 nanoparticles were achieved, respectively. On the other hand, they concluded that, use of these nanoparticles in transformer oil leads to deterioration in dielectric strength of the insulating fluid. Choi et al. [6] investigated the effect of dispersing AlN and Al_2O_3 nanoparticles in transformer oil on the thermal conductivity of the mixture. They showed that, the thermal conductivity of the mixture increases with particle volume fraction and thermal conductivity of the solid particles itself. Also, it was revealed that, higher convective heat transfer coefficient, as well as, natural convection properties could be reached using nanofluids instead of pure oil.

However, despite the promising results obtained from the nanofluids, the important issue of suspension stability should not be neglected. The stability is a significant parameter for application of nanofluids and affects the thermal and electrical properties of the transformer oil. Poor stability and sedimentation of the nanoparticles may lead to the dielectric breakdown and also decrease in the expected thermal characteristics of the stable nanofluids. There are several methods to increase the nanofluids' stability, such as using ultrasound bath, employing surfactant, changing pH, chemical modification, etc. [11-13]. Also, there are a variety of techniques to study the stability of the nanofluids, including UV-vis spectrophotometer, zeta potential, turbidity test, etc. [14-16], by which sedimentation rate (or percentage) can be determined.

In the current study, diamond nanoparticles with high thermal conductivity and low electrical conductivity were utilized to prepare transformer oil based nanofluids to investigate their stability, as well as thermal and electrical properties. Considering the fact that, thermal conductivity of diamond nanoparticle (approximately 2,000 W/m.K) is much higher than that of pure transformer oil (about 0.115 W/m.K at room temperature), oil suspensions of diamond nanoparticles are expected to offer higher thermal conductivity compared to pure transformer oil, while dielectric properties are preserved.

2. EXPERIMENTAL

2. 1. Materials Nanofluids based on transformer oil were prepared by dispersion of diamond nanoparticles in the oil using both surfactant and free-surfactant techniques. The characteristics of transformer oil are shown in Table 1. Furthermore, Table 2 presents the properties of the purchased diamond nanoparticles with the average size of 4-6 nm. Also, different surfactants were applied as nanofluids' stabilizers, whose codes and descriptions are shown in Table 3. Figure 1 represents the transmission electron microscope (TEM) micrograph of the mentioned nanoparticles.

2. 2. Preparation of Nanofluids and Stability Analysis A two-stage method was employed for preparation of the diamond oil nanofluid (D-O nanofluid); magnetic stirrer and the ultrasonic bath were to disperse the diamond nanoparticles in the base fluid.

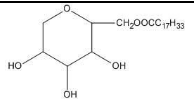
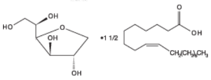
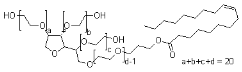
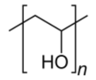
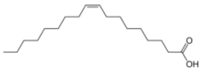
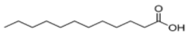
TABLE 1. Specifications of the transformer oil used as base fluid for nanofluid preparation

Property	Specification
Kin.Viscosity at 40 °C (*mm^2/s*)	8.539
Kin.Viscosity at 100 °C (*mm^2/s*)	2.28
DDf at 90 °C	0.0013
Density at 15 °C (*g/mL*)	0.88
Interfacial (*mN/m*)	47.1

TABLE 2. Properties of diamond nanoparticles

Purity	98-99%
Average particle size (*nm*)	4-6
Shape	Ball
Density (*g/cm^3*)	3.05-3.3
Dielectric constant (*F/m*)	$3.4\varepsilon_o$

TABLE 3. Structure and chemical formula of the stabilizers

Stablizer No.	Stabilizer	Chemical structures	Chemical formula
No. 1	Span80, Sorbitanmonooleat		$C_{24}H_{44}O_6$
No. 2	Span83, Sorbitansesquioleate		$C_{66}H_{126}O_{16}$
No. 3	Tween80, Polysorbat 80		$C_{64}H_{126}O_{16}$
No. 4	PVA, polyvinyl alcohol		$(C_2H_4O)_x$
No. 5	Oleic acid		$C_{18}H_{34}O_2$
No. 6	Lauric acid		$C_{12}H_{24}O_2$

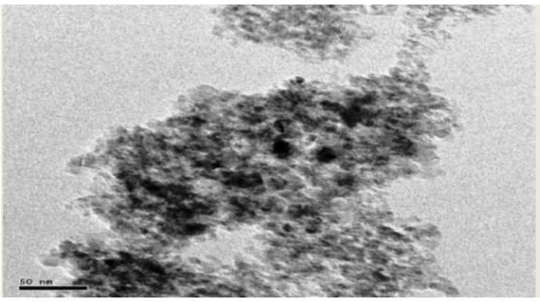


Figure 1. TEM micrograph of diamond nanoparticles

The effects of different parameters including ultrasonication time, usage of ball milling process, the concentration and also type of stabilizer on the suspension stability were investigated. In general, three procedures were applied for the preparation of several nanofluids, which are discussed in the following sections.

2. 2. 1. The First Procedure: Containing Surfactant Nanofluids were prepared in four different contents of nanoparticles: 0.1, 0.15, 0.2, and 0.6 wt%. At first, weighted nanoparticles with the accuracy of 0.001 g were added to the oil and the fluid was stirred by a magnetic stirrer at 700 rpm for 15 minutes. In the next stage, each sample was placed in an ultrasonic bath for 30 minutes. Then, the surfactant was added (the ratio of surfactant to nanoparticles was 2:1) and the samples were stirred by the magnetic stirrer for 15 minutes, with the same speed. Finally, the samples were placed in the ultrasonic bath for 30 minutes.

2. 2. 2. The Second Procedure: Containing Surfactant and Using Ball Milling In this procedure, in order to increase scattering of diamond nanoparticles in the oil, the ball milling was applied on the 0.6 wt% nanofluid prepared by the first method. The fluid was milled for 72 hours in tubes using ten balls of carbide tungsten. Then, the resulted suspension was stirred for 45 minutes in an ultrasonic bath.

2. 2. 3. The Third Procedure: Using Ball Milling without Surfactant In this procedure, nanofluids were prepared at four aforementioned concentrations. First, the nanoparticles were added to the base fluid in the desired value and the samples were stirred by means of magnetic stirrer at 750 rpm for 15 minutes. Afterwards, the samples were stirred for 72 hours in tubes containing ten balls of carbide tungsten. Then, the derived suspension was placed in an ultrasonic bath for 45 minutes. It is worth noting that, surfactant was not used in the third procedure.

2. 2. 4. Studying the Stabilizer Type and Concentration To investigate the effect of the stabilizer type on the D-O nanofluid’s stability, one of the mentioned surfactants in Table 3 was added to the samples prepared using the first procedure. In all samples, the surfactant to nanoparticles ratio was 2:1 wt%.

In order to study the impact of stabilizer concentration, different ratios of stabilizer to nanoparticles including 1:1, 2:1 and 3:1 were studied. The nanofluids were prepared, as mentioned before.

2. 2. 5. Studying the Ultrasonication Time In order to study the effect of ultrasonication time, in all of the samples, the nanoparticles were added to the oil and stirred for 15 minutes on a magnetic stirrer (750 rpm). The derived suspension was transferred to the ultrasonic bath and stirred for 30 minutes. Then, the surfactant (with the surfactant-nanoparticles ratio of 2:1 wt%) was added and once again the sample was stirred on the magnetic stirrer (750 rpm for 15 minutes). Finally, the sample was transferred to the ultrasonic bath and stirred for 30 and 90 minutes.

2. 3. The Instruments of the Analysis Nephelometry was used to evaluate the stability of the suspensions. Diel test was employed for measuring the dielectric loss of the prepared nanofluids according to IEC 247 standard, at 90 °C.

The breakdown voltage of the prepared nanofluids was quantified using a portable oil test set, considering IEC 60156 standard, at room temperature. In order to reduce the data scattering, the breakdown voltage was measured six times and the average values have been reported.

3. RESULTS AND DISCUSSION

3. 1. Stability Analysis

Table 4 represents the resultss of investigating the effect of the stabilizer type on the nanofluids' stability. The stability is considered to be the ratio of turbidity difference between initial amount and the turbidity after specific time to the initial turbidity. The obtained results could be explained as follows.

Span 80 (stabilizer 1) can make strong bonds with the nanoparticles due to its hydrophilic parts consisted of three OH groups. On the other hand, lipophilic head group, which has 18 carbon molecules, made the surfactant soluble in the oil.

The lipophilic group in span 83 (stabilizer 2), containing 18 carbon molecules, instead of one OH group in the hydrophilic part, resulted in a weak bond between the diamond nanoparticles and the hydrophilic part, and subsequently a lower stability compared with span 80.

TABLE 4. The results of stabilizer type on the nanofluids' stability

Stabilitzer type, concentration ratio	Time (h)	Turbidity (NTU)	Stability (%)
Stabilizer 1, ratio 1:2	0	177.93	-
	1	174.22	97.91
	24	139.53	78.41
	96	112.48	63.21
Stabilizer 2, ratio 1:2	0	177.99	-
	1	173.24	97.33
	24	159.42	89.56
	96	41.26	23.18
Stabilizer 3, ratio 1:2	0	77.14	-
	1	68.47	88.76
	24	15.43	20
	96	5.55	7.19
Stabilizer 4, ratio1:2	0	153.5	-
	1	124.335	81
	24	13.87	9.03
	96	2.22	1.44
Stabilizer 5, ratio 1:2	0	165.19	-
	1	141.25	85.5
	24	26.55	16.07
	96	3.62	2.19
Stabilizer 6, ratio 1:2	0	146.36	-
	1	64.43	44
	24	44.21	30.2
	96	5.27	3.6

In the process of preparing Tween80 (stabilizer 3), 20 moles of ethylene oxide reacted under pressure and through a catalytic process on Sorbitan hydroxyl groups and carboxyl oxide groups in Sorbitan oxide ring. Thus, the fat-soluble emulsifier (span80) was replaced with the water-soluble Tween80. In Tween80 stabilizer, the hydrophilic group is more powerful than the lipophilic group. Therefore, the surfactant was not capable of dispersing the diamond nanoparticles in the transformer oil.

PVA (stabilizer 4) was not able to create the required intermolecular forces with the nanoparticles due to its low polarity. Stabilizer 5, oleic acid, has 18-carbon molecules with one OH group and its lipophilic part is strong like span80. However, with the lower number of OH groups, it makes a weaker bond with nanoparticles compared to span80. Thus, it resulted in less stability in the transformer oil compared to span80 stabilizer.

Stabilizer 6, lauric acid, contains 12 carbon molecules with one OH group. Therefore, its lipophilic head group is weaker than span 80 which causes a less ability to be dissolved in the oil. Having just one OH group, the stabilizer made weaker bonds with the diamond nanoparticles. These led to a lower stability of the diamond nanoparticles in the oil.

From these results, Span 80 was concluded to be a suitable stabilizer for modifying the diamond nanoparticles in the transformer oil, in order to have a suspension with acceptable stability.

In the next step, the effect of the stabilizer concentration on the stability was studied and the results are presented in Figure 2.

The samples were prepared with surfactant to nanoparticle weight ratios of (1:1), (2:1) and (3:1). Based on the experimental results, after 360 hours, the stability percentages of the samples were 3.02, 50.61 and 38.65% for the first, second and third samples, respectively.

When the surfactant percentage is too low, a small amount of nanoparticles would be modified. On the other hand, in case of having excessively high amount of surfactant, more energy is needed to separate the surfactant molecules. Thus, the best results were achieved for the sample with 2:1 ratio.

In addition, the effect of the ultrasonic time on the stability of the nano-diamond particles in the oil is shown in Figure 3. Thirty and ninety minutes were considered for the ultrasonic process of the samples. The results indicated that, after 360 hours, the stability of the first sample was 70.83%, while the stability of the second sample was only 34.49 %.

As it can be seen in Figure 3, in the presence of surfactant, increasing the ultrasonic time would decrease the stability. Probably, the high ultrasonic time causes the separation of the surfactants from the nanoparticle. It seems that, 30 min is enough for the nanoparticles to be dispersed in the oil.

After determining the proper surfactant type, amount and also the optimal ultrasonication time, the electrical and thermal properties of the most stable nanofluids at different concentrations were investigated.

3. 2. Evaluation of the Nanofluids' Properties

3. 2. 1. Breakdown Voltage The effect of diamond nanoparticle concentration on the breakdown voltage of the samples prepared by the first procedure is shown in Figure 4. As illustrated in the figure, at a concentration of 0.15 wt%, the breakdown voltage increased, while by increasing the consistency, the breakdown voltage reduced. However, the nanofluid breakdown voltage was greater than that of pure transformer oil at all studied concentrations.

Since nanoparticles act as a surface trap, they can entrap the surface electrons, which make an electric field in the oil. The fast electron changed to the slow one, and subsequently an increase in the breakdown voltage was resulted [6].

3. 2. 2. Dielectric Loss Figure 5 shows the variation of the dielectric loss of the oil reinforced with different concentrations of the nano-diamond. As one can see, the dielectric loss of the oil enhances as the nano-diamond content increases.

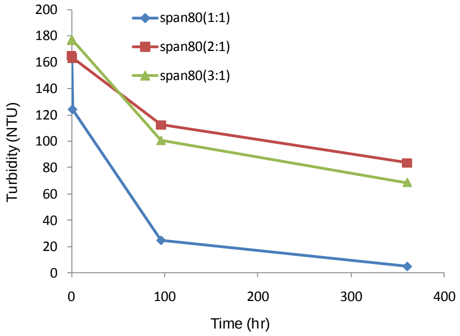


Figure 2. Effect of surfactant percentage on the stability of the nanofluids

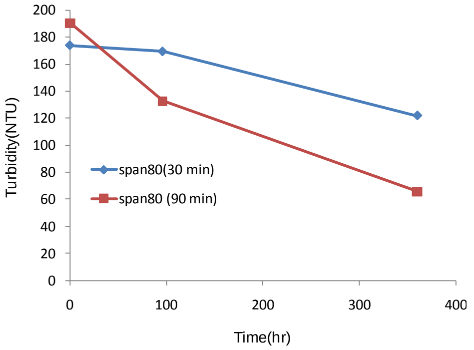


Figure 3. Effect of ultrasonication time on the nanofluids stability in transformer mineral oil

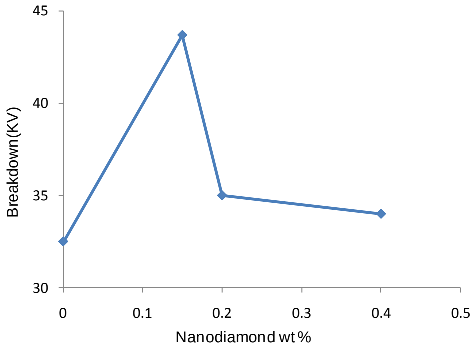


Figure 4. Effect of diamond nanoparticle concentration on breakdown voltage

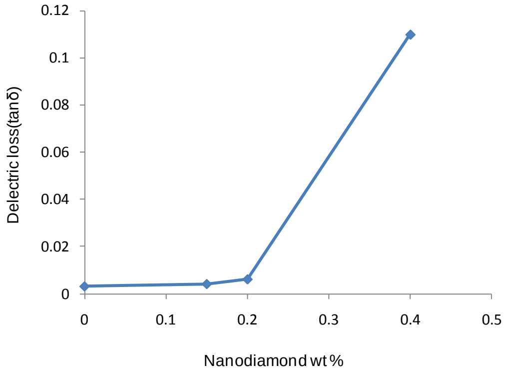


Figure 5. Variation of dielectric loss of the transformer oil with different diamond nanoparticle contents

The results show that, at a lower consistency, the presence of nanoparticles does not affect the loss index remarkably. Nevertheless, at higher consistencies, the index enhances significantly. This is due to the fact that, the impurities and the moisture content increase the dielectric loss factor.

3. 2. 3. Viscosity Figure 6 shows the effect of temperature and nanoparticles content on the viscosity of the transformer oil-nanofluids prepared by the first procedure. The viscosity of pure transformer oil is equal to 8.539 mm^2/s at 40 ^oC, while the figure shows that the viscosity of the oil containing 0.15 wt% nanodiamond particles increased up to 9.25 mm^2/s. Indeed, oil viscosity rises slightly by an increment in the content of diamond nanoparticles in oil, which is the result of an increase in the intermolecular forces.

On the other hand, by increase of temperature, the viscosity had a decreasing trend as reported before [17, 18]. This is due to the decline in adhesion forces.

3. 2. 4. Thermal Conductivity Figures 7 and 8 show the thermal conductivity indexes of the nanofluids prepared by the first and third procedures, respectively, at different temperatures. The experimental data show that by increasing the consistency of diamond nanoparticles in the oil, the thermal conductivity increases. Same as a previous research [19], enhancement in thermal conductivity was observed by adding even little amounts of nanoparticles. In the current study, by adding 0.6 wt% of nanodiamond to the transformer oil (using the first preparing procedure), 6.2% enhancement was observed at 20 °C, while Cheesa et al. reported 1% enhancement for a mixture of 1.19 wt% of Al_2O_3 nanoparticles in oil. Indeed, natural properties of diamond nanoparticles affect the nanofluids thermal conductivity. Since nanodiamond and alumina thermal conductivities are 2000 and 20-30 W/m.K respectively, different enhancements are reasonable.

Considering these figures, by increasing temperature for all contents of diamond nanoparticles in the transformer oil, the thermal conductivity raises. This enhancement is caused by Brownian motion, which led to increase in interactions between nanoparticles and oil.

Regarding Figures 7 and 8, two distinct regions are distinguishable. At low concentrations (less than 0.2 wt %), the rate of thermal conductivity enhancement is greater than that of the higher ones. A similar trend has been reported by other researchers [20, 21] in their experiments on TiO_2-water nanofluids, in which transition typically occurred at nearly 1% volume fraction.

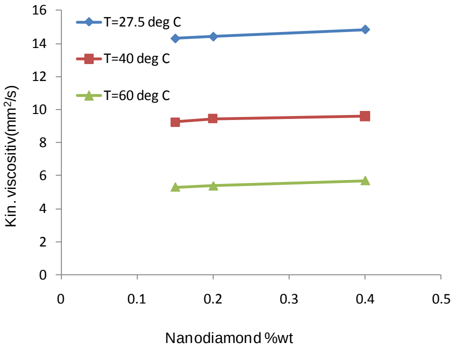


Figure 6. Effect of temperature and nanoparticles' content on the viscosity

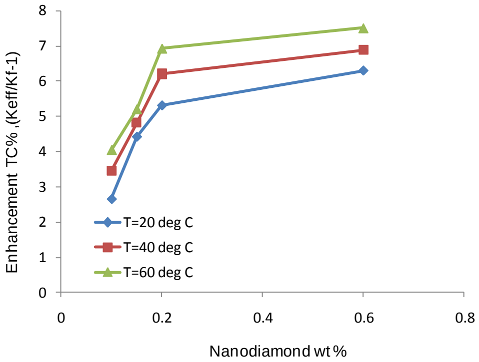


Figure 7. Thermal conductivity index versus nanoparticle %wt for the prepared nanofluids by the first procedure

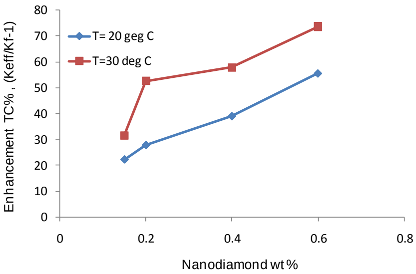


Figure 8. Thermal conductivity index versus nanoparticle %wt for the prepared nanofluids using the third procedure

TABLE 5. Thermal conductivity indexes for 0.6%wt nanofluids prepared by different procedures at 20 °C

Procedure	Enhancement (%)
The 1st procedure	6.2
The 2nd procedure	15.92
The 3rd procedure	55.56

Zhu et al. [22] also observed the same behavior, with a transition at around 2% volume fraction. Here, the obtained results show a comparable trend, but transition appeared at 0.2 wt% fraction (equal to 0.056% volume fraction). This difference may be the result of different base fluids.

In addition, a comparison of the thermal conductivity indexes (at 20 °C) of the prepared 0.6% nanofluids by the three mentioned procedures is shown in Table 5.

As one can see, the highest value for the thermal conductivity index was achieved for the nanofluid prepared by the third method. Here, the main difference is in the method used for dispersing nanoparticles in the fluid. Although surfactants are well-known materials for enhancement of suspension stability, they could negatively affect the total thermal conductivity by surrounding nanoparticle surface. Ball milling (used in the second and third preparation procedures) is another method of dispersion which increases the stability [19]. This process segregates nano agglomerates into smaller clusters and prepares a larger interface for heat transfer.

Nanofluids made by the first and second procedures presented appropriate results for understanding the parallel effects of using surfactant and ball milling. Since the thermal conductivity enhancement of the nanofluid prepared by the second procedure was greater than that prepared by the first method, so it could be concluded that use of ball milling after adding surfactant is a proper way for increasing thermal conductivity. Although both methods of adding surfactant and ball milling are proper methods to have stable suspension, but lower thermal conductivity of surfactants in comparison with nanoparticles, restricts the total enhancement in thermal conductivity.

3. 3. Examining the Consistency with the Theoretical Models

In order to explain the anomalous enhancement of thermal conductivity of nanofluids, researchers have proposed many theoretical models. One of the earliest attempts was comparing the obtained results with the classical Maxwell model. This model matched well with experimental results for low concentrations of spherical particles with millimeter or micrometer size. Hamilton and Crosser (H C model) extended the Maxwell's model for non-spherical particles by introducing a parameter which considers the non-sphericity. Maxwell model is [20]:

$$\frac{k_e}{k_f} = \frac{k_p + 2k_f + 2\varnothing(k_p - k_f)}{k_p + 2k_f - \varnothing(k_p - k_f)} \tag{1}$$

where, k_e is the effective thermal conductivity of the suspension, k_f is the thermal conductivity of the base fluid, k_p is the thermal conductivity of nanoparticle and $\varnothing$ is the volume fraction.While, Hamilton and Crosser model (HC Theory) is [20]:

$$\frac{k_e}{k_f} = \frac{k_p + (n-1)k_f + (n-1)\varnothing(k_p - k_f)}{k_p + (n-1)k_f - \varnothing(k_p - k_f)} \tag{2}$$

In this relation, n is the non-spherical shape factor given as:

$$n = 3/\psi \tag{3}$$

where, ψ is the sphericity, defined as the ratio of the surface area of a sphere with a volume equal to that of the particle to the surface area of the particle.

Thermal conductivities of nanofluids made by the third procedure (Figure 9) are in agreement with results obtained by Xuan and Li [23]. They showed that for $\psi = 0.7$, their experimental results for thermal conductivity of nanofluids with different volume fractions and shape factors match HC theory well. While ball milling affect the structure of nanoparticle [24], it is reasonable to assume that nanoparticle shape is non-spherical and use HC model. In Figure 9, the experimental results were compared to the derived data from HC and Maxwell theoretical models.

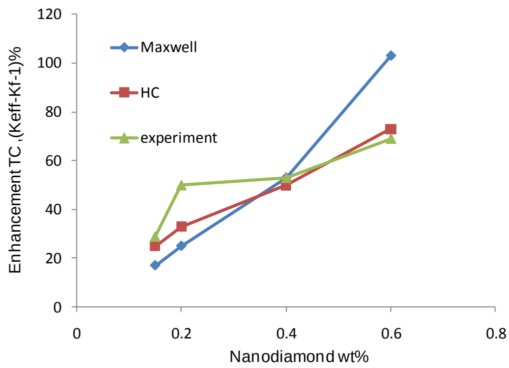


Figure 9. Theoretical model comparison of thermal conductivity versus weight fraction

4. CONCLUSIONS

Transformer oil nanofluids were prepared using diamond nanoparticles with three different procedures, in order to study electrical and thermal properties of the prepared nanofluids. In the first preparation procedure, magnetic stirrer, surfactant and ultrasonic bath were employed, while in the second one ball milling was also applied. In the third procedure, magnetic stirrer, ultrasonic bath and ball milling were used in the absence of surfactants.

The stability of nanofluids was studied as a function of stabilizer type, amount and sonication time. The most stable nanofluid was prepared by employing Span 80 stabilizer, with 2:1 surfactant to nanoparticle content ratio, and when ultrasonication time was 30 minutes.

Furthermore, breakdown strength and dielectric loss of the prepared transformer oil nanofluids were investigated. The breakdown strength of the transformer oil first increased to a specific value, while by more increase in the concentration of diamond nanoparticles, it decreased. The maximum value of about 38% increscent was achieved for 0.15 wt% nanofluid. Dielectric loss was also enhanced by increasing the nanodiamond content. At low concentrations, insulating losses were low, while by increasing the concentration, the losses increased, significantly.

Based on the experimental results, viscosity of the nanofluid declines with temperature increase. This is due to decreasing of the adhesion forces. On the other hand, oil viscosity increases with the rise in the content of diamond nanoparticles in the oil, which is the result of an increase in the intermolecular forces.

Comparing the thermal conductivity index for the nanofluids prepared by the three mentioned procedures showed that, the best results were achieved in the absence of surfactant while ball milling was employed. However, ball milling led to an increase in the thermal conductivity index in the presence of surfactant.

In addition, experimental data showed that, by increasing the content of the diamond nanoparticles in the oil, the thermal conductivity raises. The best result of 73% increase in the thermal conductivity index (at 30°C) was achieved for 0.6% nanofluid prepared by the third procedure.

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5. REFERENCES

1. Board, I., "IEEE guide for loading mineral-oilimmersed transformers", ***IEEE Std C***, Vol. 57, (1995), 1-112.
2. Ahuja, A. S., "Augmentation of heat transport in laminar flow of polystyrene suspensions. I. Experiments and results", ***Journal of Applied Physics***, Vol. 46, No. 8, (1975), 3408-3416.
3. Das, S. K., Choi, S. U., Yu, W. and Pradeep, T., "Nanofluids: Science and technology, John Wiley & Sons, (2007).
4. Keblinski, P., Eastman, J. A. and Cahill, D. G., "Nanofluids for thermal transport", ***Materials Today***, Vol. 8, No. 6, (2005), 36-44.
5. Godson, L., Raja, B., Lal, D. M. and Wongwises, S., "Enhancement of heat transfer using nanofluids—an overview", ***Renewable and Sustainable Energy Reviews***, Vol. 14, No. 2, (2010), 629-641.
6. Choi, C., Yoo, H. and Oh, J., "Preparation and heat transfer properties of nanoparticle-in-transformer oil dispersions as advanced energy-efficient coolants", ***Current Applied Physics***, Vol. 8, No. 6, (2008), 710-712.
7. Lv, Y., Wang, W., Ma, K., Zhang, S., Zhou, Y., Li, C. and Wang, Q., "Nanoparticle effect on dielectric breakdown strength of transformer oil-based nanofluids", in 2013 Annual Report Conference on Electrical Insulation and Dielectric Phenomena, IEEE, (2013), 680-682.
8. Du, Y.-f., Lv, Y.-z., Jian-quan, Z., Li, X.-x. and Li, C.-r., "Breakdown properties of transformer oil-based TiO_2 nanofluid", in Electrical Insulation and Dielectric Phenomena (CEIDP), 2010 Annual Report Conference on, IEEE, (2010), 1-4.
9. Karthik, R., Raja, T. S. R. and Madavan, R., "Enhancement of critical characteristics of transformer oil using nanomaterials", ***Arabian Journal for Science and Engineering***, Vol. 38, No. 10, (2013), 2725-2733.
10. Chiesa, M. and Das, S. K., "Experimental investigation of the dielectric and cooling performance of colloidal suspensions in insulating media", ***Colloids and Surfaces A: Physicochemical and Engineering Aspects***, Vol. 335, No. 1, (2009), 88-97.
11. Peng, X.-f., Yu, X.-l., Xia, L.-f. and Zhong, X., "Influence factors on suspension stability of nanofluids", ***Journal-Zhejiang University Engineering Science***, Vol. 41, No. 4, (2007), 1557-1562.
12. Chang, H., Wu, Y., Chen, X. and Kao, M., "Fabrication of Cu based nanofluid with superior dispersion", ***National Taipei University of Technology, Taipei, Taiwan***, (2000).
13. Hwang, Y., Lee, J.-K., Lee, J.-K., Jeong, Y.-M., Cheong, S.-i., Ahn, Y.-C. and Kim, S. H., "Production and dispersion stability of nanoparticles in nanofluids", ***Powder Technology***, Vol. 186, No. 2, (2008), 145-153.
14. Hwang, Y., Park, H., Lee, J. and Jung, W., "Thermal conductivity and lubrication characteristics of nanofluids", ***Current Applied Physics***, Vol. 6, (2006), 67-71.
15. Hwang, Y., Lee, J., Lee, C., Jung, Y., Cheong, S., Lee, C., Ku, B. and Jang, S., "Stability and thermal conductivity characteristics of nanofluids", ***Thermochimica Acta***, Vol. 455, No. 1, (2007), 70-74.
16. Ghadimi, A., Saidur, R. and Metselaar, H., "A review of nanofluid stability properties and characterization in stationary conditions", ***International Journal of Heat and Mass Transfer***, Vol. 54, No. 17, (2011), 4051-4068.
17. Jamshidi N., Farhadi M., Ganji D. D. and Sedighi K., "Experimental investigation on the viscosity of nanofluids", ***International Journal of Engineering***, Vol. 25, (2012), 201-209.
18. Jamal-Abad, M. T. and Zamzamian, A., "Thermal conductivity of Cu and al-water nanofluids", ***International Journal of Engineering Transactions B: Application***, Vol. 26, No. 8, (2013), 821-828.
19. Shima, P. D. and Philip, J., "Role of thermal conductivity of dispersed nanoparticles on heat transfer properties of nanofluid", ***Industrial & Engineering Chemistry Research***, Vol. 53, No. 2, (2014), 980-988.
20. Sachdeva, P., "Molecular dynamics study of thermal conductivity enhancement of water based nanofluids", University of Central Florida Orlando, Florida, (2009),
21. Murshed, S., Leong, K. and Yang, C., "Determination of the effective thermal diffusivity of nanofluids by the double hot-wire technique", ***Journal of Physics D: Applied Physics***, Vol. 39, No. 24, (2006), 5316-5322.
22. Zhu, H., Zhang, C., Liu, S., Tang, Y. and Yin, Y., "Effects of nanoparticle clustering and alignment on thermal conductivities of fe3o4 aqueous nanofluids", ***Applied Physics Letters***, Vol. 89, No. 2, (2006), 23123-23123.
23. Xuan, Y. and Li, Q., "Heat transfer enhancement of nanofluids", ***International Journal of heat and fluid flow***, Vol. 21, No. 1, (2000), 58-64.
24. Vallal Peruman, K. and Mahendran, M., "Ball milling effect on structural and magnetic properties of ni–mn–ga ferromagnetic nanoparticles", ***Pure and Applied Chemistry***, Vol. 83, No. 11, (2011), 2071-2077.

An Investigation on Stability, Electrical and Thermal Characteristics of Transformer Insulting Oil Nanofluids

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چکیده

نانوسیال روغنی ترانسفورماتور با بکارگیری نانوذراتی با خواص مناسب و به منظور بهبود خواص حرارتی و عایقی روغن تهیه می‌شود. در مطالعه حاضر، نانوسیالاتی بر پایه روغن معدنی ترانسفورماتور با بکارگیری نانوذرات الماس که دارای ضریب هدایت حرارتی بالا و همچنین خواص عایقی مطلوبی هستند، با استفاده از سه روش، با در نظر گرفتن اثر حضور پایدار کننده ها و فرایند آسیاب گلوله ای، تهیه گردیدند. تاثیر چندین پایدار کننده (از نظر نوع و میزان) و همچنین زمان اعمال امواج آلتراسونیک بر میزان پایداری نانوذرات در روغن به صورت آزمایشگاهی بررسی و بر اساس نتایج حاصله بهینه سازی صورت گرفت. سپس با استفاده از نانوسیالات بهینه، ضریب هدایت حرارتی و ویسکوزیته نانوسیالات روغنی مقایسه و مورد بحث واقع گردید. علاوه بر این، مقایسه نتایج آزمایشگاهی ضریب هدایت حرارتی با مدل های نظری ماکسول و همچنین همیلتون و کراسر انجام شد. براساس نتایج حاصله مشخص گردید که، روند تهیه نانوسیال، دما و غلظت نانوذرات بر ضریب هدایت حرارتی نانوسیال روغنی تاثیرگذار می باشد. این در حالی است که حضور نانوذرات منجر به تغییرات ناچیزی در میزان ویسکوزیته سیال می‌گردد. همچنین, تایر حضور نانودرات بر خواص الکتریکی روغن ترانسفورماتور مورد مطالعه قرار گرفت. بر اساس نتایج آزمایشگاهی، افزودن نانوذرات الماس می تواند منجر به افزایش ولتاژ شکست روغن ترانسفورماتور، بدون ایجاد تغییر در اتلاف دی الکتریکی در غلظت های پایین، گردد.

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