Effect of Base-Fluids on Thermo-Physical Properties of SiO2 Nano-Fluids and Development of New Correlations

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Abstract

The enhanced thermal properties being the prominent objective behind the usage of nanofluids. Hence it is necessary to study the base/nanofluid physical properties at various conditions. This article projects the experimental results of thermal conductivity and viscosity of two different nanofluids. The ratio was considered as 60:40 and 40:40 by volume in water and ethylene glycol respectively. The preparation of nanofluids was started by scattering SiO2 nano-particles in EG and "water" (W) blended in "60:40" (60EGW) and "40:60" (40EGW) ratio by volume. The ratio was considered as 60:40 and 40:40 by volume in water and ethylene glycol respectively. The regression analysis was conducted with available data and correlations were formulated for thermal properties. The nanofluids were used in evaluating "viscosity" and "thermal conductivity" experimentally. From the results, the SiO2 particles have achieved enhancement of 34% and 32% in thermal conductivity with the two base-fluids. Similarly, enhancement of 102% and 62% were reported in viscosity. Hence, it can be observed that SiO2 nanofluids in 40EGW nanofluid are a better heat transfer fluid when compared to SiO2 in 60EGW nanofluid.

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Keywords: Nano-fluids; Base-fluids; Heat transfer analysis; Nano-particles; Silicon dioxide; Thermal conductivity, Viscosity

Introduction:

Some of the renowned conventional working fluids include refrigerants, oil, glycol, ethylene, and water. Indeed, nanofluids, which represent new fluid trends, can be used to enhance these conventional working fluids' characteristics. Imperative to note is that nanofluids constitute nano-sized solid particle suspensions, which are found in liquids and have their sizes ranging between 1 nm to 100 nm. Some of the applications in which the new particles (nanofluids) could gain application include manufactured drug delivery systems, solar water heating, thermal storage, lubrications, drilling, refrigeration, cooling electronics, engine oil transmissions, and engine cooling [1–4]. Some of the enhanced thermal properties with which nanofluids are associated, which account for their increasing application, include heat transfer[5], thermal conductivity[6,7], specific heat conductivity[8], viscosity[9], and density [10]. With enhanced thermal conductivity, the eventuality is that there is likely to be a state of enhanced heat transfer. These mixed, but promising outcomes point to the criticality of examining the nanofluids and base fluids' thermal physical properties at different experimental or operating conditions [11–13].

Several scholarly investigations have been conducted to understand the extent to which there could be enhanced convective heat transfer, especially regarding the use of different nano particles [14–20]. Some of the particles that have been investigated included Silicon Dioxide, Titanium Dioxide, Zinc Oxide, Copper Oxide, and Aluminum Dioxide. Upon dispersing these nano particles in water, most of the outcomes suggest good results. Apart from water as a base fluid that has been used, other materials that have continually been embraced included glycerin, ethylene glycol, and oil. In situations where the volume of water and ethylene glycol mixtures as base fluids has been set at 40:60 (40EGW) and 60:40 (60 EGW), promising results have been reported. An enhancement of 40% was observed by Vajjha [21] for a particle concentration varying from 1.0%-10.0% concertation range and 0°C to 100 °C temperature range for 60EGW and 24% enhancement was observed by Azmi [22] for a particle concentration less than 1.0% at a working temperature of 70°C in 40EGW base fluids.

One of the prominent steps involves nanofluids preparation with stability, especially in relation to their application for industrial scale, the step remains challenging. From the previous investigation, the nano particles' setting behavior accounts for the perceived challenges [23–26]. Two procedures through which nanofluids tend to be prepared include the two-step process, as well as the one-step process. In this investigation, the method that was used in nanofluids preparation entailed the two-step procedure. To modulate the stability of the materials that were used, the study relied on the aspect of pH control whereby the shape and size of the nano particles were controlled [27,28] similarly, the surfactant and dispersant were selected appropriately [29]. It is also imperative to highlight that different methods for dispersing nanofluids exist. Some of these techniques include homogenization, ultrasonication, and ball mining, which have an impact on the stability scenario [30,31].

In the aspect of heat transfer coefficient, one of the notable parameters that play an important role entails the target fluid's state of thermal conductivity. From the majority of the previous experimental investigations, factors that affect the thermal conductivity of nanofluids include dispersion, the pH value, temperature, shape, size, volume concentration, and the base liquid; as well as material properties [32]. The transient hot-wire technique is mostly used to measure the state of thermal conductivity because of its high accuracy and quick response time – with the KD2 Pro instrument also playing a complementary role in realizing the merits. It is also notable that most of the previous experiments have seen the viscosity measured using viscometers. To take the viscosity readings, this investigation relied on the Anton Paar MCR 302 Rheometer. Given the shear rates, this tool determines the state of parameters such as viscosity and the shear stress.

In the experimental investigation by Namburu et al. [33], different particle sizes were used as the dependent variables for discerning the viscosities of SiO_2 nanoparticles, hence a comparative analysis. The selected sizes included 100, 50, and 20 nm. These particles were dispersed in 60EGW while the range reflecting the concentration was between 0% and 10%. Also, the temperature range was between -36°C and +50°C. From the findings, the study indicated that at 8% concentration and with 100 nm-sized nano particles, SiO_2 nanofluids exhibit the least velocity. In another investigation by Sundar et al. [34] in their experiments, investigated the influence of various EG/water base liquid mixture ratio , the main objective was to determine the impact of different water/EB base fluid mixture ratios on the viscosity of nanofluids; with particular reference to 60:40%, 40:60%, and 20:80% ratios by weight; having suspended the materials in Al_2O_3 nano particles. The range of temperature for these experimental conditions involved 20°C to 60°C. Also, Vajjha and Das [35] strived to unearth the state of thermal conductivity of different nanofluids. With the particle dispersal operating at 60EGW relative to the mass ratio, specific nanofluids that were investigated included ZnO, CuO and Al_2O_3. The range of temperature under which the experimental conditions were set was between 25°C and 90°C. Also, 10% was the maximum volume concentration under which the experimental study was conducted. The authors formulated a new relationship or correlation linked to β_1 and $f(T,\phi)$, which was expressed in the form:

$f(T,\phi) = \left(2.8217\times10^{-2}\phi + 3.917\times10^{-3}\right)\left(\frac{T}{T_o}\right) + (-3.0669 \times 10^{-2}\phi - 3.91123\times10^{-3})$ (1)

The relations for β_1 are listed in **Table 1** for different nanofluids.

Type of particles	β_1	∅% / temperature range	References
CuO	$9.8810(100\varnothing)^{-0.9446}$	$1.00 < \varnothing < 6.00\%$, $298.00 < T_{nf} < 363.00K$	[36]
ZnO	$8.4407(100\varnothing)^{-1.07304}$	$1.00 < \varnothing < 7\%$, $298.00 < T_{nf} < 363.00K$	[36]
Al_2O_3	$8.4407(100\varnothing)^{-1.07304}$	$1.00 < \varnothing < 10\%$, $298 < T_{nf} < 363.00K$	[36]
Al_2O_3	$0.0017(100\varnothing)^{-0.0841}$	$\varnothing > 1.00$	[37]
CuO	$0.\ 0011(100\varnothing)^{-0.7272}$	$\varnothing > 1.00$	[37]
Au-citrate, Ag-cirate&CuO	$0.0137(100\varnothing)^{-0.8229}$	$\varnothing < 1.00$	[37]

To determine the state of thermal conductivity in relation to the use of 20nm-sizd particles suspended in 60EGW, Sahoo et al. [38] focused on SiO_2 as the selected nanofluids and set their experimental temperature at 20-90°C. Also, 20% was set as the experiment's maximum concentration. Indeed, the state of enhanced thermal conductivity was reported to be 20%. However, these results only held when the temperature was 87°C and$\varnothing$ =10%. It is also worth noting that Sundar et al. Al_2O_3 focused on the behavior of nanofluids by suspending Al_2O_3 particles in 60EGW, 40EGW and 20EGW base fluids – relative to their weights. To establish the values of thermal conductivity, the temperature ranges that characterized the experimental conditions were 20 to 60°C [39]. Also, the rate of concentration of the experimental materials was set between 0.3 and 1.5%. In the results, the authors reported 32.26% as the maximum rate of enhancement. These results held when 1.5% was set as the volume concentration, as well as 20EGW as the base fluid. Also, the results emerged after the temperature of the experimental conditions was set at 60°C [40].

In circumpolar countries and other cold regions such as Alaska and Canada, most of the industrial plants' heat exchangers and automobiles have seen heat transfer fluids used widely. With subzero temperatures experienced, the fluids have also been used in building heating systems [37]. The eventuality is that propylene glycol or ethylene glycol have gained increasing use, having been mixed with water in varying proportions to serve the purpose of heat transfer [41]. However, propylene glycol solutions are seen to perform inferiorly compared to ethylene glycol solutions, with the factor of heat transfer property on focus. This outcome is also more pronounced in situations involving low temperatures. In situations involving cold climates, it is imperatively notable that 40% water and 60% ethylene glycol (translating into 40EGW is used [21,42]. However, the case of countries experiencing hot temperatures has seen this ratio altered to 60EGW (or 40:60). The alteration is informed by the affirmations that with pure water, it is challenging to maintain stability in these conditions [43]. In this investigation, the base fluid saw the water and EG mixtures' ratios used as 40:60 and 60:40.

Other factors operating independent of the role of nano particles have been investigated and documented relative to the nanofluids' thermal conductivity enhancement. Some of these factors include viscosity, temperature, and thermal conductivity. As such, this study strived to determine the thermal conductivity and viscosity properties of 40EGW and 60EGW base fluids. Given the base fluids, nano particles were dispersed, which SiO_2 utilized as the nanofluids. In the section that follows, the manner in which the nanofluids were selected and prepared is described. The third section focuses on the experimental process that was employed towards investigating the viscosity and thermal conductivity of the materials. The fourth section offers the study's resultant regression analysis, culminating into the fifth section that focuses on the experimental outcomes relative to the parameters of viscosity and thermal conductivity (in the form of a comparative analysis). Lastly, the sixth section provides a conclusion, which is a summary of the insights that were gained from this study.

Nanofluid Preparation Methodology

Initially, water forms a component of heat transfer, pointing to its wide-scale use as a liquid cooling applicant. Properties that account for this wide usage include low velocity and high thermal conductivity, as well as high heat capacity. The latter properties also imply that the fluid can be pumped easily. However, it is imperative to acknowledge that water exhibits a high freezing point, coming in the wake of the fluid's associated low boiling point. Furthermore, failure to maintain the pH at a neutral level implies that water could prove corrosive. These trends have seen scholarly attention directed to the use of ethylene glycol. The growing use of the material is attributed to its antifreeze properties. Hence, ethylene glycol has been used in situations such as those involving chilled water air condition systems whose handlers or chillers are kept outside. Also, the material has gained growing use in systems requiring to be cooled at a freezing temperature that is lower than that of water [44]. Figure 1 below summarizes the flowchart of the methodology that this study employed.

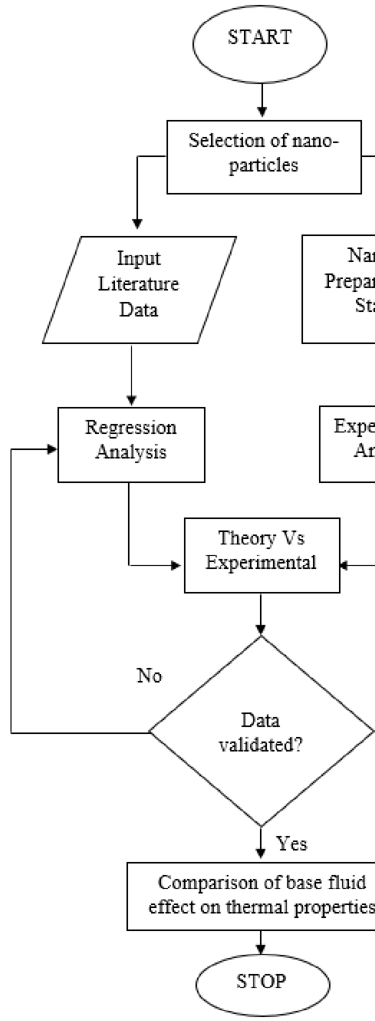


Figure 1 Flow chart for the research methodology of this study

The whole methodology can be simplified into following steps,

1. APS – Average particle size has to be determined for particle aggregation
2. Stability – The investigation on stability is a key issue that influences the properties of nanofluids for application, and it is necessary to study and analyze influencing factors to the dispersion stability of nanofluids [45].
3. pH Measurement – It determines the nano particle aggregation and stability of the nanofluid.
4. Experimental thermal conductivity and viscosity – Initially thermal conductivity values are used for degerming the stability of the nanofluid over a period and once the nanofluid is stable, further values are taken over various operating conditions.
5. Regression analysis – The thermo physical properties values collected from experimental work and literature work have analyzed and correlations were formulated.
6. Comparison - Experimental results were compared with literature and regression analysis to validate the correlations formulated.

2.1. Average Particle Size (APS) of Nanoparticles

One of the considerations for determining particle aggregation, upon suspension in the base fluid, involves nano particle size. To evaluate the solid nano particles' APS state, various techniques are employed. Given solid nano particles, techniques that could be employed include transmission electron microscopy and scanning electron microscopy. Indeed, the electron microscope does not rely on light as its source of radiation. Instead, it relies on the electron beam. Figure 2 illustrates the scanning electron microscopy image for SiO_2 nano particles. To ensure that the nano particles' APS is assessed, an appropriate approach becomes the Dynamic Light Scattering technique [46]. In this technique, the speed of the particle is correlated with its size, a trend informed by the state of Brownian motion. The Stokes-Einstein equation illustrating this relation is shown below:

$D = \frac{\mathrm{kT}}{6\pi\mu r}$ (2)

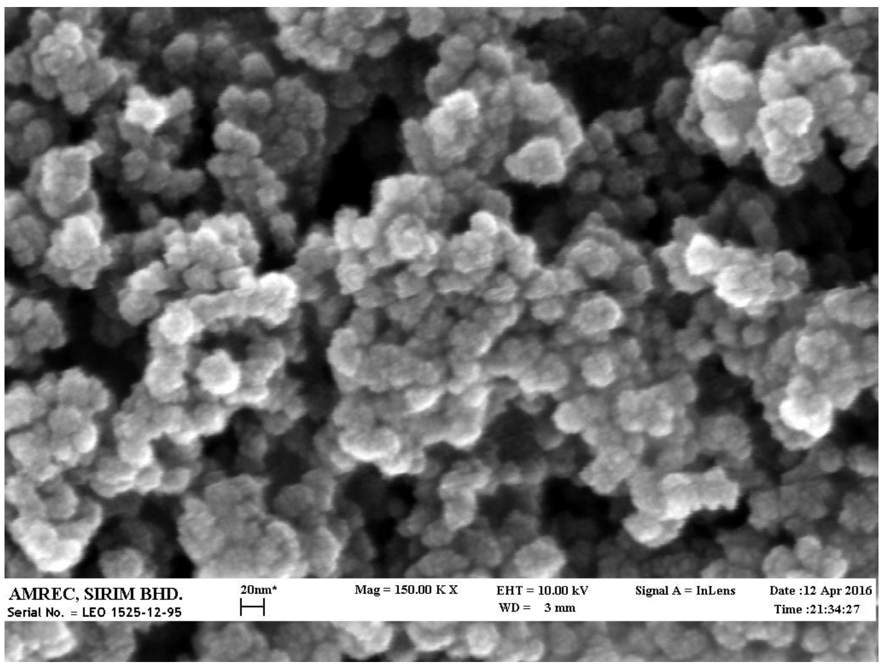


Figure 2 SEM Image of SiO_2 Nanoparticles

In this case, the diffusion coefficient becomes D while the Boltzmann constant is k . also, μ is the dynamic velocity, the particle's radius being r , and its absolute temperature being T . figure 3 (below) highlights the silica size distribution.

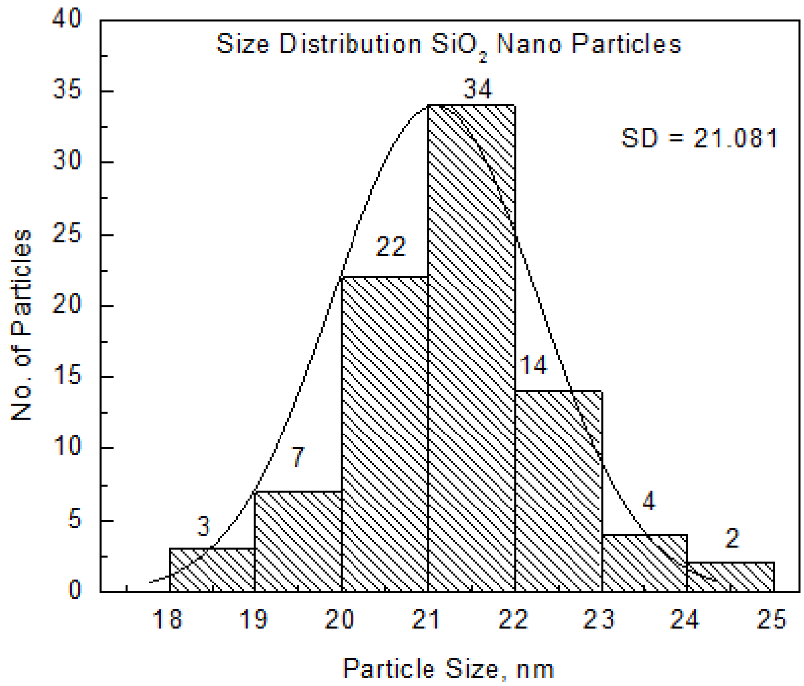


Figure 3: Particle Size Distribution of SiO_2 Nanoparticles

2.2. The Stability of Nanofluid

In nanofluids applications, one of the crucial parameters entails stability. The parameter is worth examining and analyzing relative to different factors that could influence it; hence the nanofluids' dispersion stability. To evaluate nanofluids stability, various techniques have gained application. Examples include Spectral Absorbency Analysis, Zeta Potential Analysis, and the sedimentation technique. In this investigation, the method that was employed to assess nanofluids dispersion stability involved the sedimentation approach [47,48]. The criterion was set in such a way that if the nanofluids had their supernatant particle sizes or concentration kept constant, they (the nanofluids) would be deemed stable. In test tubes, the nanofluids' sedimentation photographs play a crucial role in discerning material stability [49]. In this investigation, the stabilization of SiO2/60EGW nanofluids was realized through the addition of poly vinyl pyrrolidone (PVP) at 20% [50–52]. Given the desired volume concentration for SiO_2, pH values were adjusted for nearly one-and-a-half hours, coming after the ultra-sonication procedure was conducted on the respective samples.

The above procedure was achieved via the use of a sonicator. Regular intervals were set at 30 minutes. To ensure that the sonicator's possible heating effect was countered, the respective samples were kept in water beakers. Following the ultra-sonication procedures, the samples' pH values were assessed. To ensure that the pH values were maintained between 9 and 10, 5 mol of NaoH was added; eventually observing the behavior of the nanofluids samples for three days.

Given that the extraordinary electrical conductivity enhancement is reported, some of the major factors linked to this trend include the iso electric point (IEP), monodispersity, and surface charge (or the pH value). In some of the previous scholarly investigations, the impact of IEP and particle surface charge has also been documented (especially regarding the resultant variation in the experimental sets' states of thermal conductivity – Lee et al. [53]. In the latter investigation, findings demonstrated that colloidal particles are more likely to enhance nanofluids thermal conductivity and also exhibit stability if the target solution's pH exceeds the particles' IEP.

2.3. pH Measurements

Given a homogenous mixture solution, one of the crucial factors that determine nano particle aggregation entails the pH. Furthermore, the pH shapes the suspended nano particles' state of stability. To determine the pH of the respective nanofluids, this study relied on the Mettler Toledo pH meter. The accuracy range was set at ±0.01. For the pH meter, the initial stage involves buffer solution calibration, which is followed by the rinsing of the electrode –before placement in samples for measurement. Indeed, de-ionized water aids in the rinsing process. The read button is then placed in the meter and the measurement could only be implemented if the button is pressed. On the display appears a measurement icon and, as the decimal point starts to blink, the process suggests a measurement in progress. The resultant display reflects the target sample's pH value. He meter's default setting is A, an automated endpoint. Given temperatures levels between 0°C and 100°C, the pH ranges that could be determined lie between 0.00 and 14.00. In this case, the accuracy of the temperature could be set at ±0.5°C.

If nanoparticles exhibit a neutral electrically surface, the resultant pH reflects a zero point of charge. On the other hand, a solution that inclines towards the basic, the interface tends to experience a predominance of negative ions, reflecting a negatively charged surface. However, situations, where the solution's pH tends to be more inclined towards the acidic, there is prevalence of the positive charge, implying the presence of a positively charged surface. Should the pH be far from that which is exhibited by the IEP, the eventuality is that there are stable nanofluids [27,54]. pH values are taken after the ultra-sonication, as the ultra-sonication might affect the pH of the nanofluid prepared and are formulated in **Table 2** .

Table 2 pH values of SiO_2 nanofluids in two different base fluids

Nanofluid	∅ (%)	T, °C	pH Value
SiO_2/60EGW	0.5	22.7	7.56
SiO_2/60EGW	1.0	22.6	7.23
SiO_2/60EGW	1.5	22.7	7.22
SiO_2/40EGW	0.5	24.7	7.01
SiO_2/40EGW	1.0	24.7	6.95
SiO_2/40EGW	1.5	25.2	6.91

The pH values are taken experimentally before and after adding NaoH and the surfactant. The values of pH are needed to be studied over a period of time, to keep a check on stability. Hence, the pH values are taken experimentally after a gap of fifteen days in three sets (Day1, Day 15 and Day 30). The values were plotted against time over a time of thirty days and values were observed to be close enough to declare that the nanofluid is stable. The pH values are plotted with time and temperature and is shown in **Figure 4** .

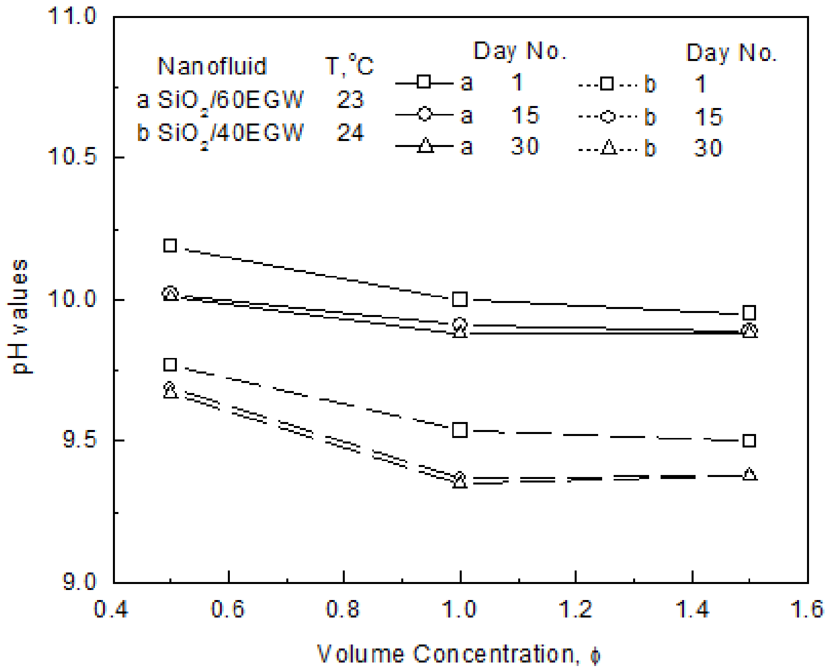


Figure 4. pH values plotted against temperature and time

Thermal conductivity and viscosity experimental setup

As mentioned earlier, the Anton Paar MCR 302 Rheometer aided in taking the viscosity readings. These readings aided in discerning viscosity and shear stress, which were the fluid parameters at the selected shear stresses. Indeed, the tool reflects an oscillatory and rotational rheometer that gives insight into the viscoelastic or viscous characteristic of different materials; including solids, gels, and fluids.

To measure the selected samples' thermal conductivity, the KD2 pro was used. The instrument had a lab thermal properties analyzer, as well as a fully portable field. Indeed, its functionality holds that the thermal conductivity is measured using the transient line heat source – relative to the IEEE and ASTM specifications. Also, the instrument constitutes a small single needle (6 cm) and a digital controller. Furthermore, it has special algorithms responsible for analyzing the resultant measurements gained during cooling and heating intervals. In this study, five consecutive measurements were used to obtain the calibration data. Also important to note is that a 2.0-percent deviation was observed. The times of reading the measurements ranged between one and ten minute. The type of measurement determined the interval of taking the readings.

3.1. Thermal Conductivity Measurements for Stability

Measuring the thermal conductivity of the given nanofluids is one of the known methods to keep a check on stability. To have a better understanding on k_{nf} and thermal conductivity enhancements, it is important to follow the time dependent k_{nf},η of stable metal and metal oxide nanofluids with time [55,56]. Thermal conductivity readings were measured for the prepared nanofluids in regular intervals of time at the same temperatures every time to check the stability of the nanofluids. Here, the SiO_2 nanoparticles were dispersed in the both the base fluids 60EGW and 40EGW in 0.5% volume concentration. The readings were taken in a set of three temperatures 25, 30 and 40°C, respectively.

After a gap of seven days the experiment will be repeated for the same nanofluid at the same temperatures and the readings were noted. Similarly, the experiments were carried in the same manner for the next three weeks. On a whole, for the same nanofluid, the thermal conductivity measurements were taken over period of thirty days at the same temperatures and the thermal conductivity values were analyzed with time. The values were observed have less than 1% deviation and are shown in **Figure 5** . Hence, it can be concluded the nanofluid was stable.

The six samples are shown in **Figure 6** are taken on the first day of preparation and the samples in **Figure 7** are taken after a month gap. The samples were observed to be stabilized as seen with naked eye. As the other two samples out of eight are base fluids, they were not shown here.

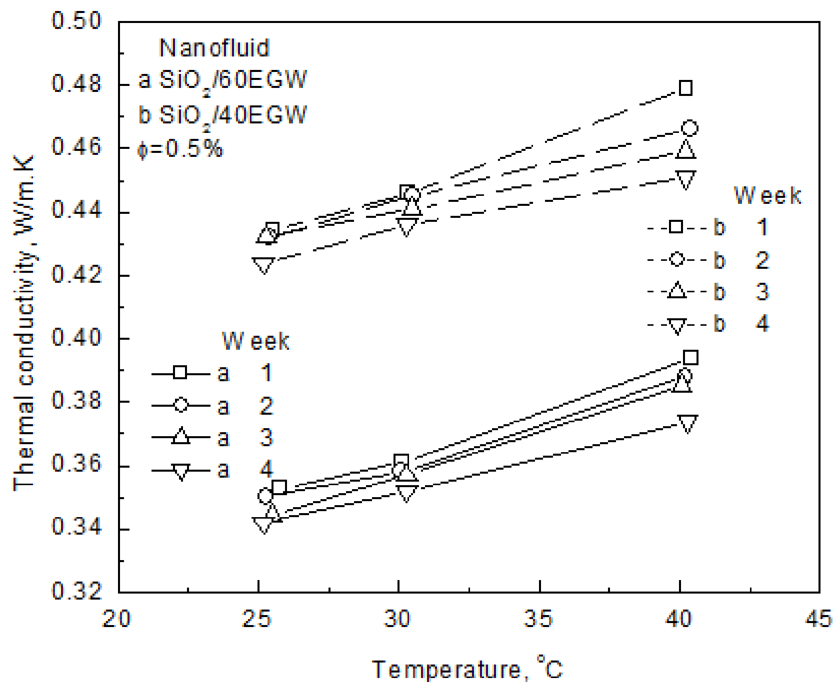


Figure 5. Thermal conductivity vs temperature weekly analysis

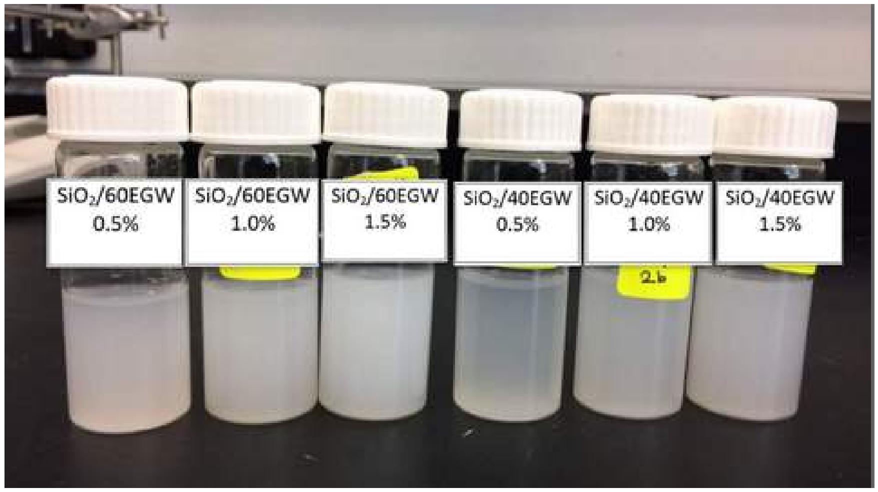


Figure 6. Nanofluid samples on the first day of preparation

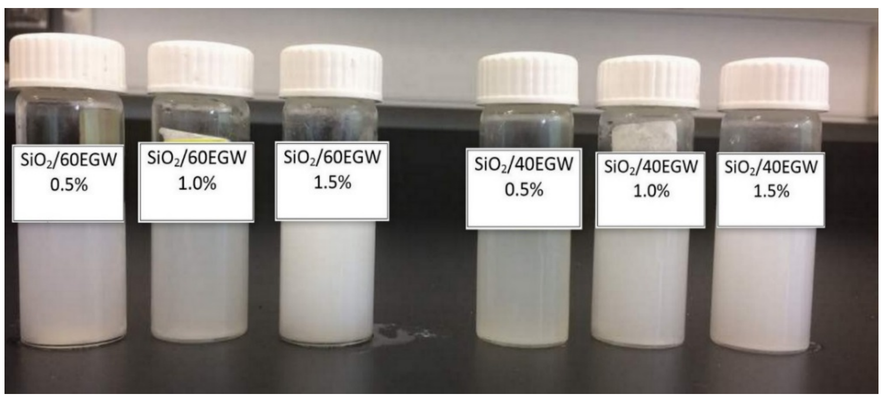


Figure 7: Nanofluid samples after one month of preparation

3.2. Uncertainty Analysis

In this experimental study, the measured values' uncertainty was achieved by focusing on errors that resulted from parameter measurements. The parameters on focus included weight, temperature, viscosity, and thermal conductivity. Regarding the examination of the thermal conductivity parameter, the study relied on a KD2 thermal properties analyzer. On the other hand, the MCR 302 Rheometer aided in assessing the nanofluids' viscosity. It is also worth noting that the Analytical Balance weighing scale was used to determine the nano particles' weight, with a resistance temperature detector utilized towards the measurement of the parameter of temperature. To determine the uncertainty, the expression that was used was [57]:

$$u_m = \sqrt{\left(\frac{k}{k}\right)^2 + \left(\frac{T}{T}\right)^2 + \left(\frac{w}{w}\right)^2}(3)$$

The accuracy of the RTD was 0.5°C. The accuracy of the Analytical Balance was 0.0001g. Hence the total uncertainty of thermal conductivity experiment was observed to be less than ±2.1%. The uncertainty of viscosity can be calculated using the Equation (3) by replacing thermal conductivity, k with viscosity, µ and the uncertainty was observed to be ±4.1%.

Regression Analysis of Thermo-Physical Properties

The experimental data that was obtained aided in conducting a theoretical analysis relative to the thermo-physical properties of interest. From the literature [21,35,38,58], some experimental data exists. This data was incorporated into this study, especially for regression. Some of the parameters to which the regression analysis, which partially relied on the data obtained from the previous studies, included thermal conductivity, viscosity, specific heat, and density. For both nanofluids and other fluids, correlations were implemented in relation to different thermo-physical properties. It is also worth acknowledging that the nanofluids and base fluids' equations in the literature were applied towards successful regression analysis for the target physical properties (4)-(15).

4.1. Base Fluid Properties for 60EGW

In the 60EGW mixture, the parameter or thermo-physical properties of thermal conductivity, viscosity, specific heat, and density were determined via the use of correlations accruing from the regression analysis. Also, some of the experimental data in the previous literature [41] was incorporated into the analysis. The correlations below summarize the base fluid properties of the investigation:

$\rho_{\mathrm{bf}} = 1090.6 - 0.32857T - 0.00286T^2 + 5.421\times10^{-19}T^3 (4)$

$C_{\mathrm{pbf}} = 3044.135 + 4.2808T - 0.00186T^2 + 0.0000155759T^3 (5)$

$\mu_{\mathrm{bf}} = 0.0087 - 0.000245439T + 0.00000282043T^2 - 0.00000001178T^3 (6)$

$k_{\mathrm{bf}} = 0.33944 + 0.00111T - 0.0000100528T^2 + 0.0000000377393T^3 (7)$

4.2. Base Fluid Properties for 40EGW

The EG-W base fluid properties were obtained from regression correlations using ASHRAE data [41],

$\rho_{\mathrm{bf}} = 1066.79734 - 0.3071T - 0.00243T^2$ (8)

$C_{\mathrm{pbf}} = 3401.21248 + 3.3443T + 9.04977E - 5T^2$ (9)

$\mu_{\mathrm{bf}} = 0.00492 - 1.24056E - 4T + 1.35632E - 6T^2 - 5.56393E - 9T^3 (10)$

$k_{\mathrm{bf}} = 0.39441 + 0.00112T - 5.00323E - 6T^2$ (11)

4.3. Nanofluid Properties with Base Fluid 60EGW

Indeed, the nanofluids' properties determine the assessment of the friction factor and the heat transfer coefficients. For the EG-water based nanofluids that included SiO_2, Al_2O_3 and CuO, the viscosity and thermal conductivity were established based on varying parameters. These parameters included material concentration, temperature, and particle size; with the data in the previous literature playing a crucial role at this stage [21,35,38,58]. The correlations below illustrate how thermal conductivity and viscosity parameters were assessed via regression analysis, which also dependent on a numerical program.

$\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{bf}}} = 4.589\left(1 + \frac{\varnothing}{100}\right)^{0.2963}\left(1 + \frac{T_{\mathrm{nf}}}{97}\right)^{0.1398}\left(1 + \frac{d_p}{53}\right)^{-0.4531} (12)$

$\frac{k_{\mathrm{nf}}}{k_{\mathrm{bf}}} = 0.852\left(1 + \frac{\varnothing}{100}\right)^{2.608}\left(1 + \frac{T_{\mathrm{nf}}}{97}\right)^{0.3889}\left(1 + \frac{d_p}{77}\right)^{-0.08427}\left(\frac{\alpha_p}{\alpha_{\mathrm{bf}}}\right)^{0.04192} (13)$

The correlations (12) and (13) are valid in the range of $0 \leq \varnothing \leq 4\%$; $20 \leq T_{\mathrm{nf}} \leq 90^{\circ}$C; $20 \leq d_p \leq 50$nm with a maximum deviation of 10

4.4. Nanofluid Properties with Base Fluid 40EGW

Given the SiO_2/40EGW nanofluids' experimental results gained from the previous literature and this study's experimental results for the Al_2O_3/40EGW nanofluids, the outcomes that were gained aided in conducting the regression correlations. These correlations would, in turn, give crucial insight into the aspects of thermal conductivity and viscosity evaluations; having targeted variables such as particle size, temperature, and volume concentration. The correlations below were used to evaluate the aforementioned parameters of thermal conductivity and viscosity.

$$\frac{\mu_{\rm nf}}{\mu_{\rm bf}} = 1.389\left(1+\frac{\varnothing}{100}\right)^{60.68}\left(1+\frac{T_{\rm nf}}{70}\right)^{-0.669}\left(1+\frac{d_p}{50}\right)^{-0.1573} \quad (14)$$

In this case, the standard deviation and average deviation were estimated and found to be 8.5% and 6.9% respectively\y.

Equation (15) shows the thermal conductivity state achieved. Particularly, the standard deviation and average deviation obtained after implementing the correlations were 2.8% and 1.9% respectively.

$$\frac{k_{\rm nf}}{k_{\rm bf}} = 0.9431\left(1+\frac{\varnothing}{100}\right)^{0.1612}\left(1+\frac{T_{\rm nf}}{70}\right)^{0.1115}\left(1+\frac{d_p}{50}\right)^{-0.003986}\left(\frac{\alpha_p}{\alpha_{\rm bf}}\right)^{0.006978} \quad (15)$$

The correlations (14) and (15) are deemed or perceived as valid; given of $0 \le \varnothing \le 1.5\%$; $20 \le T_{\rm nf} \le 70^{o}$C; $13 \le d_p \le 50$nm.

Experimental Results of Nanofluid Thermal conductivity and Viscosity

In this chapter, the main objective is to discuss the theoretical and experimental results that were reported in the previous literature and this study respectively. From the literature [21,35,38,58], thermo-physical values were obtained based on the formulated correlations. The results were compared with those that were obtained by this investigation, especially due to the need to make valid and informed conclusions and inferences about relations among the parameters or variables that were being investigated. Some of the crucial data that aided in making inferences included the viscosity and thermal conductivity values. Indeed, there was less than 20-percent deviation in relation to a comparison that was made between the experimental results and the theoretical outcomes reported in the previous literature.

The experimental thermal conductivity values are compared with correlations of 60EGW base fluid (7) and with 40EGW base fluid (11) and are shown in **Figure 8** . The experimental data was taken in the temperature range of 25°C-60°C for a particle size of 20nm. A deviation less than 7% was observed with correlation (7) and a deviation less than 3% with correlation (11). And the same data was compared with ASHRAE data as well and a maximum deviation of 8% was observed.

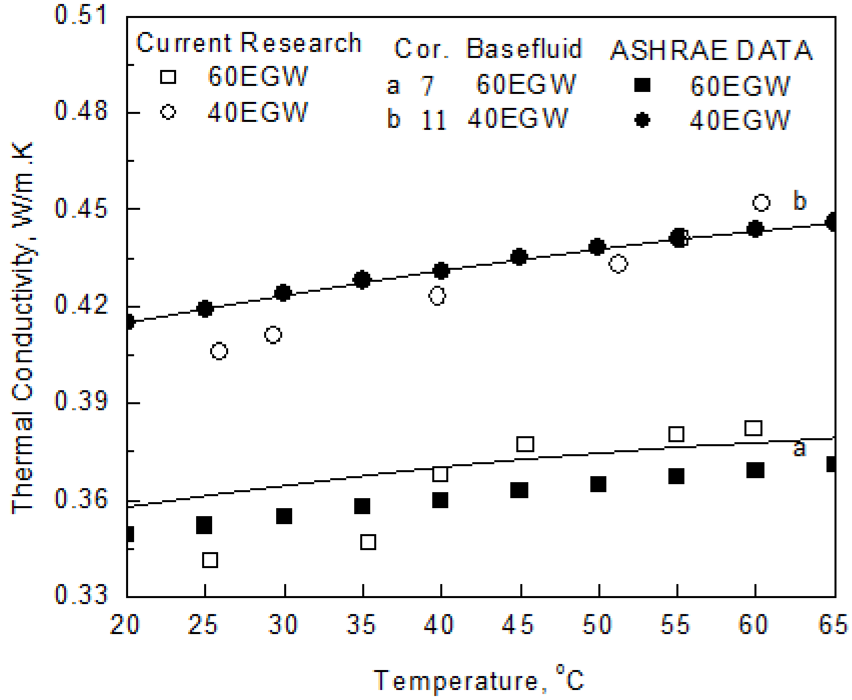


Figure 8 Comparison of experimental thermal conductivity values of base fluids with ASHRAE data

Nanofluid correlations in (13) were compared with thermal conductivity values obtained regarding this study's selected nanofluids. With the temperature range set between 25°C and 60°C and the concentrations for SiO_2/60EGW nanofluids set at 1.5%, 1.0% and 0.5%, Figure 9 highlights the outcomes. In the investigation, an additional experimental condition was that the particle size was set at 20nm. Indeed, 15% was observed as a maximum deviation experienced. Imperatively, thermal conductivity was reduced via the addition of higher thermal conductivity particles. Indeed, the temperature of the nanofluids was observed to be a key parameter affecting the thermal conductivity of the selected materials. In particular, it was established that an increase in temperature causes an increase in the state of thermal conductivity, reflecting a direct correlation between the factor of temperature and the aspect of thermal conductivity.

The nanofluid thermal conductivity was plotted against temperature along with correlation (15) for the given nanofluid SiO_2/40EGW and was shown in **Figure 10** for the similar operating conditions as mentioned for 60EGW based nanofluids.The maximum deviation observed 12% when compared to the base fluid 40EGW.

Compared to water, it was evident that ethylene glycol exhibits low thermal conductivity. Hence, adding the ethylene glycol to water would cause water's thermal conductivity suppression. As more ethylene glycol is added, the thermal conductivity of the resultant mixture would reduce. These results were not only obtained in this study but had also been reported in part of the previous literature [22]; especially for scholarly studies that had targeted or focused on Al_2O_3/40EGW nanofluids.

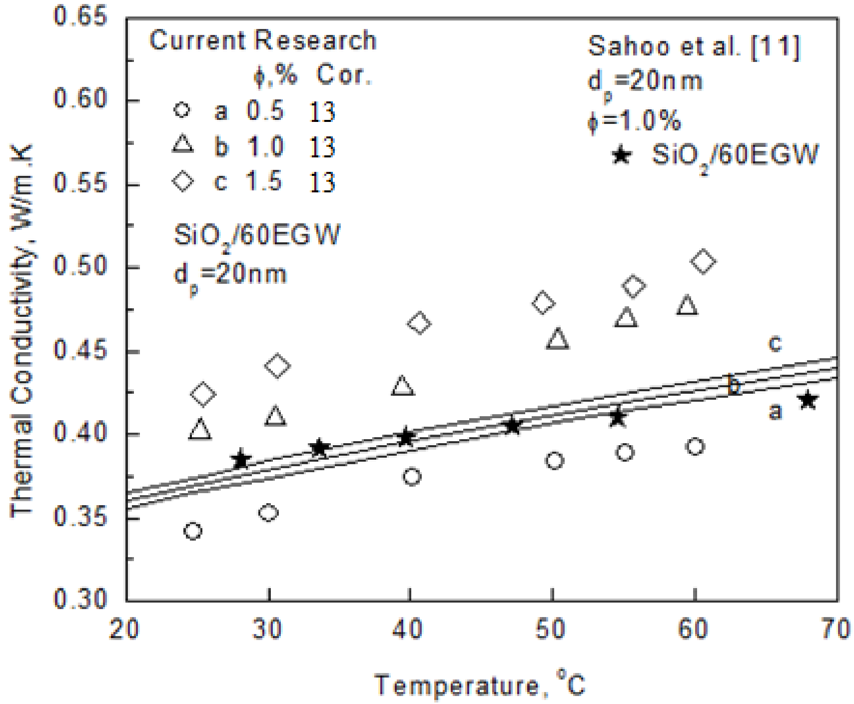


Figure 9 Comparison of experimental values of thermal conductivity for SiO_2/60EGW nanofluids with theoretical equation (14)

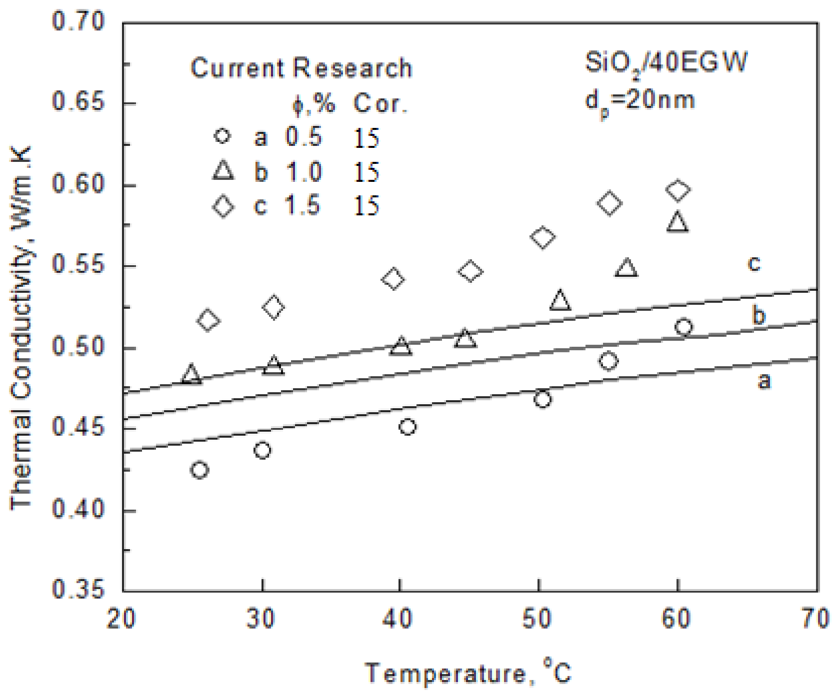


Figure 10 Comparison of experimental values of thermal conductivity for SiO_2/40EGW nanofluids with theoretical correlation (15)

Given the 60EGW and 40EGW-based nanofluids, **Figure 11**summarizes the experimental results that were obtained regarding the parameter of thermal conductivity. From the figure, it is evident that when thermal conductivity is the focal factor, SiO_2/40EGW-based nanofluids demonstrate higher enhancement, proving superior when compared to cases involving SiO_2/60EGW-based nanofluids. It is always desirable to examine the nondimensional thermal conductivity ratiokr (= $k$nf/$k$bf) of the nanofluid, when it is normalized by the base fluid value, because the thermal behavior will also include the influence of the base fluid. This ratio, called the relative thermal conductivity is plotted against temperature for the two given nanofluids.

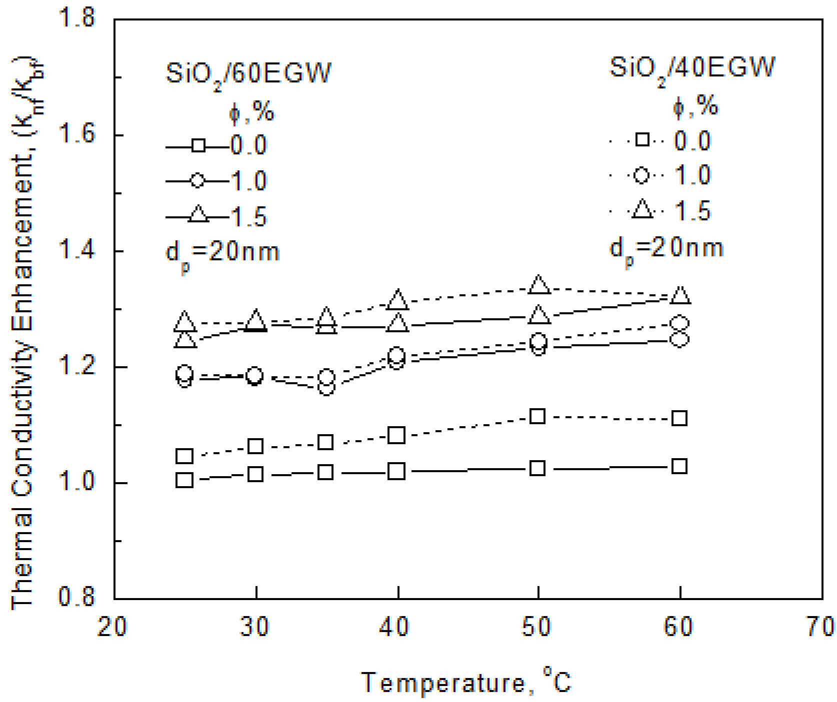


Figure 11 Comparison of thermal conductivity enhancement of SiO_2/60EGW and SiO_2/40EGW nanofluids

It is pretty clear that SiO_2/40EGW shows an enhancement in thermal conductivity with a maximum enhancement of 34% than the base fluid at 1.5% volume concentration and 55°C temperature. On the other hand, the thermal conductivity of SiO_2/60EGW shows an enhancement of 28% at 1.5% volume concentration and 55°C temperature. The reason of thermal conductivity enhancement is with the Brownian motion and micro-convection of particles in the base fluids. The thermal conductivity enhancement not only depends on the particle concentration and temperature, but it also depends on the effect of base fluid.

Based on the regression analysis, the theoretical predictions were made for thermal conductivity of SiO_2 and Al_2O_3 nanoparticles in both the base fluids and are shown plotted in **Figure 12** . At a concentration 1.5%, Al_2O_3/40EGW predicts a higher thermal conductivity when compared to other nanofluids. At the same concentration Al_2O_3nanoparticles and 40EGW based nanofluids predicts a higher thermal conductivity values when compared to SiO_2 nanoparticles and 60EGW based nanofluids respectively.

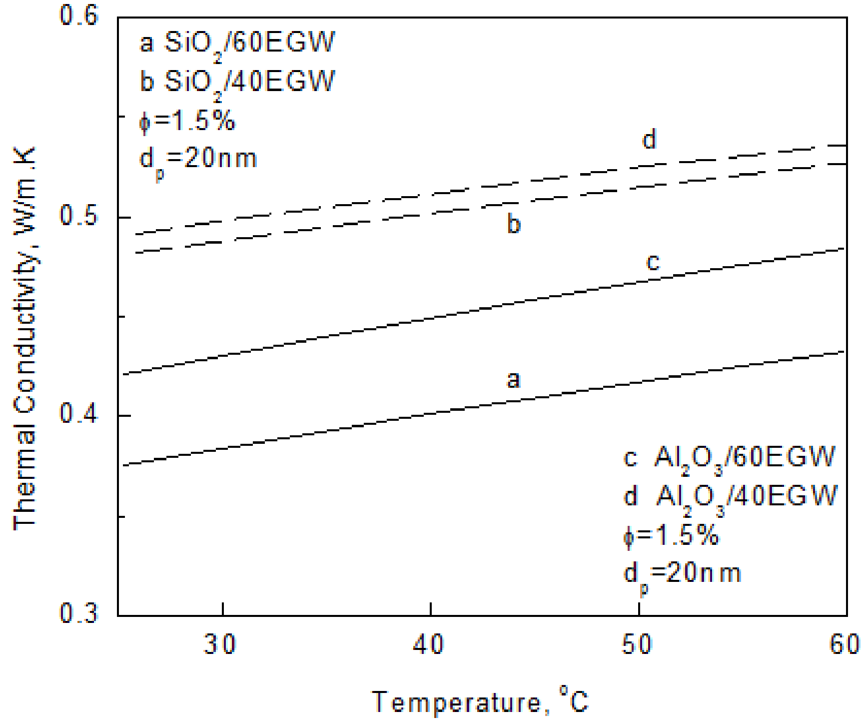


Figure 12 Comparison of theoretical thermal conductivity values for two different nanofluids

The effect of particle size on thermal conductivity was quite evident in all nanofluids, where the thermal conductivity increases with decrease in size. The reason being the increase in specific surface area with decrease in particle size. While there are few observations reported where, thermal conductivity increases with increase in particles size.

Beck et al. [59] have reported that, thermal conductivity increases with increase in particle size up to a diameter of 50nm for Al_2O_3 in both water and EG as base fluids. They have attributed this decrease in enhancement to a decrease in the thermal conductivity of the nanoparticles themselves as the particle size becomes small enough to be affected by increased phonon scattering. Li and Peterson [60] have also reported similar observations for Al_2O_3/water nanofluids for 36nm and 47nm particles sizes.

The main factor effecting the thermal conductivity is considered to be the temperature of the nanofluid as most studies have demonstrated. As there is increase in volume concentration, the thermal conductivity increases which is observed by many researchers. However, the enhancement tends to diminish at high concentration due to the initiation of arrogation.

Based on current experimental investigations the nanofluids thermal conductivity is greater than the base liquid which increase with concentration and temperature. The thermal conductivity ratio increases with volume fraction, but with different rates of increase for each nanofluid. The thermal conductivity of nanofluid increase with decrease in particle size.

The viscosity measurements were taken in the temperature range of 20-80^{o}C and in the concentration range of 0.0-1.5% for a particle size of 20nm. The viscosity of SiO_2/60EGW nanofluids are investigated experimentally and are shown plotted in**Figure 13** . As observed, the viscosity increases as the volume concentration increase. However, the viscosity decrease exponentially as the temperature increases similar to Azmi et al..On the other hand, the experimental viscosity values are compared with equations (8) and (14) for 60EGW base fluid and SiO_2/60EGW nanofluids respectively and a maximum deviation of 20% observed.

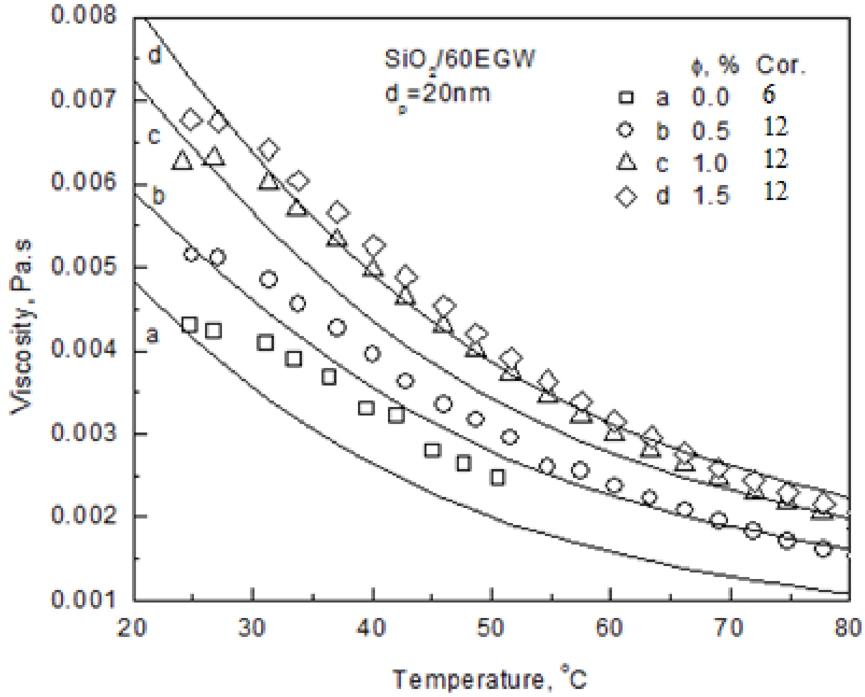


Figure 13 Comparison of experimental values of viscosity for SiO_2/60EGW nanofluids with theoretical correlations (6) and (12)

Similarly, the experimental viscosity values of SiO_2/40EGW nanofluids are compared with base fluid correlation (10) and nanofluid correlation (14) and are plotted in**Figure 14** . The viscosity measurements were taken in the same operating conditions of SiO_2/60EGW nanofluids as mentioned. A deviation less than 18% was observed with correlation (18). Additionally, the study established that given different concentrations, an increase in temperature causes a significant decrease in the nanofluids' viscosity. As such, SiO_2 nano particle loading was observed to cause an increase in flowing resistance and friction of the fluids, translating into increased viscosity.

The viscosity enhancement was plotted against temperature for the two given nanofluids in **Figure 15** . It is quite clear that SiO_2/40EGW shows a good enhancement in viscosity with a maximum enhancement of 102% than the base fluid at 1.5% volume concentration and 25°C temperature. Based on the observations 40EGW based nanofluids shows a higher enhancement in viscosity. This study indicates that, with the increase in percentage of ethylene glycol, the viscosity of SiO_2 nanofluids also increases. The measurements have similar finding as Lotfizadeh Dehkordi et al. [61] who have used Al_2O_3dispersed in 60EGW and 40EGW base fluids by mass % and also Syam [62] has observed enhancement of 300% and they attributed it to the shear resistance offered by the particles onto the fluid layer. With larger the particle concentration in the base fluid, larger the quantity is of particles are required.

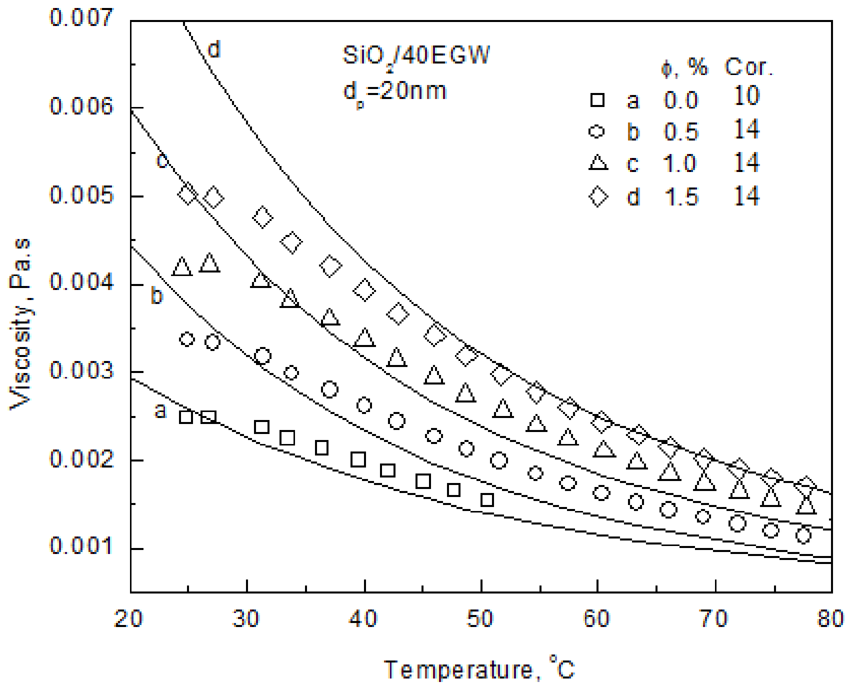


Figure 14 Comparison of experimental values of viscosity for SiO_2/40EGW nanofluids with theoretical correlations (10) and (14)

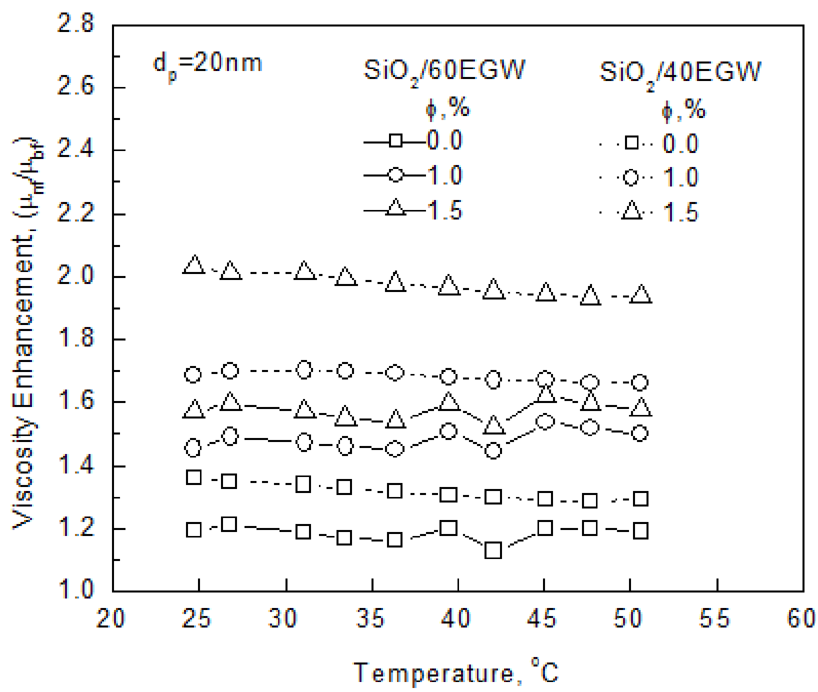


Figure 15 Comparison of viscosity enhancement of SiO_2/60EGW and SiO_2/40EGW nanofluids

Based on the research available from the literature, the factors influencing the viscosity are nanoparticle size, volume concentration and temperature whereas the material doesn't seem to be effecting much. The viscosity of nanofluids are increasing with particles sizes at higher concentrations as observed Nguyen et al. [63], where he has reported that there is no big change in viscosity for a varying sizes of 36nm and 47nm for the nanoparticles at 4% concentration. But, if the volume concentration is increased, then the viscosity of the nanofluid seems to be increasing with the particle size.

He et al. [64] have also reported similar observations with TiO_2/water nanofluids which shows that viscosity is increasing with particle size. However, contradicting observations were made by Namburu et al. [33] indicating that, viscosity of nanofluids decreasing with particles size for SiO_2/60EGW nanoparticles which have supported by results of Pastoriza-Gallego et al. [65] and Anoop et al. [66] for CuO/water and Al_2O_3/water nanofluids respectively. While analysis of Prasher et al. [67] was different from others, where he has showed that viscosity of nanofluid is irrespective of the particle size.

In case of influence of temperature on the viscosity, it is quite evident that, the temperature is the most critical and influential parameter as recommended by whole nanofluid research community. The overall research indicates a pretty common observation of downward trend in viscosity with an increase in temperature. As the temperature increases, the intermolecular attraction between the nanoparticles and their base fluids weakens [68]. Hence, the viscosity of nanofluids decreases with the increase in temperature.

Based on the research it can be concluded that, viscosity increases with concentration of the nanofluid. Viscosity of the nanofluid decrease with increase in temperature. An increase in viscosity with decrease in particle size is reported in the literature.

The enhancement ratio is plotted for the SiO_2nanoparticles in both the base fluids for the estimation of optimum heat transfer at a concentration in **Figure 16** . Enhancement ratio can be defined as ratio of viscosity enhancement to thermal conductivity enhancement as given in correlation (20). According to Garg et al. [69], the enhancement in heat transfer under turbulent flow is a maximum when the value of ER [?] 5. As shown the figure 16, the optimum heat transfer enhancement can be obtained at 1.0% and 1.4% volume concentrations for a given temperature of 70°C in 60EGW and 40EGW based nanofluids respectively.

$$ER = \frac{\left(\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{bf}}} - 1\right)}{\left(\frac{k_{\mathrm{nf}}}{k_{\mathrm{bf}}} - 1\right)} (16)$$

Hence, the optimum parameters for obtaining enhancements will be 1.0% and 1.4% for 60EGW and 40EGW based nanofluids at 70°C temperature. The predicted values of thermal conductivity are compared, Al_2O_3 nanoparticles show some better values than SiO_2 nanoparticles in both the base fluids such as 60EGW and 40EGW. When compared in SiO_2nanofluids, the influence of 40EGW base fluid has better impact on SiO_2 nanofluids. Though change of material doesn't have any influence on viscosity, 40EGW based nanofluids have shown higher values than 60EGW based nanofluids.

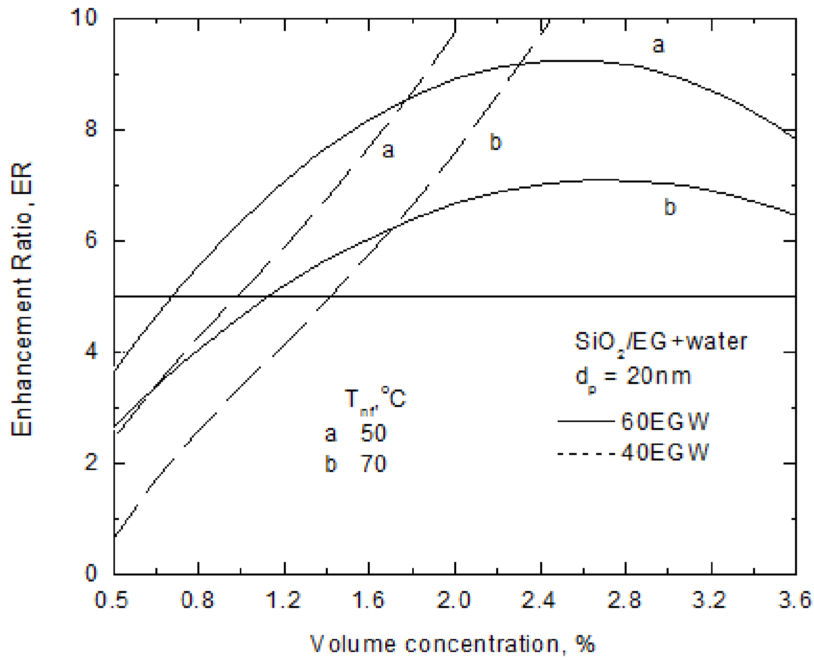


Figure 16 Variation of property enhancement ratio with temperature for the turbulent flow condition

Conclusions:

In summary, factors that aid in discerning the stability of nanofluids include the zeta potential, electrical conductivity, and the pH value. Even if higher values are obtained for the parameter of thermal conductivity, they are not adequate to enhance the state of heat transfer; findings that have been documented by most of the previous literature focusing on CuO, SiO_2 and Al_2O_3 nanofluids. Rather, additional parameters such as the temperature of nanofluids, the diameter of nano particles, and the volume fraction determine the capacity of the nanofluids to enhance the heat transfer aspect; with the factor of the ratio of heat transfer between the nanofluids and the nano particles unexceptional. In the regression equation, the oxide nanofluids' thermal conductivity is seen to be predicted by the heat capacity term; outcomes that concur with some of the previous studies. Also, the change in the density of the particles relative to the nano particles' specific heat and their size is seen to affect the nanofluids' thermal conductivity. The latter trend aids in inferring the value deviations that have been reported by different scholarly researchers. Overall, this study established that higher values of thermal conductivity were associated with 40EGW-based nanofluids.

References

[1] R. Saidur, K.Y. Leong, H.A. Mohammed, A review on applications and challenges of nanofluids, Renew. Sustain. Energy Rev. 15 (2011) 1646–1668. https://doi.org/10.1016/J.RSER.2010.11.035.

[2] M. Sadeghzadeh, M.H. Ahmadi, M. Kahani, H. Sakhaeinia, H. Chaji, L. Chen, Smart modeling by using artificial intelligent techniques on thermal performance of flat-plate solar collector using nanofluid, Energy Sci. Eng. 0 (2019). https://doi.org/10.1002/ese3.381.

[3] M.A. Nazari, M.H. Ahmadi, M. Sadeghzadeh, M.B. Shafii, M. Goodarzi, A review on application of nanofluid in various types of heat pipes, J. Cent. South Univ. 26 (2019) 1021–1041. https://doi.org/10.1007/s11771-019-4068-9.

[4] M.H. Ahmadi, M. Ghazvini, M. Sadeghzadeh, M. Alhuyi Nazari, M. Ghalandari, Utilization of hybrid nanofluids in solar energy applications: A review, Nano-Structures & Nano-Objects. 20 (2019) 100386. https://doi.org/10.1016/J.NANOSO.2019.100386.

[5] M. Kahani, M.H. Ahmadi, A. Tatar, M. Sadeghzadeh, Development of multilayer perceptron artificial neural network (MLP-ANN) and least square support vector machine (LSSVM) models to predict Nusselt number and pressure drop of TiO_2 /water nanofluid flows through non-straight pathways, Numer. Heat Transf. Part A Appl. 0 (2018) 1–17. https://doi.org/10.1080/10407782.2018.1523597.

[6] M.H. Ahmadi, A. Baghban, M. Sadeghzadeh, M. Hadipoor, M. Ghazvini, Evolving connectionist approaches to compute thermal conductivity of TiO2/water nanofluid, Phys. A Stat. Mech. Its Appl. (2019) 122489. https://doi.org/10.1016/J.PHYSA.2019.122489.

[7] M.H. Ahmadi, M. Sadeghzadeh, A.H. Raffiee, K. Chau, Applying GMDH neural network to estimate the thermal resistance and thermal conductivity of pulsating heat pipes, Eng. Appl. Comput. Fluid Mech. 13 (2019) 327–336. https://doi.org/10.1080/19942060.2019.1582109.

[8] A.I. Alsabery, R. Mohebbi, A.J. Chamkha, I. Hashim, Impacts of magnetic field and non-homogeneous nanofluid model on convective heat transfer and entropy generation in a cavity with heated trapezoidal body, J. Therm. Anal. Calorim. 138 (2019) 1371–1394. https://doi.org/10.1007/s10973-019-08249-x.

[9] M.H. Ahmadi, M. Sadeghzadeh, H. Maddah, A. Solouk, R. Kumar, K. Chau, Precise smart model for estimating dynamic viscosity of SiO2/ethylene glycol–water nanofluid, Eng. Appl. Comput. Fluid Mech. 13 (2019) 1095–1105. https://doi.org/10.1080/19942060.2019.1668303.

[10] V.P. Zhelezny, I. V. Motovoy, E.E. Ustyuzhanin, Prediction of nanofluids properties: The density and the heat capacity, J. Phys. Conf. Ser. 891 (2017). https://doi.org/10.1088/1742-6596/891/1/012347.

[11] M. Ramezanizadeh, M.H. Ahmadi, M.A. Nazari, M. Sadeghzadeh, L. Chen, A review on the utilized machine learning approaches for modeling the dynamic viscosity of nanofluids, Renew. Sustain. Energy Rev. 114 (2019) 109345. https://doi.org/10.1016/J.RSER.2019.109345.

[12] H. Maddah, R. Aghayari, M. Mirzaee, M.H. Ahmadi, M. Sadeghzadeh, A.J. Chamkha, Factorial experimental design for the thermal performance of a double pipe heat exchanger using Al2O3-TiO2hybrid nanofluid, Int. Commun. Heat Mass Transf. 97 (2018) 92–102. https://doi.org/10.1016/j.icheatmasstransfer.2018.07.002.

[13] Nasirzadehroshenin, Fatemeh, Sadeghzadeh, Milad, Khadang, Amirhossein, Maddah, Heydar, Ahmadi, Mohammad Hossein, Sakhaeinia, Hossein, Chen, Lingen, Modeling of heat transfer performance of carbon nanotube nanofluid in a tube with fixed wall temperature by using ANN-GA, Eur. Phys. J. Plus. 135 (2020) 217. https://doi.org/10.1140/epjp/s13360-020-00208-y.

[14] N.S. Shashikumar, G. B.J., M. B., B.C. Prasannakumara, C.A. J., Entropy generation analysis of magneto-nanoliquids embedded with aluminium and titanium alloy nanoparticles in microchannel with partial slips and convective conditions, Int. J. Numer. Methods Heat & Fluid Flow. 29 (2019) 3638–3658. https://doi.org/10.1108/HFF-06-2018-0301.

[15] T. Tayebi, A.J. Chamkha, M. Djezzar, Natural convection of CNT-water nanofluid in an annular space between confocal elliptic cylinders with constant heat flux on inner wall, Sci. Iran. 26 (2019) 2770–2783. https://doi.org/10.24200/sci.2018.21069.

[16] A.S. Dogonchi, T. Armaghani, A.J. Chamkha, D.D. Ganji, Natural Convection Analysis in a Cavity with an Inclined Elliptical Heater Subject to Shape Factor of Nanoparticles and Magnetic Field, Arab. J. Sci. Eng. 44 (2019) 7919–7931. https://doi.org/10.1007/s13369-019-03956-x.

[17] A.J. Chamkha, S. Sazegar, E. Jamesahar, M. Ghalambaz, Thermal Non-Equilibrium Heat Transfer Modeling of Hybrid Nanofluids in a Structure Composed of the Layers of Solid and Porous Media and Free Nanofluids, Energies. 12 (2019) 541. https://doi.org/10.3390/en12030541.

[18] I.M. Safwan, A.A. I., C. A., H. Ishak, Effect of finite wall thickness on entropy generation and natural convection in a nanofluid-filled partially heated square cavity, Int. J. Numer. Methods Heat & Fluid Flow. 30 (2019) 1518–1546. https://doi.org/10.1108/HFF-06-2019-0505.

[19] T. Tahar, C.A. J., Entropy generation analysis during MHD natural convection flow of hybrid nanofluid in a square cavity containing a corrugated conducting block, Int. J. Numer. Methods Heat & Fluid Flow. 30 (2019) 1115–1136. https://doi.org/10.1108/HFF-04-2019-0350.

[20] S.A.M. Mehryan, E. Izadpanahi, M. Ghalambaz, A.J. Chamkha, Mixed convection flow caused by an oscillating cylinder in a square cavity filled with Cu–Al2O3/water hybrid nanofluid, J. Therm. Anal. Calorim. 137 (2019) 965–982. https://doi.org/10.1007/s10973-019-08012-2.

[21] R.S. Vajjha, D.K. Das, D.P. Kulkarni, Development of new correlations for convective heat transfer and friction factor in turbulent regime for nanofluids, Int. J. Heat Mass Transf. 53 (2010) 4607–4618. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2010.06.032.

[22] W.H. Azmi, N.A. Usri, R. Mamat, K.V. Sharma, M.M. Noor, Force convection heat transfer of Al2O3 nanofluids for different based ratio of water: Ethylene glycol mixture, Appl. Therm. Eng. 112 (2017) 707–719. https://doi.org/10.1016/J.APPLTHERMALENG.2016.10.135.

[23] M. SHIRATO, H. KATO, K. KOBAYASHI, H. SAKAZAKI, ANALYSIS OF SETTLSNG OF THICK SLURRIES DUE TO CONSOLIDATION, J. Chem. Eng. Japan. 3 (1970) 98–104. https://doi.org/10.1252/jcej.3.98.

[24] R. Buscall, L.R. White, The consolidation of concentrated suspensions. Part 1.—The theory of sedimentation, J. Chem. Soc.{,} Faraday Trans. 1. 83 (1987) 873–891. https://doi.org/10.1039/F19878300873.

[25] R.S. Bowles, J.J. Kolstad, J.M. Calo, R.P. Andres, Generation of molecular clusters of controlled size, Surf. Sci. 106 (1981) 117–124. https://doi.org/10.1016/0039-6028(81)90188-6.

[26] T.S. Lundgren, Slow flow through stationary random beds and suspensions of spheres, J. Fluid Mech. 51 (1972) 273–299. https://doi.org/https://doi.org/10.1017/S002211207200120X.

[27] J. Huang, X. Wang, Q. Long, X. Wen, Y. Zhou, L. Li, Influence of pH on the Stability Characteristics of Nanofluids, in: 2009 Symp. Photonics Optoelectron., 2009: pp. 1–4. https://doi.org/10.1109/SOPO.2009.5230102.

[28] X. Wang, D. Zhu, S. yang, Investigation of pH and SDBS on enhancement of thermal conductivity in nanofluids, Chem. Phys. Lett. 470 (2009) 107–111. https://doi.org/10.1016/J.CPLETT.2009.01.035.

[29] A. Ghadimi, R. Saidur, H.S.C. Metselaar, A review of nanofluid stability properties and characterization in stationary conditions, Int. J. Heat Mass Transf. 54 (2011) 4051–4068. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2011.04.014.

[30] L. Fedele, L. Colla, S. Bobbo, S. Barison, F. Agresti, Experimental stability analysis of different water-based nanofluids, Nanoscale Res. Lett. 6 (2011) 300. https://doi.org/10.1186/1556-276X-6-300.

[31] Y. Hwang, J.-K. Lee, J.-K. Lee, Y.-M. Jeong, S. Cheong, Y.-C. Ahn, S.H. Kim, Production and dispersion stability of nanoparticles in nanofluids, Powder Technol. 186 (2008) 145–153. https://doi.org/10.1016/J.POWTEC.2007.11.020.

[32] J. Eapen, R. Rusconi, R. Piazza, S. Yip, The Classical Nature of Thermal Conduction in Nanofluids, J. Heat Transfer. 132 (2010). https://doi.org/10.1115/1.4001304.

[33] P.K. Namburu, D.P. Kulkarni, A. Dandekar, D.K. Das, Experimental investigation of viscosity and specific heat of silicon dioxide nanofluids, Micro Nano Lett. 2 (2007) 67–71. https://doi.org/10.1049/mnl:20070037.

[34] L. Syam Sundar, E. Venkata Ramana, M.K. Singh, A.C.M. Sousa, Thermal conductivity and viscosity of stabilized ethylene glycol and water mixture Al2O3 nanofluids for heat transfer applications: An experimental study, Int. Commun. Heat Mass Transf. 56 (2014) 86–95. https://doi.org/10.1016/J.ICHEATMASSTRANSFER.2014.06.009.

[35] R.S. Vajjha, D.K. Das, Experimental determination of thermal conductivity of three nanofluids and development of new correlations, Int. J. Heat Mass Transf. 52 (2009) 4675–4682. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2009.06.027.

[36] J. Koo, C. Kleinstreuer, Impact analysis of nanoparticle motion mechanisms on the thermal conductivity of nanofluids, Int. Commun. Heat Mass Transf. 32 (2005) 1111–1118. https://doi.org/10.1016/J.ICHEATMASSTRANSFER.2005.05.014.

[37] R. Vajjha, D. Das, Specific Heat Measurement of Three Nanofluids and Development of New Correlations, J. Heat Transf. Asme. 131 (2009). https://doi.org/10.1115/1.3090813.

[38] B.C. Sahoo, D.K. Das, R.S. Vajjha, J.R. Satti, Measurement of the Thermal Conductivity of Silicon Dioxide Nanofluid and Development of Correlations, J. Nanotechnol. Eng. Med. 3 (2013) 41006–41010. http://dx.doi.org/10.1115/1.4024003.

[39] R.L. Virdi, S.S. Chatha, H. Singh, Experiment evaluation of grinding properties under Al $_2$ O $_3$nanofluids in minimum quantity lubrication, Mater. Res. Express. 6 (2019) 096574. https://doi.org/10.1088/2053-1591/ab301f.

[40] S. Aziz, S. Khalid, H. Khalid, Influence of surfactant and volume fraction on the dispersion stability of TiO $_2$/deionized water based nanofluids for heat transfer applications, Mater. Res. Express. 6 (2018) 015031. https://doi.org/10.1088/2053-1591/aae6ac.

[41] ASHRAE, Handbook of fundamentals, American Society of Heating 774 Refrigerating and Air Conditioning Engineers, Atlanta, GA, 2005.

[42] D.P. Kulkarni, D.K. Das, R.S. Vajjha, Application of nanofluids in heating buildings and reducing pollution, Appl. Energy. 86 (2009) 2566–2573. https://doi.org/10.1016/J.APENERGY.2009.03.021.

[43] N.A. Usri, W.H. Azmi, R. Mamat, K.A. Hamid, G. Najafi, Heat Transfer Augmentation of Al2O3 Nanofluid in 60:40 Water to Ethylene Glycol Mixture, Energy Procedia. 79 (2015) 403–408. https://doi.org/10.1016/J.EGYPRO.2015.11.510.

[44] R. W, M. Khalid, S. Ong, S. Rahman, Preparation, thermo-physical properties and heat transfer enhancement of nanofluids, Mater. Res. Express. 1 (2014) 32001. https://doi.org/10.1088/2053-1591/1/3/032001.

[45] W. Yu, H. Xie, A review on Nanofluids: preparation, stability mechanisms, and applications, J. Nanomater. 2012 (2012) 17 pages. https://doi.org/http://dx.doi.org/10.1155/2012/435873.

[46] D.K. Carpenter, Dynamic Light Scattering with Applications to Chemistry, Biology, and Physics (Berne, Bruce J.; Pecora, Robert), J. Chem. Educ. 54 (1977) A430. https://doi.org/10.1021/ed054pA430.1.

[47] X. Wei, L. Wang, Synthesis and thermal conductivity of microfluidic copper nanofluids, Particuology. 8 (2010) 262–271. https://doi.org/10.1016/J.PARTIC.2010.03.001.

[48] X. Li, D. Zhu, X. Wang, Evaluation on dispersion behavior of the aqueous copper nano-suspensions, J. Colloid Interface Sci. 310 (2007) 456–463. https://doi.org/10.1016/J.JCIS.2007.02.067.

[49] Y. Li, J. Zhou, S. Tung, E. Schneider, S. Xi, A review on development of nanofluid preparation and characterization, Powder Technol. 196 (2009) 89–101. https://doi.org/10.1016/J.POWTEC.2009.07.025.

[50] S. Akilu, K.V. Sharma, T.B. Aklilu, M.S.M. Azman, P.T. Bhaskoro, Temperature Dependent Properties of Silicon Carbide Nanofluid in Binary Mixtures of Glycerol-Ethylene Glycol, Procedia Eng. 148 (2016) 774–778. https://doi.org/10.1016/J.PROENG.2016.06.555.

[51] X. Li, C. Zou, X. Lei, W. Li, Stability and enhanced thermal conductivity of ethylene glycol-based SiC nanofluids, Int. J. Heat Mass Transf. 89 (2015) 613–619. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2015.05.096.

[52] S. Magdassi, M. Grouchko, A. Kamyshny, Copper Nanoparticles for Printed Electronics: Routes Towards Achieving Oxidation Stability., Mater. (Basel, Switzerland). 3 (2010) 4626–4638. https://doi.org/10.3390/ma3094626.

[53] D. Lee, J.-W. Kim, B.G. Kim, A New Parameter to Control Heat Transport in Nanofluids: Surface Charge State of the Particle in Suspension, J. Phys. Chem. B. 110 (2006) 4323–4328. https://doi.org/10.1021/jp057225m.

[54] Y. Hwang, J.K. Lee, C.H. Lee, Y.M. Jung, S.I. Cheong, C.G. Lee, B.C. Ku, S.P. Jang, Stability and thermal conductivity characteristics of nanofluids, Thermochim. Acta. 455 (2007) 70–74. https://doi.org/10.1016/J.TCA.2006.11.036.

[55] B. Wright, D. Thomas, H. Hong, P. Smith, Time Dependent Thermal Conductivities of Nanofluids Containing Carbon Nanotubes and Metal Oxides, J. Nanofluids. 2 (2013) 45–49. https://doi.org/10.1166/jon.2013.1038.

[56] P.D. Shima, J. Philip, Role of Thermal Conductivity of Dispersed Nanoparticles on Heat Transfer Properties of Nanofluid, Ind. Eng. Chem. Res. 53 (2014) 980–988. https://doi.org/10.1021/ie403086g.

[57] T.-P. Teng, Y.-H. Hung, T.-C. Teng, H.-E. Mo, H.-G. Hsu, The effect of alumina/water nanofluid particle size on thermal conductivity, Appl. Therm. Eng. 30 (2010) 2213–2218. https://doi.org/10.1016/J.APPLTHERMALENG.2010.05.036.

[58] W.H. Azmi, K.V. Sharma, P.K. Sarma, R. Mamat, S. Anuar, Comparison of convective heat transfer coefficient and friction factor of TiO2 nanofluid flow in a tube with twisted tape inserts, Int. J. Therm. Sci. 81 (2014) 84–93. https://doi.org/10.1016/J.IJTHERMALSCI.2014.03.002.

[59] M.P. Beck, Y. Yuan, P. Warrier, A.S. Teja, The effect of particle size on the thermal conductivity of alumina nanofluids, J. Nanoparticle Res. 11 (2009) 1129–1136. https://doi.org/10.1007/s11051-008-9500-2.

[60] C.H. Li, G.P. Peterson, The effect of particle size on the effective thermal conductivity of Al2O3-water nanofluids, J. Appl. Phys. 101 (2007) 044312. https://doi.org/10.1063/1.2436472.

[61] B. LotfizadehDehkordi, S.N. Kazi, M. Hamdi, A. Ghadimi, E. Sadeghinezhad, H.S.C. Metselaar, Investigation of viscosity and thermal conductivity of alumina nanofluids with addition of SDBS, Heat Mass Transf. 49 (2013) 1109–1115. https://doi.org/10.1007/s00231-013-1153-8.

[62] L. Syam Sundar, E. Venkata Ramana, M.K. Singh, A.C.M. De Sousa, Viscosity of low volume concentrations of magnetic Fe3O4 nanoparticles dispersed in ethylene glycol and water mixture, Chem. Phys. Lett. 554 (2012) 236–242. https://doi.org/10.1016/J.CPLETT.2012.10.042.

[63] C.T. Nguyen, F. Desgranges, G. Roy, N. Galanis, T. Maré, S. Boucher, H. Angue Mintsa, Temperature and particle-size dependent viscosity data for water-based nanofluids – Hysteresis phenomenon, Int. J. Heat Fluid Flow. 28 (2007) 1492–1506. https://doi.org/10.1016/J.IJHEATFLUIDFLOW.2007.02.004.

[64] Y. He, Y. Jin, H. Chen, Y. Ding, D. Cang, H. Lu, Heat transfer and flow behaviour of aqueous suspensions of TiO2 nanoparticles (nanofluids) flowing upward through a vertical pipe, Int. J. Heat Mass Transf. 50 (2007) 2272–2281. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2006.10.024.

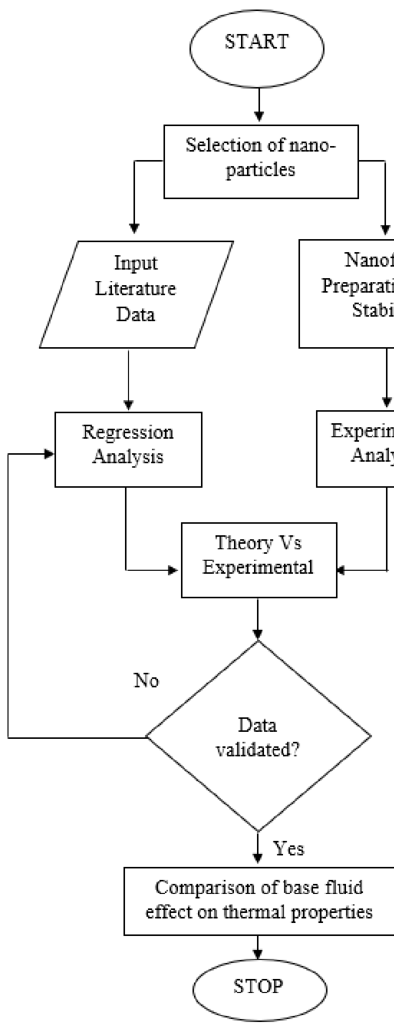
[65] M.J. Pastoriza-Gallego, C. Casanova, J.L. Legido, M.M. Piñeiro, CuO in water nanofluid: Influence of particle size and polydispersity on volumetric behaviour and viscosity, Fluid Phase Equilib. 300 (2011) 188–196. https://doi.org/10.1016/J.FLUID.2010.10.015.

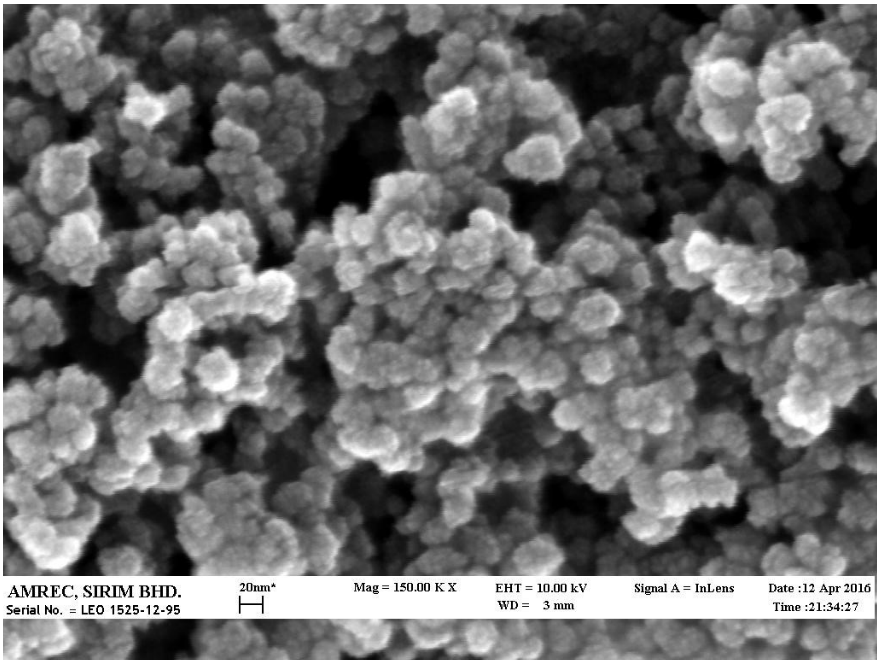
[66] K.B. Anoop, T. Sundararajan, S.K. Das, Effect of particle size on the convective heat transfer in nanofluid in the developing region, Int. J. Heat Mass Transf. 52 (2009) 2189–2195. https://doi.org/10.1016/J.IJHEATMASSTRANSFER.2007.11.063.

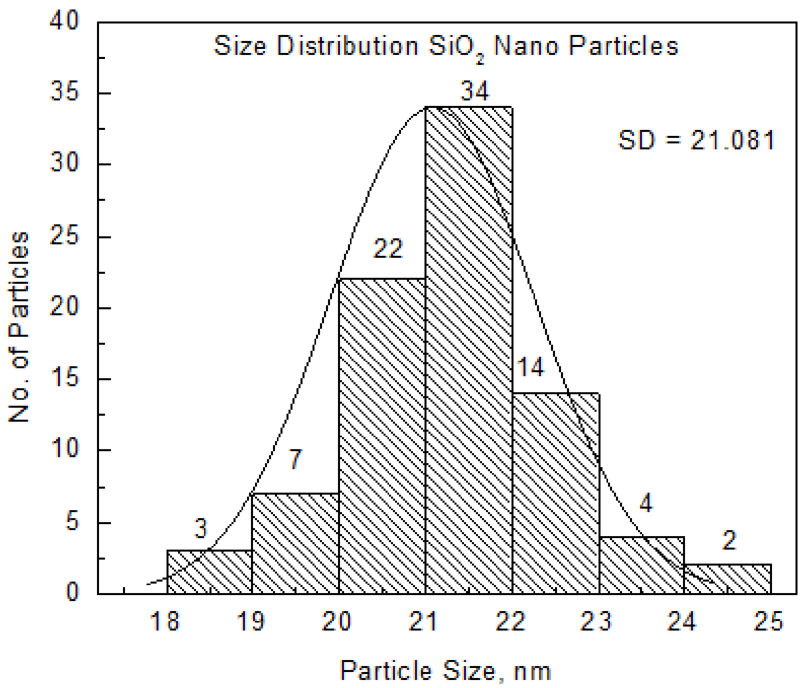
[67] R. Prasher, D. Song, J. Wang, P. Phelan, Measurements of nanofluid viscosity and its implications for thermal applications, Appl. Phys. Lett. 89 (2006) 133108. https://doi.org/10.1063/1.2356113.

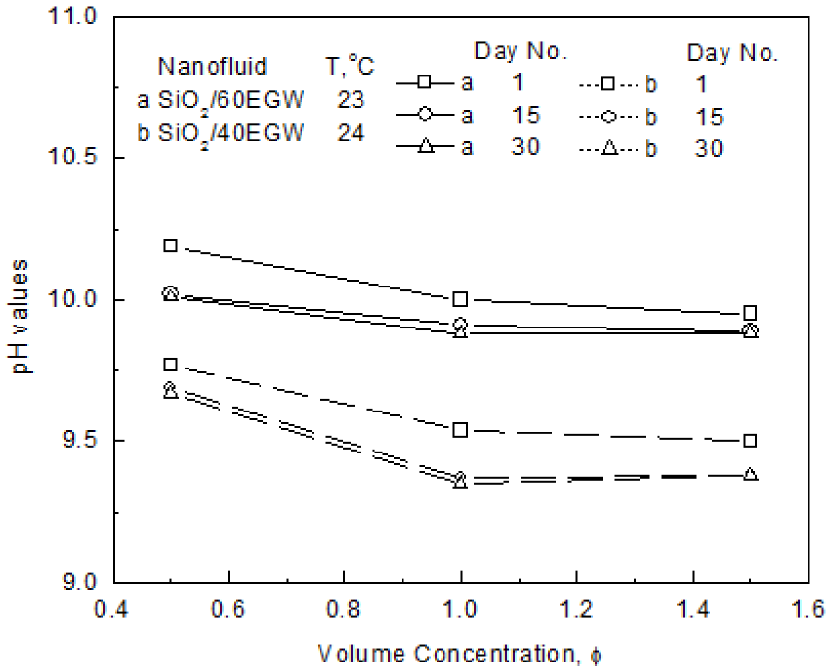
[68] E.N. da C. Andrade, XLI. A theory of the viscosity of liquids.—Part I, London, Edinburgh, Dublin Philos. Mag. J. Sci. 17 (1934) 497–511. https://doi.org/10.1080/14786443409462409.

[69] J. Garg, B. Poudel, M. Chiesa, J.B. Gordon, J.J. Ma, J.B. Wang, Z.F. Ren, Y.T. Kang, H. Ohtani, J. Nanda, G.H. McKinley, G. Chen, Enhanced thermal conductivity and viscosity of copper nanoparticles in ethylene glycol nanofluid, J. Appl. Phys. 103 (2008) 074301. https://doi.org/10.1063/1.2902483.

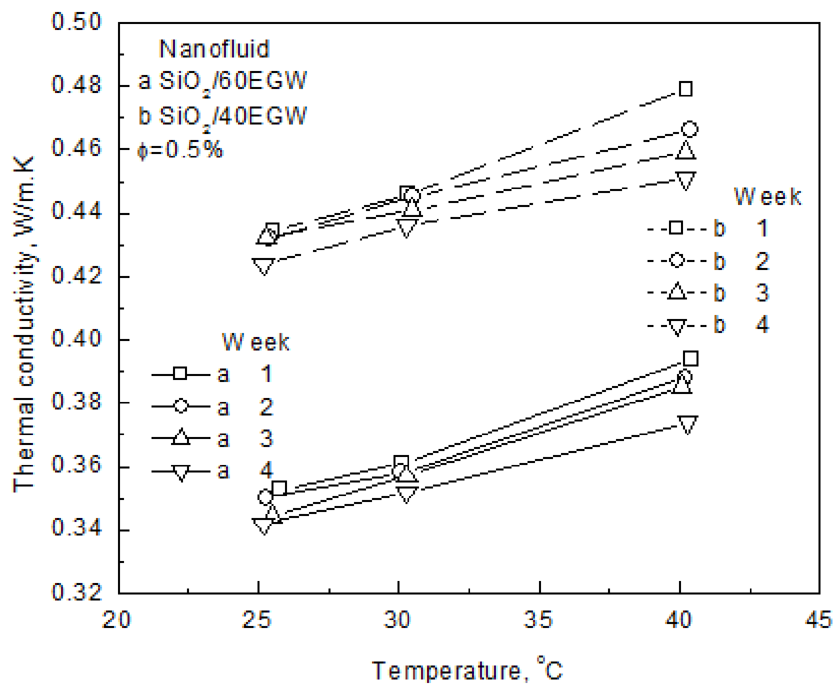



AMREC, SIRIM BHD.
Serial No. = LEO 1525-12-95
20nm*
Mag = 150.00 K X
EHT = 10.00 kV
WD = 3 mm
Signal A = InLens
Date :12 Apr 2016
Time :21:34:27

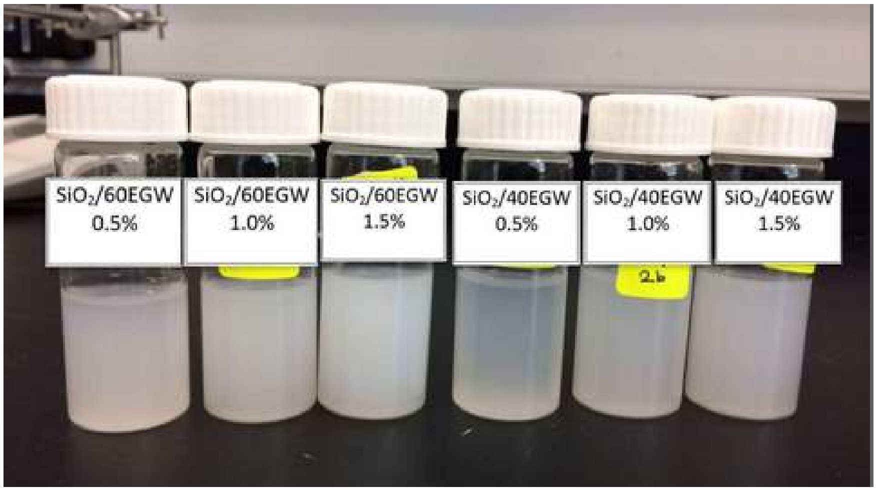

Size Distribution SiO2 Nano Particles
SD = 21.081
No. of Particles
Particle Size, nm
3
7
22
34
14
4
2
0
5
10
15
20
25
30
35
40
18
19
20
21
22
23
24
25

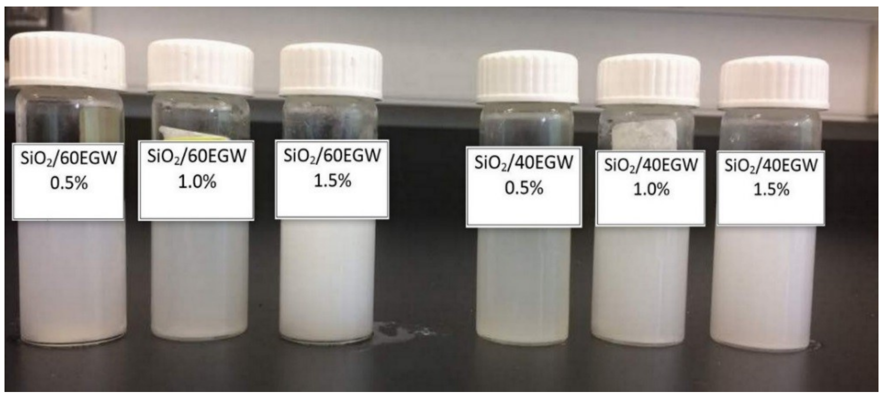


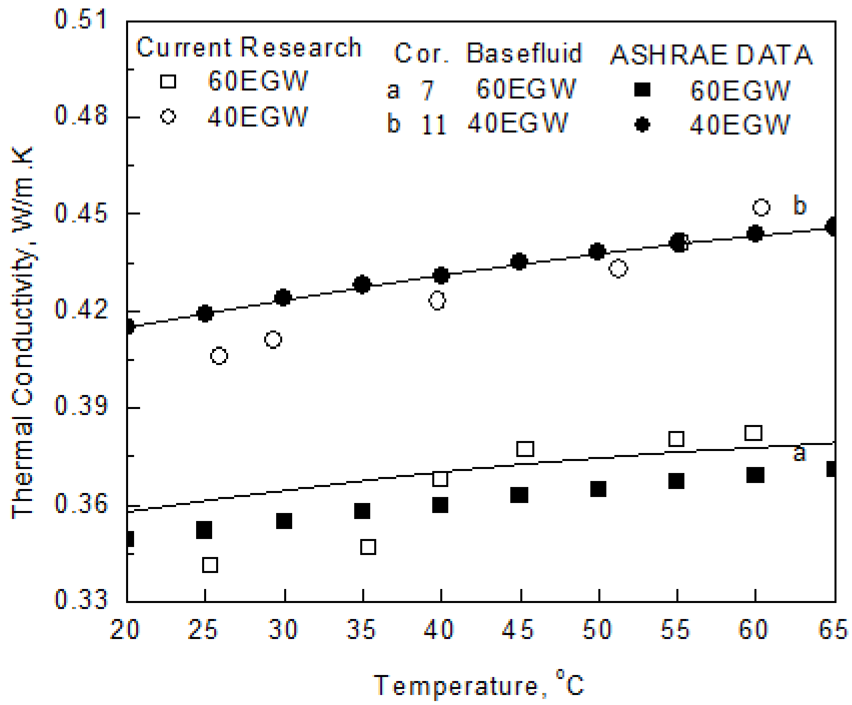
11.0
10.5
10.0
9.5
9.0
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Nanofluid T,°C
a SiO2/60EGW 23
b SiO2/40EGW 24
Day No.
a 1
a 15
a 30
Day No.
b 1
b 15
b 30
pH values
Volume Concentration, ϕ

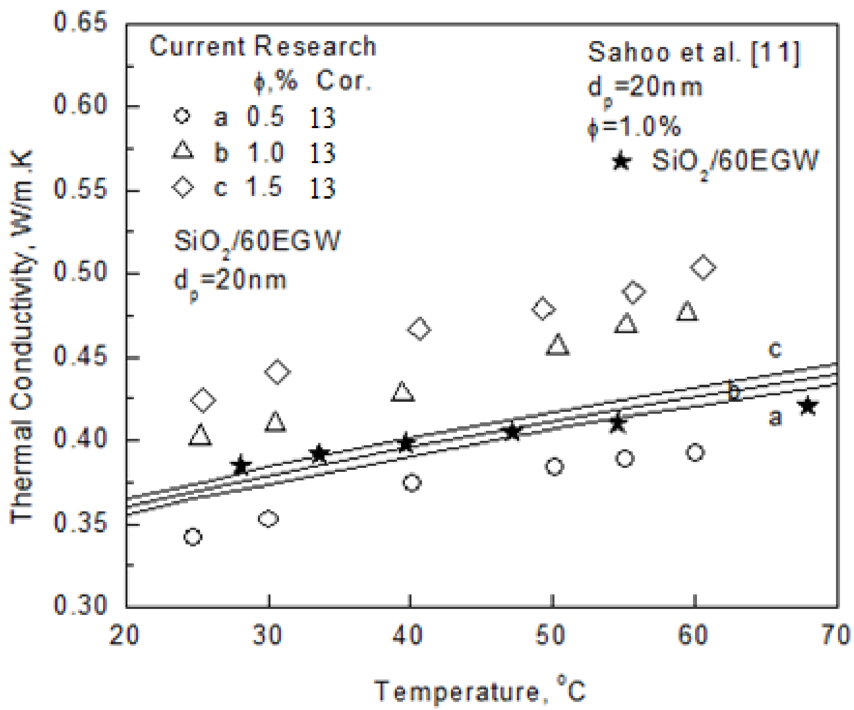


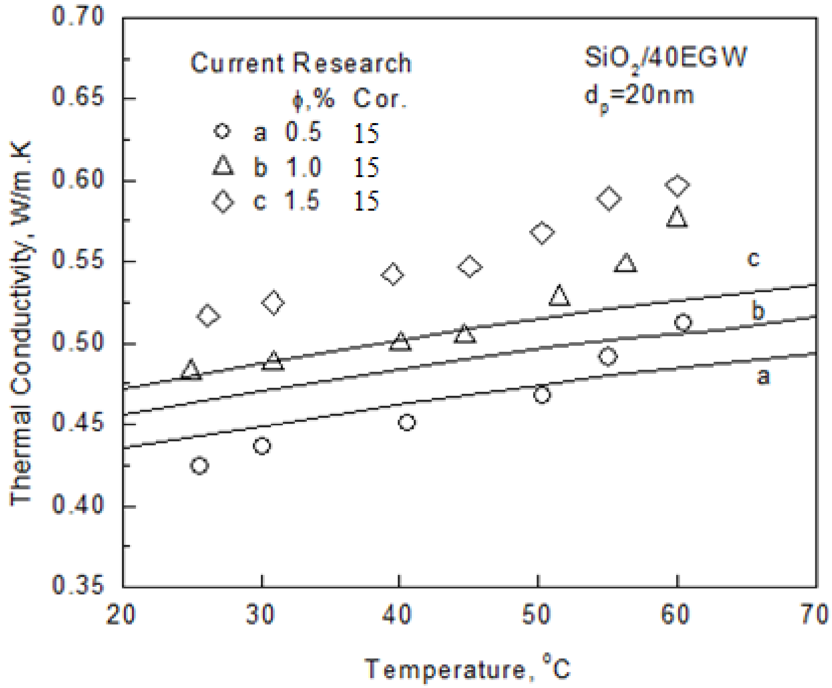
0.50
0.48
0.46
0.44
0.42
0.40
0.38
0.36
0.34
0.32
20
25
30
35
40
45
Nanofluid
a SiO2/60EGW
b SiO2/40EGW
ϕ=0.5%
Week
b 1
b 2
b 3
b 4
Week
a 1
a 2
a 3
a 4
Thermal conductivity, W/m.K
Temperature, °C

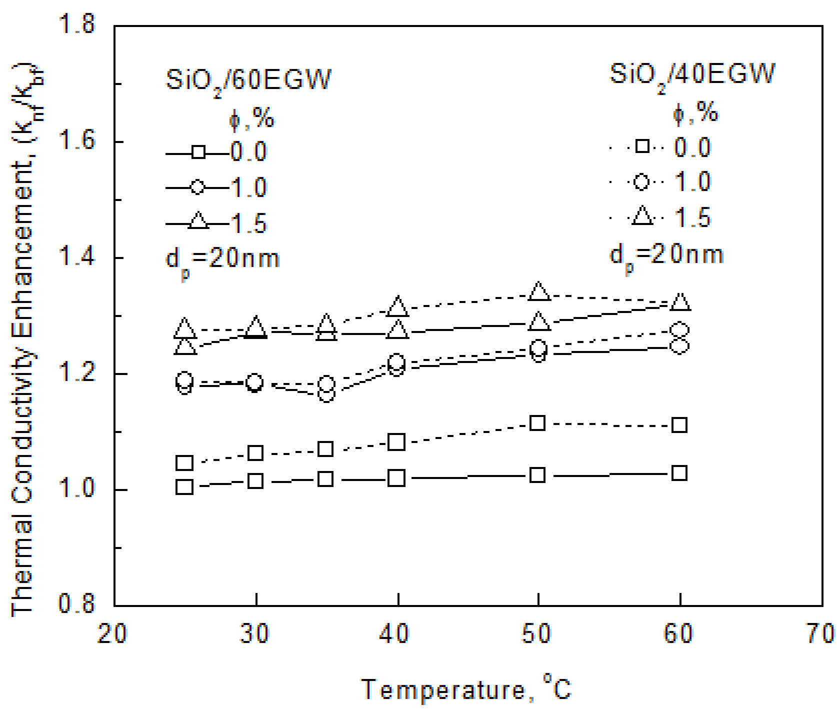

SiO2/60EGW 0.5%
SiO2/60EGW 1.0%
SiO2/60EGW 1.5%
SiO2/40EGW 0.5%
SiO2/40EGW 1.0%
SiO2/40EGW 1.5%

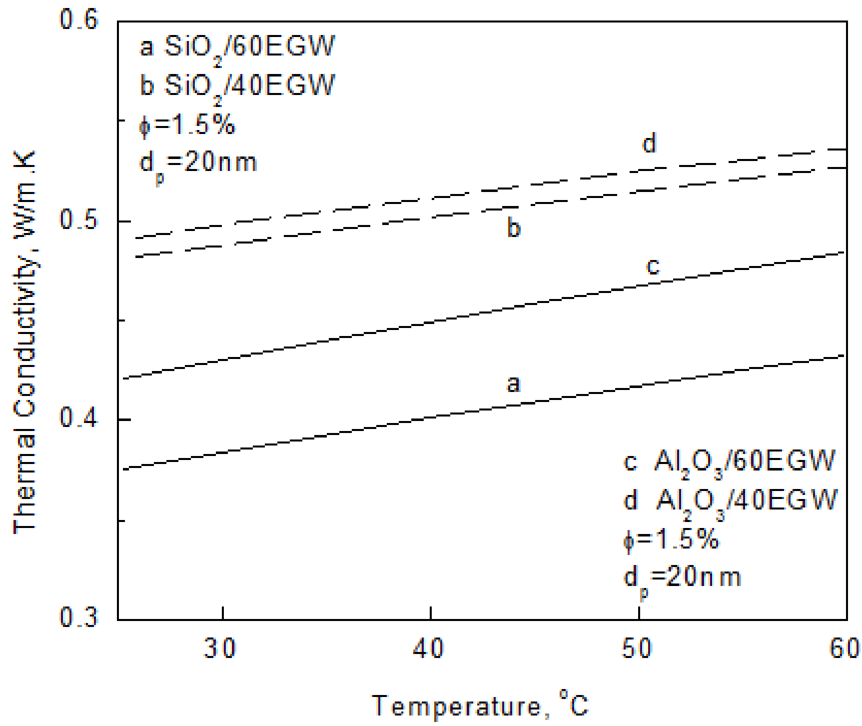

SiO2/60EGW 0.5%
SiO2/60EGW 1.0%
SiO2/60EGW 1.5%
SiO2/40EGW 0.5%
SiO2/40EGW 1.0%
SiO2/40EGW 1.5%

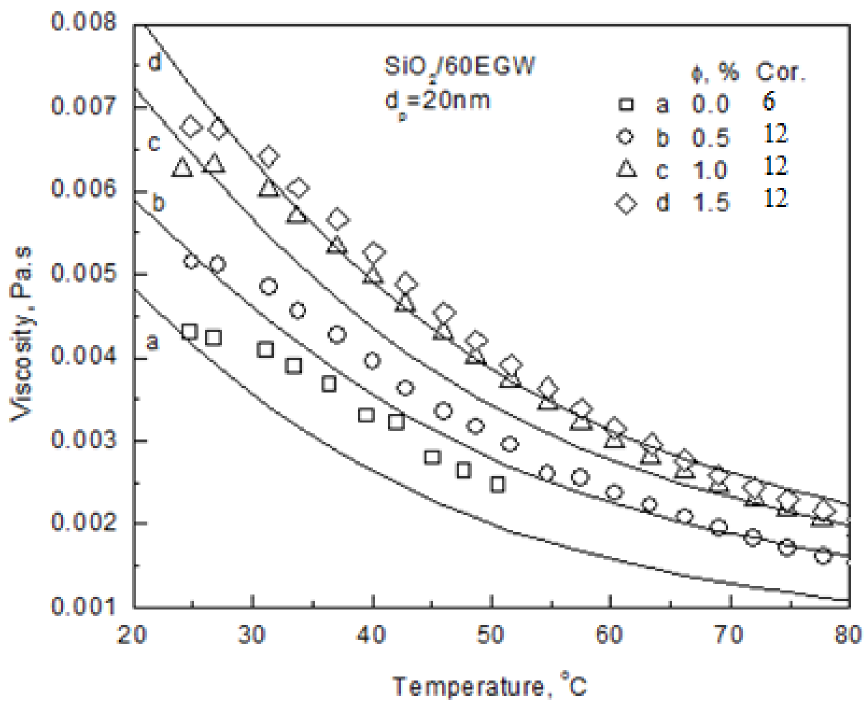

Current Research
60EGW
40EGW
Cor. Basefluid
a 7 60EGW
b 11 40EGW
ASHRAE DATA
60EGW
40EGW
Thermal Conductivity, W/m.K
Temperature, °C
a
b

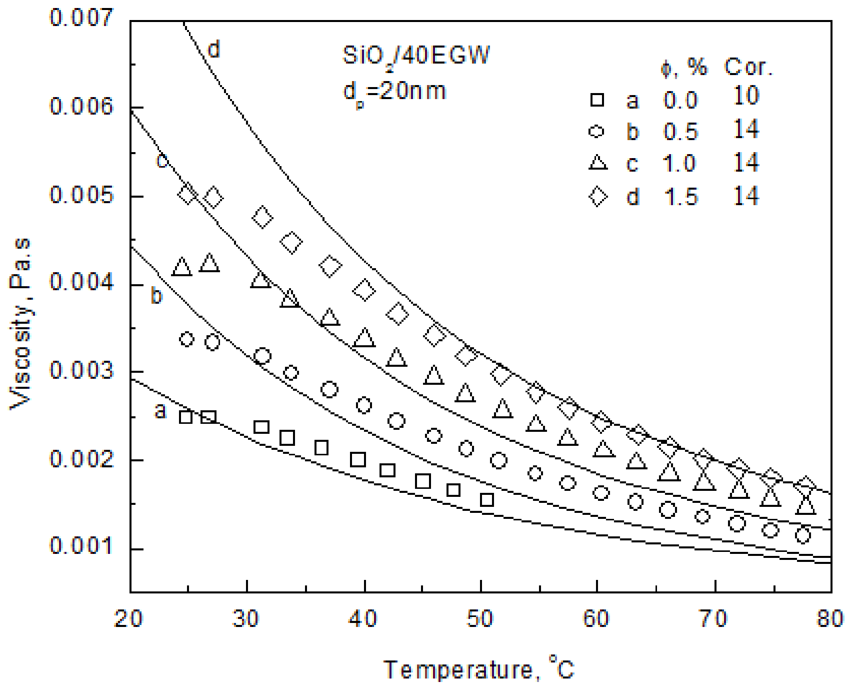

Current Research
ϕ,% Cor.
a 0.5 13
b 1.0 13
c 1.5 13
SiO2/60EGW
dp=20nm
Sahoo et al. [11]
dp=20nm
ϕ=1.0%
SiO2/60EGW
Thermal Conductivity, W/m.K
Temperature, °C
a
b
c


0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
20
30
40
50
60
70
Thermal Conductivity, W/m.K
Temperature, °C
Current Research
ϕ,% Cor.
a 0.5 15
b 1.0 15
c 1.5 15
SiO2/40EGW
dp=20nm
c
b
a

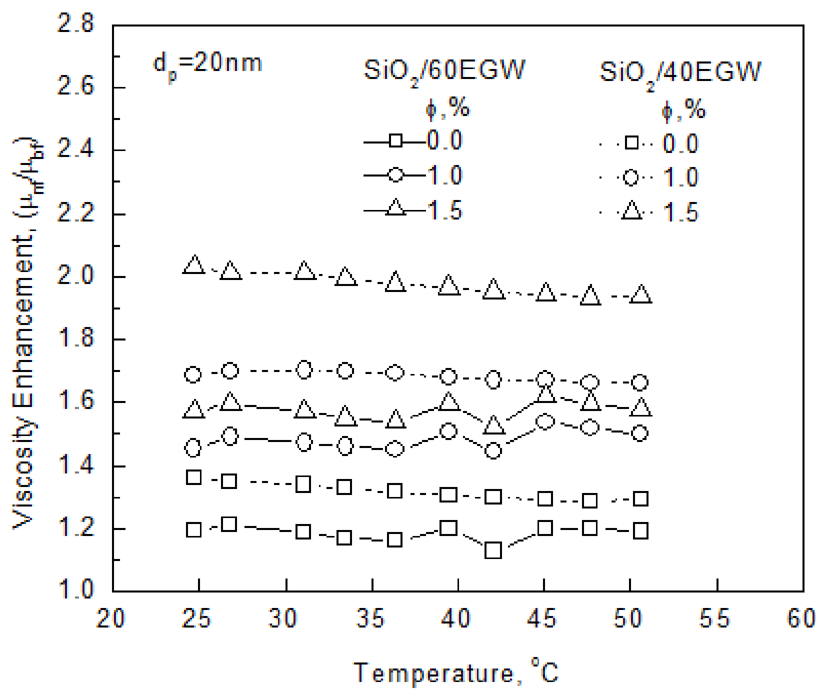

1.8
1.6
1.4
1.2
1.0
0.8
20
30
40
50
60
70
Thermal Conductivity Enhancement, (knf/Kbf)
Temperature, °C
SiO2/60EGW
ϕ,%
0.0
1.0
1.5
dp=20nm
SiO2/40EGW
ϕ,%
0.0
1.0
1.5
dp=20nm


a SiO2/60EGW
b SiO2/40EGW
ϕ=1.5%
dp=20nm
c Al2O3/60EGW
d Al2O3/40EGW
ϕ=1.5%
dp=20nm
Thermal Conductivity, W/m.K
Temperature, °C

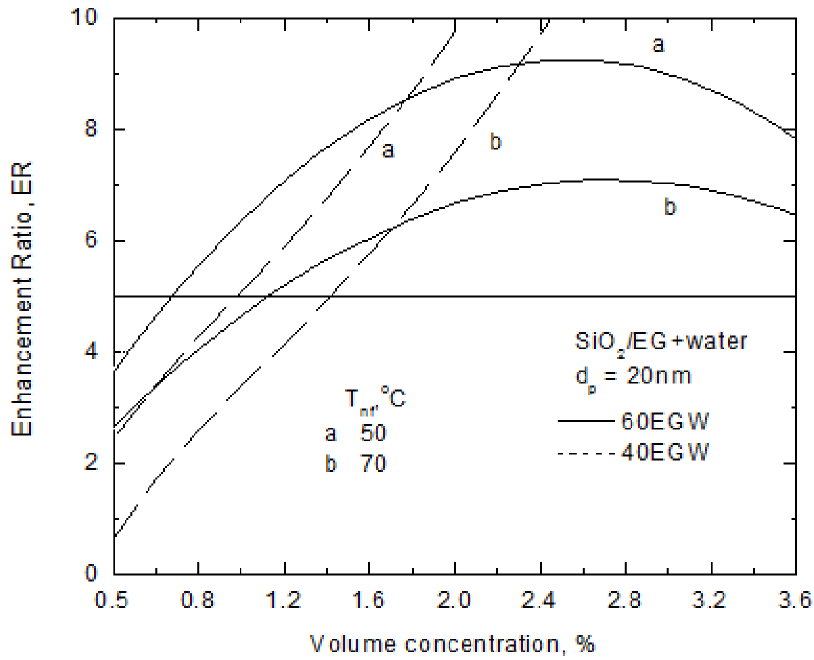

SiO2/60EGW
dp=20nm
ϕ, % Cor.
a 0.0 6
b 0.5 12
c 1.0 12
d 1.5 12
Viscosity, Pa.s
Temperature, °C



SiO2/40EGW
dp=20nm
ϕ, % Cor.
a 0.0 10
b 0.5 14
c 1.0 14
d 1.5 14
Viscosity, Pa.s
Temperature, °C



dp=20nm
SiO2/60EGW
ϕ,%
0.0
1.0
1.5
SiO2/40EGW
ϕ,%
0.0
1.0
1.5
Viscosity Enhancement, (μnf/μbf)
Temperature, °C


Enhancement Ratio, ER
Volume concentration, %
0
2
4
6
8
10
0.5
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
a
b
a
b
SiO2/EG+water
dp = 20nm
60EGW
40EGW
Tnf, °C
a 50
b 70