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# Experimental Investigation on the Viscosity of Nanofluids

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*ABSTRACT*

In this study, the effect off adding $SiO_2$ nanoparticles on the viscosity of base fluid is investigated experimentally. Base fluids are chosen among common heat transfer fluids such as ethylene glycol, transformer oil and water. In addition different volume percentages of ethylene glycol in water are used as ethylene glycol-water solution. In every base fluid different volume fractions of $SiO_2$ nanoparticles is added. It is shown that the viscosity of solution enhance by adding nanoparticles. The effect of cooling and heating process on the viscosity of nanofluid is also discussed. The presented data show that as the temperature increases the viscosity of base fluid and nanofluid decrease. It is also revealed that there are very little differences between the viscosity of nanofluid in a specific temperature at cooling and heating cycles. According to the experimental results new correlations for predicting the viscosity of nanofluids is presented. These correlations relate the viscosity of nanofluid to the particle volume fraction and temperature.

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## 1. INTRODUCTION

Heat transfer plays an important role in many applications. Ethylene glycol and water solutions are common in heat transfer systems such as cars and machines with water cooled engines. The specific heat capacity, viscosity and specific weight of water and ethylene glycol solution vary by the ethylene glycol percentages and temperature. The thermophysical properties of ethylene glycol-water are far from water and ethylene glycol properties so these properties should be calculated thoroughly for actual temperature and solution. For transmission and distribution of electric energy power transformers are used. A typical transformer consists of coils which is a conducting wire wrapped around a core and covered with a paper-based insulator and transformer oils which is a highly-refined mineral oil for electrical insulation and heat dissipation. The lower the viscosity of transformer oil, the higher circulation speed for oil and a better efficiency of cooling system.

The need for having compact systems and saving energy made scientists to search for ways to enhance the heat transfer rates. One of these new techniques for improving the heat transfer characteristics of systems is adding high thermal conductivity solids to the base fluid. Micro and milli sized particles may cause sedimentation, clogging and erosion in systems so Choi [1] proposed using nanofluid which consist of nano sized particles in the base fluid. Nanofluids have higher thermal conductivity [2-5] without mentioned problems. According to Maxwell's theory [2] thermal conductivity of a mixture is related to the thermal conductivity of base fluid and volume fraction of particles in the sample. Experiments show that the thermal conductivity enhancement in nanofluid is much higher than the predicted ones by Maxwell's theory which is in favor but according to Einstein's theory [6] the viscosity of mixture enhance too and enhanced viscosity means higher pumping power for heat transfer systems. A few theoretical formulas can be used to estimate the suspension viscosity and most of them are derived from the work of Einstein [6]. The formula is based on the assumption that a linearly viscous fluid is containing dilute, suspended and spherical particles. This formula is applicable at low volume fractions of particles $(¤ \le 0.02)$.

$$«_{nf} = «_{f}\left(1 + 2.5¤\right) \tag{1}$$

Brinkman [7] improved Einstein formula to be applicable for moderate volume fractions of particles.

$$«_{nf} = «_{f} \big/ \left(1 - 2.5¤\right) \tag{2}$$

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Batchelor [8] in an approximately isotropic suspension of rigid and spherical particles considered the effect of Brownian motion of particles on the bulk stress and proposed the following formula.

$$\mu_{nf} = \mu_f \left(1 + 2.5\phi + 6.5\phi^2\right) \quad (3)$$

In these equations $\mu_{nf}$, $\mu_f$ and $\phi$ are the viscosity of suspensions, the viscosity of base fluid and the volume fraction of particles, respectively. From these formulas it is revealed that viscosity of suspension is a function of the viscosity of base fluid and the volume fraction of solid particles. All these formulas may be used for estimation of the viscosity of nanofluid but the ranges that these formula are applicable for nanofluids should be studied. For example, Brinkman's formula which was adopted in various studies considering nanofluids[9,10], has been found to severely underestimate the nanofluid viscosity [11] .

Duangthongsuk and Wongwises [12] reported the thermal conductivity and viscosity of $TiO_2$ nanoparticles in water. They compared the experimental results with existing correlations and proposed a new thermophysical correlation for predicting the thermal conductivity and viscosity of nanofluid for nanoparticles volume fraction ranging 0.2-2% and temperature ranging from 15 ℃ to 35℃ . Yu et al. [13,14] in several articles presented the viscosity and thermal conductivity data of different nanofluids such as nano diamonds, nano coppers, Aluminum nitride nanoparticles (AlNs) and ZnO dispersed in the ethylene glycol. They noted that by adding nano diamonds the thermal conductivity enhanced by 17.23% for 1% vol nanoparticles. The increased thermal conductivity in copper / ethylene glycol nanofluid with temperature is due to Brownian motions of copper nanoparticles. By 0.1%vol AlN nanoparticles thermal conductivity increased by 38.71% and thermal conductivity did not vary much by temperature. They related this behavior of nanofluid to the high viscosity of base fluid. The viscosity data revealed Newtonian behavior in nano diamond nanofluid. Chopkar et al. [15] used 0.2-1.5%vol $Al_2Cu$ and $Ag_2Al$ nanoparticles in ethylene glycol and water. They noted an increase in thermal conductivity ratio with loading nanoparticles. For 2.5%vol nanoparticles in water and ethylene glycol reported 2.6 and 2.2 thermal conductivity ratios (defined as the ratio of nanofluid thermal conductivity to base fluid thermal conductivity). Namburu et al. [16] dispersed copper oxide nanoparticles in 60:40(by weight) ethylene glycol and water mixture. Nanoparticles volume fraction ranges from 0% to 6.12% and in these ranges nanofluid acts as a Newtonian fluid. They developed a correlation for estimating the nanofluid viscosity with respect to particle volume fraction and temperature. Choi et al. [17] used $Al_2O_3$ and AlN nanoparticles in transformer oil. The volume fraction of nanoparticles in the base fluid is 0.5%. They used oleic acid as dispersant and transient hot wire technique for measuring thermal conductivity. They reported that the thermal conductivity enhanced about 20% in this volume fraction but they mentioned no data about how viscosity changed in this ranges. Lee et al. [18] dispersed fullerene nanoparticles in mineral oil. The volume fraction of nanoparticles in their study was 0.1% and by the use of nano-oil in refrigerator compressor, the friction factor decreased to 90%.

In this study $SiO_2$ nanoparticles are chosen to make nanofluid because they have an electric insulation property. The stability of nanoparticles in different volume fractions in ethylene glycol, transformer oil and water is studied and then measurements for investigating the effect of volume fraction of nanoparticles and temperature on the viscosity are done.

## 2. EXPERIMENTAL PROCEDURE

**2. 1. Materials** $SiO_2$ nanoparticles are used in this study. The physical properties of nanoparticles are summarized in Table 1. Nanofluid samples were prepared by dispersing $SiO_2$ nanoparticles in ethylene glycol/water solution (EG-W solution), pure ethylene glycol, transformer oil and water at volume fractions 0.0-0.1%. XRD and TEM images of $SiO_2$ particles are illustrated in Figure 1.

**TABLE 1.** Physical properties of nanoparticles

| Purity (%) | SSA | Size | Nanoparticle |
|---|---|---|---|
| +99 | 600 $m^2$/g | 10nm | $SiO_2$ |

**2. 2. Preparation of Nanofluids and Stability Analysis** There are two techniques for preparing nanofluid, one step and two step method. Two step method is used in this study. In the two-step method, at first nanoparticles are prepared and then they are dispersed in the base fluid. The dispersion can be done with various physical treatment techniques, such as the stirrer, the ultrasonic bath, the ultrasonic disruptor, and the high-pressure homogenizer.

These techniques deagglomerate the particle clusters in order to obtain homogeneous suspensions. For dispersing $SiO_2$ nanoparticles in the base fluid ultrasonic disruptor technique is used. In Figure 2 (left) the high intensity ultrasonic processor (Sonics, 20 kHz, 750 W) is shown. Ultrasonic wave propagate directly to the test sample from a vibrating horn. These waves increase the fluid temperature. For example if transformer oil is subjected to these waves for 10 min the temperature increases from $24^\circ C$ to $106^\circ C$. So the sample is put in the cooling unit (right picture in Figure 2) in order to control the temperature.

For preparing nanofluid, according to the volume fraction, the amount of nanoparticles is calculated and then with a 0.001 precision balance (AND-FX300GD, 0.001-320 gram) is weighed and slightly is added to the base fluid. Thermophysical properties of materials used in this study are shown in Table 2. With a handy stirrer the nanoparticles and base fluid are mixed but as it is clear in the figure (right hand side picture in Figure 3) the clusters are seen in the mixture.

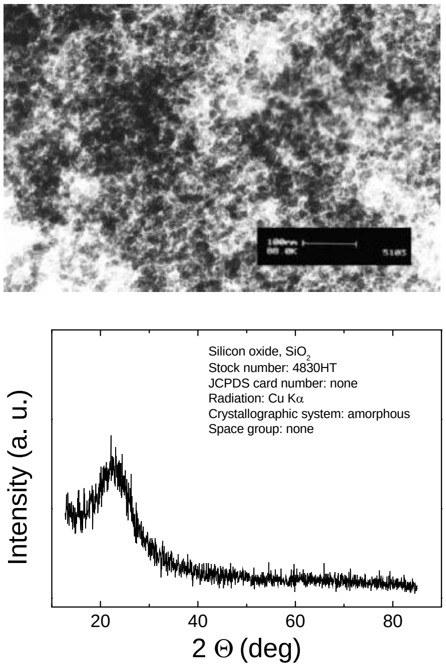


**Figure 1.** XRD and TEM images of $SiO_2$ nanoparticles

**Figure 2.** Left: ultrasonic disrupter, right: controlling the suspension temperature

**2. 3. Uncertainty in Experimental Data** In this experiment, the uncertainty of experimental data is resulted from measuring errors of parameters such as temperature, weight and temperature [20]. The accuracy of measuring scale is 0.001 milligrams, viscometer is 0.01 cp, volume measuring pot is 1 milliliter and the accuracy of thermocouple is 0.01 centigrade degrees. Nanoparticle volume fraction, ¤ , is calculated from readings weight and volume. Therefore, the uncertainty of the volume fraction experiment for all experiments is less than 4.5 percent.

**Figure 3.** EG and transformer oil mixed with $SiO_2$ nanoparticles before sonication

**TABLE 2.** Thermo physical properties of fluids and nanoparticles [19]

| **Physical properties** | **$SiO_2$** | **Water** | **EG** |
|---|---|---|---|
| $\rho$ $(kg/m^3)$ | 2220 | 997.1 | 1132 |
| $C_p$ $(J/kg.K)$ | 745 | 4183 | 2349 |
| $k$ $(W/m.K)$ | 1.38 | 0.6 | 0.258 |
| $\mu$ $(cP)$ | --- | 1 | 15.1 |

## 3. RESULTS AND DISSCUSSION

**3. 1. The Stability Analysis** In Figure 4 the pictures of stable nanofluid are depicted. After 1 hour sonication of the ethylene glycol, transformer oil and water nanofluids at different volume fractions are stable for more than 24, 8 and 6 h, respectively. After sedimentation of nanoparticles the lower part of the mixture behaves as a jelly.

**3. 2. Validity of Measurement** The Viscolite (VL700) which is a vibrational instrument for instant measurement of viscosity is used in this study (Figure 5). For calibration the viscometer is checked in air and water. This instrument shows the dynamic viscosity of whatever fluid is surrounding the sensor in centipoises (cP). As long as the sensor is clean and is wholly in air and not touching anything, the display unit should read 0.0 and the display should show 1.0 (exactly one) if the sensor is immersed in water at 20°C. Specific gravity and viscosity of EG-water solution at room temperature are noted in Table 3. According to the reference [19], the results are in good agreements.

Then the viscosity of pure ethylene glycol and ethylene glycol solutions at different temperatures are measured and the results are shown in Figure 6. The following correlations are proposed for the viscosity of ethylene glycol solution and transformer oil according to the experimental results. The viscosity of water does not change considerably by temperature.

$$\mu\,(25\%\ EG-W)=\exp(-0.01779\ T+1.0305) \tag{4}$$

$$\mu\,(50\%\ EG-W)=\exp(-0.02045\ T+1.7203) \tag{5}$$

Figure 4. Water (up), EG (left) and transformer oil (right) nanofluid after sonication

Figure 5. Measuring viscosity by viscometer

$$\mu\,(75\%\ EG-W)=\exp(-0.02583\ T+2.6044) \tag{6}$$

$$\mu\,(EG)=\exp(-0.04452\ T+4.0316) \tag{7}$$

$$\mu\,(Transformer\ Oil)=\exp(-0.04355\ T+3.5617) \tag{8}$$

T is the temperature of solution in °C.

**TABLE 3.** Specific gravity and viscosity of EG-water mixture at room temperature

| | Water | EG-W (25%) | EG-W (50%) | EG-W (75%) |
|---|---|---|---|---|
| Specific Gravity | 1 | 1.0155 | 1.03928 | 1.0742 |
| Viscosity (cP) | 1 | 1.7335 | 3.21604 | 6.7328 |

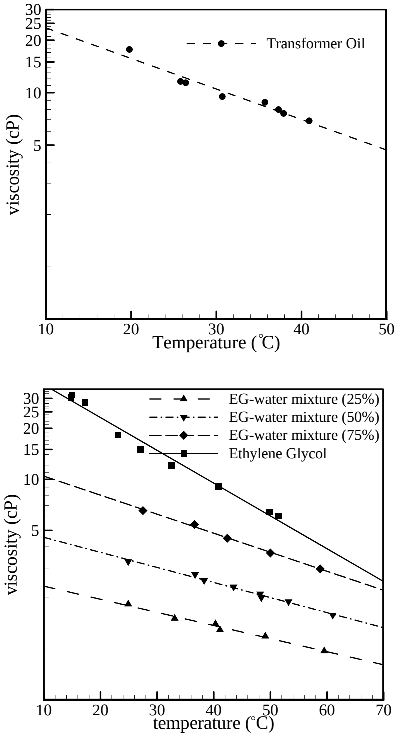


**Figure 6.** EG -water solution and transformer oil viscosity variation with temperature

## 3. 3. Nanofluid Viscosity Variation with Particle Volume Fraction

In Figure 7 the experimental results of nondimensional viscosity of nanofluids are compared with the models of other researchers. In the range of our study the viscosity data of Einstein [6], Brinkman [7] and Batchelor [8] are the same so only the data from Einstein are shown in this figure. As can be seen from the Figure7 the results of our experimental work are far from the classic formula and it can be concluded that these formula are poor when applying to nanofluid. In the other word, they underestimate the viscosity and therefore are not valid when measuring nanofluid viscosity. Generally it is observed from the Figure7 that with increasing particle volume fraction, the viscosity of nanofluid increases considerably which is a result of the direct effect of increasing $SiO_2$ nanoparticles volume fraction, on the internal viscous shear stresses. Viscosity of nanofluid increases exponentially with respect to the volume fraction of nanoparticles.

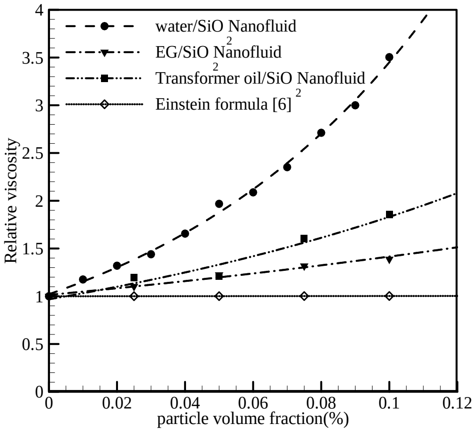


**Figure 7.** The effect of particles volume fraction on nanofluid viscosity

### 3. 4. Nanofluid Viscosity Variation with Temperature

In this section the effect of temperature on the viscosity of nanofluid is discussed. Though viscosity variation with temperature is studied by many researchers but very few researchers studied the impact of temperature cycles on the viscosity of nanofluids.

Nguyen et al. [21, 22] experimentally investigated the effect of temperature and particle size on the viscosity of water based nanofluid. They used alumina and copper oxide nanoparticles and in cooling and heating cycles examined the effect of temperature on the viscosity. It was found in their study that Einstein's and other linear fluid theory based formula are not applicable for nanofluids.

In practical application nanofluids go through heating and cooling so it is important to know how they behave in these cycles. The experiments are done for different volume fractions. The trend of changing nanofluid viscosity in different volume fractions are compared with the data from the effect of varying temperature on the viscosity of base fluid. Then for a fixed volume fraction two set of experiments are done: heating and cooling. After preparing nanofluid and measuring the viscosity at room temperature, the nanofluid in graduated cylinder is put in the thermal bath. The temperature of bath is increased at first and then at the temperature about 70 °C the nanofluid is cooled by decreasing the bath temperature. This experiment is done for each volume fraction and for ensuring the measured data of temperature and viscosity each experiment is done twice. The results show (Figure 8) that the variation of viscosity during the heating and cooling in all samples is less and it can be ignored. It is revealed that the viscosity of nanofluid is decreased with increasing the temperature. This effect is due to that, increasing temperature cause decreasing the inter-particle/inter-molecular forces. The temperature gradient at lower temperature is higher for example at $¤ = 0.075$ with increasing the temperature from 25 to 30 °C the viscosity decreases by 44.89% but increasing the temperature from 35 to 40 °C the viscosity decreases by 18.85%.

In another figure (Figure 9) the effect of increasing temperature and volume fraction on the viscosity of $SiO_2$ -transformer oil nanofluid is shown. The following correlation is proposed for use of $SiO_2$ -transformer oil nanofluid and particle volume fractions of 0 to 1%. In this equation T(ºC) is the fluid temperature.

$$«_{nf} = \exp\left(aT + b\right) \qquad (9)$$

Where

$$a = -0.03959 - 0.01523\, ¤ \qquad (10a)$$

$$b = 3.53267 + 6.3848\, ¤ \qquad (10b)$$

where in Equations (9-10b), $R^2$ (the goodness of fitting data with correlations) are about 0.96, 0.94 and 0.97 respectively. The temperature gradient at low temperatures for higher volume fraction of nanoparticles is higher than lower volume fractions and for temperature more than $40^\circ C$ it is shown that the viscosity is independent of volume fraction. From this point of view it is reasonable to use nanofluids for transformer applications. It has been proved [5, 8-11] that the conductivity of transformer oil based nanofluid increase with increasing the nanoparticles volume fraction. So the usage of transformer oil based nanofluid at higher volume fractions and at higher temperature is fairly good.

The following correlations are proposed for use of $SiO_2$ /EG-W solution nanofluid and particles volume fractions of 0 to 0.1% based on the experimental results (Figure 10). In this equation T (ºC) is fluid temperature.

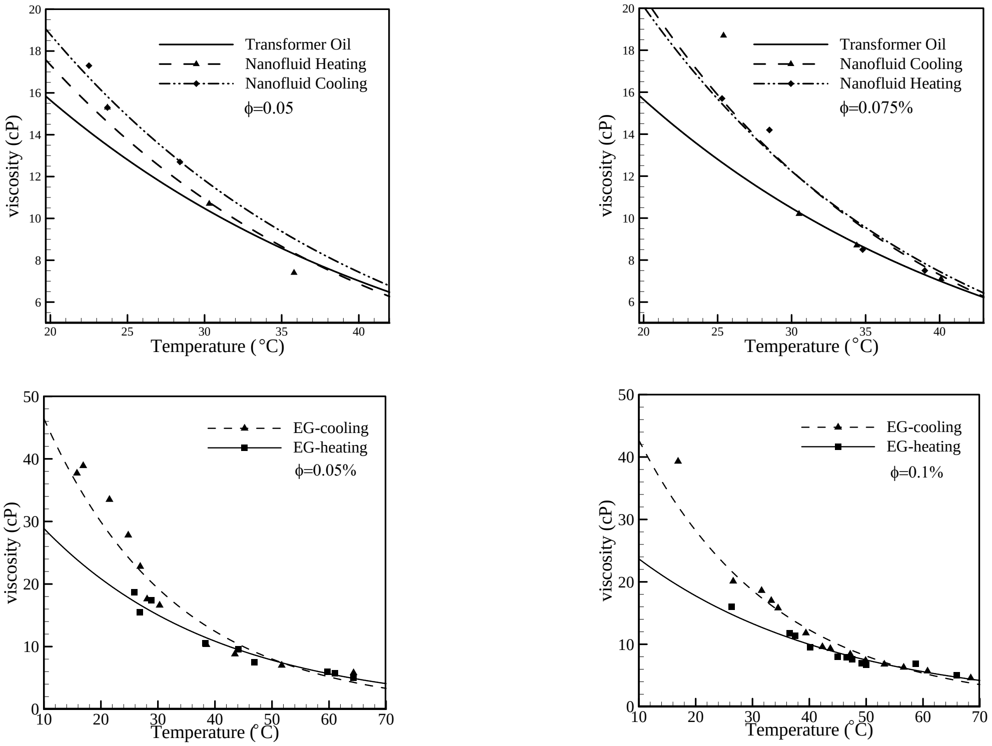


**Figure 8.** The effect of temperature on the viscosity of nanofluid in cooling and heating cycles

$$\text{«}\,(25\%\ EG-W)=\exp(-0.01894\ T+1.0882),\quad \text{¤}=0.05\% \tag{11}$$

$$\text{«}\,(25\%\ EG-W)=\exp(-0.01759\,T+1.1339),\quad \text{¤}=0.1\% \tag{12}$$

$$\text{«}\,(50\%\ EG-W)=\exp(-0.01918\ T+1.7429),\quad \text{¤}=0.05\% \tag{13}$$

$$\text{«}\,(50\%\ EG-W)=\exp(-0.02109\ T+1.8392),\quad \text{¤}=0.1\% \tag{14}$$

$$\text{«}\,(75\%\ EG-W)=\exp(-0.02713\ T+2.6624),\quad \text{¤}=0.05\% \tag{15}$$

$$\text{«}\,(75\%\ EG-W)=\exp(-0.03026\ T+2.8198),\quad \text{¤}=0.1\% \tag{16}$$

In these Equations (11-16), the goodness of fit is about 0.995, 0.996, 0.995, 0.984, 0.998 and 0.951 respectively. The temperature gradient at low temperatures for higher volume fraction of nanoparticles is higher than lower volume.

Namburu et al. [16] dispersed copper oxide nanoparticles in 60:40 (by weight) ethylene glycol and water mixture. Nanoparticles volume fractions range 0 to 6.12% and in these ranges the nanofluid acts as a Newtonian fluid. They developed a correlation for estimating the nanofluid viscosity with respect to particles volume fraction and temperature. In Figure 11 the comparison between new data based on presented correlation and data reported by Namburu et al. [16] data are done. Results are in good agreements.

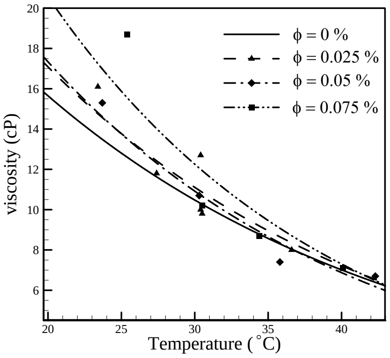


**Figure 9.** The effect of increasing temperature and volume fraction on the viscosity of transformer oil nanofluid

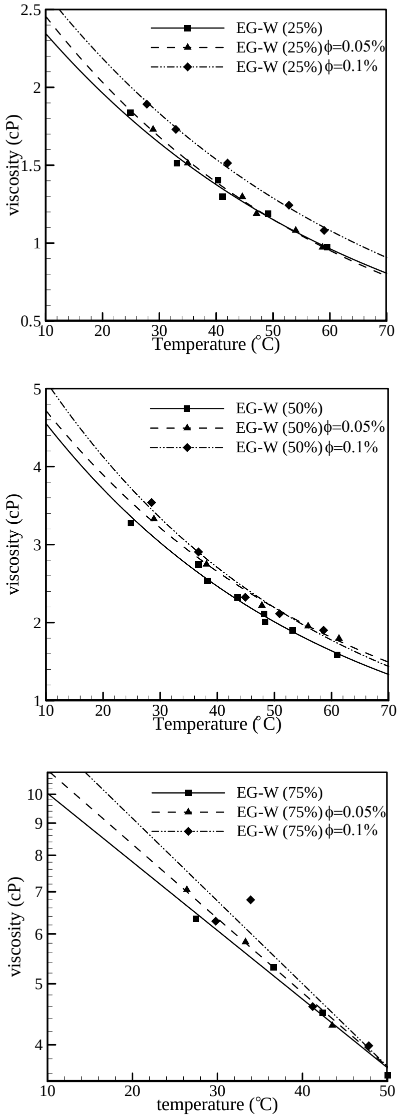
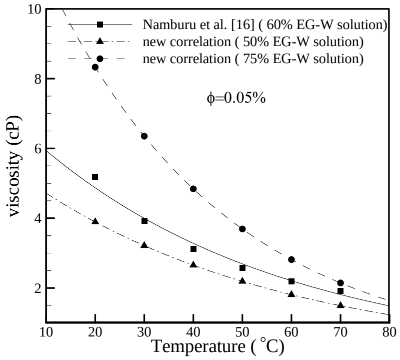


**Figure 10.** The effect of temperature and volume fraction on the viscosity of $SiO_2$ /EG-W solution nanofluid



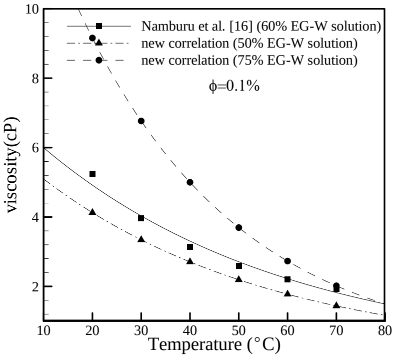


**Figure 11.** Comparison of new data based on presented correlation and data reported by Namburu et al. [16] data

## 4. CONCLUSION

The effect of adding $SiO_2$ nanoparticles on the viscosity of different base fluids is investigated experimentally in this study. Base fluids are ethylene glycol, transformer oil and water. In every base fluid, different volume fractions of $SiO_2$ nanoparticles are added. By increasing the nanoparticles volume factions in the base fluid, the viscosity increases. The increase of viscosity does not obey the conventional formula such as Einstein's formula and the increasing rate of viscosity for fluids with lower viscosity such as water is higher than fluids with higher viscosity such as ethylene glycol. The effect of cooling and heating process on the viscosity of nanofluid is also discussed. The presented data show that as the temperature increases the viscosity of base fluid and nanofluid decrease. It is also revealed that there are very little differences between the viscosity of nanofluid in a specific temperature at cooling and heating cycles. According to the experimental results new correlations for predicting the viscosity of nanofluids are presented. These correlations relate the viscosity of nanofluid to the particles volume fraction and temperature.

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## چکیده

رشد در این تحقیق اثرات افزایش نانوذرات $SiO_2$ بر روی ویسکوزیته گروهی از سیالات به صورت آزمایشگاهی بررسی شده است. سیال پایه از میان سیالات پایه رایج در انتقال حرارت مانند اتیلن گلیکول، روغن ترانسفورماتور و آب انتخاب شده است. علاوه براین از درصدهای مختلفی از اتیلن گلیکول در آب نیز جهت بررسی استفاده شده است. در هر سیال پایه درصدهای مختلفی از نانوذرات $SiO_2$ استفاده شده است. آزمایشات نشان می‌دهند که ویسکوزیته سیال پایه با اضافه نمودن نانوذرات افزایش می‌یابد. اثرات سیکل‌های سرمایش و گرمایش بر روی ویسکوزیته نانوسیال نیز مورد بررسی قرار گرفته است. در اثر افزایش دما ویسکوزیته سیال پایه نیز افزایش می‌ابد و تفاوت اندکی در ویسکوزیته نانوسیال در سیکل‌های سرمایش و گرمایش در یک دمای ثابت وجود دارد. بر اساس داده‌های آزمایشگاهی روابط جدیدی جهت محاسبه ویسکوزیته نانوسیالات به صورت توابعی از دما و درصدحجمی نانوذرات ارائه شده است.

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