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Experimental Investigation of Thermal Conductivity and Viscosity of SiO₂/Multiwall Carbon Nanotube Hybrid Nanofluid

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Department of Mechanical Engineering, University of Tehran, Tehran 11155-4563, Iran

In this study, the thermal conductivity and viscosity of SiO₂/multiwall carbon nanotube (MWCNT) hybrid nanofluids are investigated. The volume fraction of the nanofluids varied in the range of 0.5% to 2%, while the SiO₂ to MWCNT volume proportion is either 95-5 or 90-10. The nanofluids are synthesized using a wet chemical method and a two-step technique is used to disperse nanoparticles in glycerol (base fluid). The thermal conductivities and viscosities of the nanofluids are measured using a modified transient hot-wire method and falling ball viscometer, respectively. The colloidal stability of the dispersion was investigated visually. Effective application of an ultrasonic disruptor and a suitable surfactant (gum arabic) enhance the dispersion behavior. When the effects of temperature and volume fraction on the thermal conductivity and viscosity of SiO₂/multiwall carbon nanotube (MWCNT) hybrid nanofluids are studied, the results showed that the thermal conductivity of nanofluids increased with an increase in the volume fraction and temperature. Further, their viscosities increased with an increase in the volume fraction but decreased when the temperature increased. The thermal conductivity and viscosity of the hybrid nanofluids increased by 16.7% and 105.4%, respectively, at a volume fraction of 2% and volume proportion of 90-10. The experimental results are compared with those predicted by classical theoretical models. Two correlations for thermal conductivity and viscosity of hybrid nanofluids are proposed on the basis of the experimental results.

Keywords: Multiwall Carbon Nanotube, SiO₂, Glycerol, Hybrid Nanofluid, Thermal Conductivity, Viscosity, New Correlation.

1. INTRODUCTION
The formation of a heat transfer fluid in solar thermal collectors requires overcoming several practical constraints. Using water-based heat transfer fluids leads to corrosion in the system. Alternatively, heat transfer fluids, comprising of a mixture of water and glycerol, can be used. The properties of glycerol-based fluids include corrosion inhibition, low viscosity, low freezing point, and biologically and environmentally safe characteristics. The application of such fluids in direct solar collectors can efficiently increase the heat transfer efficiency of direct solar absorbance. Using glycerol-based nanofluids as the working fluids in direct solar collectors can improve the optical and thermal properties as well as the efficiency of direct solar collectors. Han et al. investigated the photothermal properties, optical properties, rheological behavior, and thermal conductivities of carbon black-based nanofluids for use in solar absorption collectors. Yousefi et al. studied the efficiency of a flat-plate solar collector using a nanofluid containing MWCNTs in water as the absorbing medium. Rose et al. developed a wave-optics model to estimate the optical properties of nanofluids to assist in sizing the absorber tubes and selecting working fluids for directly absorbing solar concentrators. They compared the model-predicted results with actual experimental results.

Nanofluids have broad applications in cooling and heating thermal energy storage systems to increase thermal energy absorption and heat transfer rate. Carbon nanotubes (CNTs) were first developed in 1991 by Iijima, a Japanese electron microscopist. CNTs are carbon allotropes with a cylindrical nanostructure and are appealing to many researchers due to their unique properties, such as high physical strength, chemical stability, mechanical resistance, and very good absorbance in...
Experimental Investigation of Thermal Conductivity and Viscosity of SiO2/MWCNT Hybrid Nanofluid

Table I. Specification of MWCNT and SiO2 nanoparticles.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>MWCNTs</th>
<th>SiO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purity</td>
<td>&gt;97%</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>Color</td>
<td>Black</td>
<td>White</td>
</tr>
<tr>
<td>Size</td>
<td>Outer diameter: 5–15 (nm) 20–30 (nm)</td>
<td>Inner diameter: 3–5 (nm)</td>
</tr>
<tr>
<td></td>
<td>Length: 50 (µm)</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1500 (W/m K)</td>
<td>1.3 (W/m K)</td>
</tr>
<tr>
<td>Bulk density</td>
<td>0.27 (g/cm³)</td>
<td>&lt;0.10 (g/cm³)</td>
</tr>
<tr>
<td>True density</td>
<td>~2.1 (g/cm³)</td>
<td>2.4 (g/cm³)</td>
</tr>
<tr>
<td>Specific surface area (SSA)</td>
<td>233 (m²/g)</td>
<td>180-600 (g/fg)</td>
</tr>
</tbody>
</table>

A summary of proposed correlation for thermal conductivity of nanofluids.

\[
\frac{k_{knf}}{k_{bf}} = \left(1 + 0.135 \times \left(\frac{k_p}{k_{bf}}\right)^{0.273} \times (\varphi^{0.407} \times \left(\frac{T}{20}\right)^{0.547} \times (\frac{100}{d_p})^{0.224})\right)
\]

thermal conductivity of CuO-ethylene glycol, MWCNT-ethylene glycol, MWCNT-water, and MWCNT-synthetic engine oil suspensions increased by 22.4%, 12.4%, 17%, and 30%, respectively, at volume fractions of 0.5%, 1%, 1.5%, and 2%. Nabati Shoghl et al.19 investigated the electrical conductivity, viscosity, and density of CuO, TiO2, MgO, MWCNT, Al2O3, and ZnO water-based nanofluids as functions of concentration and temperature. Further, they compared experimental and theoretical results.

In another study,20 MWCNT-water nanofluids were formulated using GA as a dispersant and the influence of temperature and concentration on the viscosity of the nanofluids was investigated. Pakdaman et al.21 evaluated the thermophysical properties of MWCNT-heat transfer oil nanofluids at different temperatures and mass concentrations to assess the overall performance of fluid flow inside vertical helically coiled tubes. Phuoc et al.22 studied the thermal conductivity, viscosity, and stability of a nanofluid containing MWCNTs and stabilized by cationic chitosan.

A hybrid material can exhibit a combination of the physical and chemical properties of distinct materials. Therefore, various properties of nanoparticles can be achieved by making a hybrid nanofluid. As the applications of hybrid nanofluids are not as well established as those of monotype nanofluids, further research should be carried out in this area.

Baghbanzadeh et al.23 investigated the thermal conductivity of nanofluids consisting of distilled water as the base fluid, MWCNTs, and silica nanospheres; the suspended nanoparticles are a hybrid of MWCNTs and silica nanospheres. The researchers aimed at improving the thermal and rheological properties of water-based drilling nanofluids.

Table II. Most increase in thermal conductivity.

<table>
<thead>
<tr>
<th>Nanoparticle</th>
<th>T (°C)</th>
<th>Volume fraction (%)</th>
<th>Most increase in thermal conductivity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>50</td>
<td>2</td>
<td>14.9</td>
</tr>
<tr>
<td>SiO2/MWCNT hybrid</td>
<td>50</td>
<td>2</td>
<td>15.7</td>
</tr>
<tr>
<td>SiO2/MWCNT hybrid</td>
<td>50</td>
<td>2</td>
<td>16.7</td>
</tr>
</tbody>
</table>

Table III. Enhancement of nanofluid viscosity.

<table>
<thead>
<tr>
<th>Nanoparticle</th>
<th>T (°C)</th>
<th>Volume fraction (%)</th>
<th>The increase in viscosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>40</td>
<td>2</td>
<td>84.9</td>
</tr>
<tr>
<td>SiO2/MWCNT hybrid</td>
<td>40</td>
<td>2</td>
<td>90.2</td>
</tr>
<tr>
<td>SiO2/MWCNT hybrid</td>
<td>40</td>
<td>2</td>
<td>91.1</td>
</tr>
<tr>
<td>SiO2/MWCNT hybrid</td>
<td>50</td>
<td>2</td>
<td>96.7</td>
</tr>
<tr>
<td>SiO2/MWCNT hybrid</td>
<td>50</td>
<td>2</td>
<td>105.4</td>
</tr>
</tbody>
</table>

thermal conductivity of CuO-ethylene glycol, MWCNT-ethylene glycol, MWCNT-water, and MWCNT-synthetic engine oil suspensions increased by 22.4%, 12.4%, 17%, and 30%, respectively, at volume fractions of 0.5%, 1%, 1.5%, and 2%. Nabati Shoghl et al.19 investigated the electrical conductivity, viscosity, and density of CuO, TiO2, MgO, MWCNT, Al2O3, and ZnO water-based nanofluids as functions of concentration and temperature. Further, they compared experimental and theoretical results.

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The synthesis of water-based Al_2O_3/MWCNT nanoparticles in the weight proportion of 97.5-2.5 to 90-10 over a concentration range of 1 wt.% to 6 wt.%. They reported the synthesis process and observed an enhancement in the thermal conductivity of nanofluids obtained by mixing ground and un-ground CNTs with oxide nanoparticles. In another investigation, the dynamic viscosity of a MWCNT/ZnO-SAE40 hybrid nano-lubricant was examined at various solid volume fractions at different temperatures. The preparation process of nanofluids plays an important role in controlling their thermo-physical properties. Nanofluids with the same nanoparticles and base fluid can behave differently owing to the preparation method. Sadri et al. provided experimental data on the effects of ultrasonication, temperature, and surfactant on the thermo-physical properties of MWCNTs nanofluids. In general, nanofluids are prepared in two ways:

1. One-step direct method in which nanoparticles are synthesized in the base fluid.
2. Two-step technique in which nanoparticles are fabricated first and then dispersed in the base fluid.

The two-step approach is utilized in this study. GA is used as the surfactant for the preparation of nanofluids. Rashmi et al. investigated the aqueous dispersion of CNTs in the presence of GA; they studied the effects of CNT concentration, GA concentration, and sonication time on the stability of the homogeneous dispersion. Although numerous studies have been conducted on the effective thermal conductivity of nanofluids, there are only a few reports available on the viscosity of hybrid nanofluids based on MWCNTs. However, viscosity has a significant impact on the fluid flow and thermal energy absorption and hence has to be investigated.

In this study, the application of a glycerol-based nanofluid containing SiO_2/MWCNT hybrid nanoparticles as the working fluid in direct solar collectors is proposed. The main purpose of this study is to exploit the beneficial properties of both nanoparticles and improve the thermal, rheological, optical, and photo-thermal properties of the glycerol-based hybrid nanofluids. In previous studies, it was reported that SiO_2 nanoparticles have several advantageous features, including their easy, direct, and cheap synthesis at room temperature, suitable yield, and nontoxic nature. Using SiO_2 nanoparticles in glycerol-based fluids enhances the rheological properties of the fluid but we need a nanostructure with better thermal and optical properties and suitable rheological properties. The exceptional thermal, optical, and photo-thermal properties of MWCNTs nanofluids prompted us to synthesize a hybrid nanostructure of SiO_2/MWCNTs to achieve our goal. MWCNTs have a thermal conductivity of 1500 W/m K and good absorbance in the wavelength range of 200 to 2500 nm, owing to which they can markedly increase the thermal conductivity, optical properties, and photo-thermal properties of a base fluid. In fact, our purpose is to develop a nanostructure that exhibits characteristics of both SiO_2 nanoparticles (suitable rheological properties) and MWCNTs (suitable thermal, optical, and photo-thermal properties) in a homogeneous phase. In this study, the wet chemical method and two-step technique are used to synthesize SiO_2/MWCNT hybrid nanofluids. Thermal conductivity and viscosity of the synthesized fluids are measured using a transient hot-wire method and falling ball viscometer, respectively.

### 2. EXPERIMENTAL DETAILS

#### 2.1. Synthesis of Nanoparticle

To synthesize nanotubes covered by SiO_2 nanoparticles, initially, the surfaces of the nanotubes are functionalized with carboxylic acid functional groups (–COOH). The synthesis of nanoparticles is then carried out using these functional groups. For this purpose, 5 g of carbon nanotubes, 100 mL of nitric acid, and 20 mL of sulfuric acid are amalgamated and blended for 5 h at 40 °C using a magnetic blender. By doing so, the surfaces of the nanotubes are covered by carboxylic groups (–COOH). Carboxylation of the surfaces of carbon nanotubes causes enhanced interactions between SiO_2 nanoparticles and the nanotube surfaces. Consequently, the surfaces of the nanotubes will be coated by SiO_2. In the next step, functionalized carbon nanotubes are separated using a filter, washed thrice with distilled water and alcohol, and dried at 60 °C. Eshgarf and Afrand investigated the rheological behavior

#### Table V. A summary of proposed correlation for viscosity of nanofluids.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[44]</td>
<td>( \mu_{nf} = 1 + 2.5 \varphi )</td>
</tr>
<tr>
<td>[45]</td>
<td>( \mu_{sf} = \frac{1}{(1 - \varphi)^2} )</td>
</tr>
<tr>
<td>[46]</td>
<td>( \mu_{nf} = (1 + 2.5 \varphi + 6.2 \varphi^2) )</td>
</tr>
<tr>
<td>[47]</td>
<td>( \mu_{sf} = (1 + 7.3 \varphi + 123 \varphi^2) )</td>
</tr>
<tr>
<td>[48]</td>
<td>( \frac{\mu_{nf}}{\mu_{sf}} = \frac{1}{1 - 34.87(d_m/d_f)^{0.8} \varphi^{0.8}} )</td>
</tr>
<tr>
<td>( d_f = 0.1 \left( \frac{6M}{N \pi \rho \sigma} \right)^{1/3} )</td>
<td></td>
</tr>
</tbody>
</table>

#### Table VI. The value of coefficient used in correlation 2.

<table>
<thead>
<tr>
<th>Nanoparticle</th>
<th>Coefficient</th>
<th>Maximum error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO_2 95-5</td>
<td>31.62</td>
<td>0.04677</td>
</tr>
<tr>
<td>(SiO_2-MWCNT) 95-5</td>
<td>35.59</td>
<td>0.05331</td>
</tr>
<tr>
<td>SiO_2 90-10</td>
<td>39.01</td>
<td>0.06400</td>
</tr>
<tr>
<td>(SiO_2-MWCNT) 90-10</td>
<td>588.2</td>
<td>0.06400</td>
</tr>
</tbody>
</table>
of COOH-functionalized MWCNT/SiO$_2$-EG-water hybrid nano-coolants. They prepared nano-coolant samples at various solid volume fractions and experimented at different temperatures. For silicatization of the surfaces of carbon nanotubes, 3 g of sodium silicate is dissolved in 50 mL of distilled water; to this solution, 0.3 g of COOH-functionalized carbon nanotubes is added. The dispersion is blended with a magnetic blender for 20 min for homogenization. Subsequently, this solution is transported to an ultrasonic tank and held there for 2 h at 50 °C. Following this step, carbon nanotubes covered with SiO$_2$ nanoparticles are washed with distilled water and dried at 45 °C.

### 2.2. Characterization of Prepared Powder Sample

Figure 1 shows different images of the nanoparticles synthesized in this study. Figures 1(a)–(c) show the TEM images of SiO$_2$/MWCNT hybrid nanoparticles. It is obvious from the images that MWCNTs are covered by silica nanoparticles. The XRD pattern of SiO$_2$/MWCNTs is illustrated in Figure 1(d); the first peak at 2θ = 3°–4° and the second peak at 2θ = 20°–21° are characteristic of SiO$_2$ and MWCNTs, respectively.

### 2.3. Preparation of Nanofluid

In this study, SiO$_2$/MWCNT hybrid nanofluids at volume fractions of 0.5% to 2% and SiO$_2$/MWCNT volume proportions of 95:5 and 90:10 are prepared. By dispersing the required volume of SiO$_2$/MWCNT nanoparticles in glycerol and implementing the two-step method, hybrid nanofluids of the desired volume fraction can be obtained. GA is used as the dispersant. For the preparation of nanofluids, firstly, 2 mass% GA is added to glycerol. This solution is exposed to an ultrasonic disruptor for 30 min. Subsequently, the nanomaterial is added to the disrupted solution, which is then subjected to ultrasonic vibration using the ultrasonic disruptor; it produces three ultrasonic pulses of 180 W at 400 kHz and each pulse lasts 30 min. The stability of the solution is tested visually. Visual observation showed that the hybrid nanofluid samples exhibit good stability for 72 h with no obvious sedimentation during this time. The obtained uniform dispersions and stable suspensions are used for the determination of the characteristics of the hybrid nanofluids.

### 2.4. Measurement of Thermophysical Properties of Hybrid Nanofluid

#### 2.4.1. Thermal Conductivity

The thermal conductivities of SiO$_2$/MWCNT hybrid nanofluids are measured using a KD2 thermal property analyzer (Decagon Devices, Inc., USA). The measurement is based on the transient hot-wire method. KD2 contains a microcontroller and sensor needle. The controller consists of a battery, 16-bit microcontroller, 16-bit AD converter,
and power-control circuitry. The KS-1 type single needle sensor is made of stainless steel and its length and diameter are 60 mm and 1.3 mm, respectively. The sensor contains a heating element as well as a thermo-resistor; the sensor needle is initially calibrated by measuring the thermal conductivity of glycerol. The measured value for glycerol is 0.275 W/m K (∼3.5% variation from the reference value, 0.285 W/m K). The sensor can measure the thermal conductivity of fluids in the range of 0.2–2 W/m K with an accuracy of 5%. The two main assumptions used during thermal conductivity measurements are as follows. 1—A long heat source can act as an infinitely long heat source. 2—The environment is homogenous, isotropic, and the temperature is uniform. Each measurement cycle lasts 90 s. During the first 30 s, the instrument undergoes equilibration. The next 30 s are devoted to heating, while in the final 30 s, cooling occurs. The data is classified in 1 s and 20 final points sourced during heating and cooling are used for simultaneous least-squares computations. At the end of the cycle, a microcontroller calculated thermal conductivity by utilizing the alteration of temperature-time data

\[ k = \frac{q(\ln t_2 - \ln t_1)}{4\pi(\Delta T_2 - \Delta T_1)} \]

In this equation, \( q \) is the heat imposed by the infinitely long and small line source and \( \Delta T \) and \( \Delta T_2 \) are variations in temperature at \( t_1 \) and \( t_2 \) (time), respectively. Temperature is measured using a 16-bit analog to digital converter and the calculations are done using a 16-bit microcontroller. The KD2 pro sensor needle is calibrated at room temperature.

2.4.2. Viscosity

The viscosities of the hybrid nanofluids are measured using a falling ball viscometer (Lovis 2000 M microviscometer, Anton Paar, USA). The measurement system contains a capillary tube and a ball. The ball rolls in a closed liquid-filled capillary at a specific angle. According to Newton’s laws of motion for a falling ball, the net forces, including buoyancy, gravity, and viscosity are equal to zero at equilibrium. Newton’s laws of motion are utilized with balanced forces on a spherical ball rolling at a constant velocity. The inductive sensors specify the rolling time of the ball when it reaches a constant velocity between two fixed signs. The viscosity of the sample is proportional to the rolling time of the ball. Using three sensors, the whole distance of measurement in the capillary tube is divided into a short first part and a longer second part. The testing time is about three minutes. The volume of the capillary tube in the standard form is 1.5–3 mm³. The viscosities of the nanofluids are measured in the temperature range of 20–50 °C with an accuracy of 0.5%. This method can be used to measure viscosity in the range of 0.3 to 10000 mPa.s.

3. RESULTS AND DISCUSSION

3.1. Thermal Conductivity of Hybrid Nanofluid

The thermal conductivities of SiO₂ nanoparticles and SiO₂/MWCNT hybrid nanoparticles dispersed in glycerol as the base fluid at volume fractions of 0.5%–2% and volume proportions of 95-5 and 90-10 are measured using a KD2 thermal property analyzer. During the measurement, it is ensured that there are no disturbances.
The temperature rises by about 0.3–0.4 °C during the heating cycle. Therefore, the occurrence of convection caused by a temperature gradient is negligible. The thermal conductivities of the nanofluids are measured after 120 min from solution sonication because the thermal conductivity of the fluid is stabilized after this time period. Figure 3(a) presents the thermal conductivity of SiO₂/MWCNT hybrid nanofluids as a function of volume fraction at various temperatures ranging from 20 °C to 50 °C.

It can be seen in Figure 3(b) that with an increase in the temperature and volume fraction of the nanoparticles, the thermal conductivity of SiO₂/MWCNT hybrid nanofluids increases. The main reason behind the increase in thermal conductivity upon increasing the temperature can be attributed to Brownian motion and an enhancement in the interactions between the nanoparticles. Upon increasing the volume fraction, the number of suspended nanoparticles increases, which leads to a rise in the ratio of surface area to volume as well as an increase in the effect of thermophoresis, interfacial ordering, nanoparticle clustering, and ballistic transport of energy carriers. In the case of the SiO₂/MWCNT hybrid nanofluids at 50 °C and volume fractions of 0.5%, 1%, 1.5%, and 2%, thermal conductivity increases by 9.1%, 10.9%, 14.2%, and 16.7%, respectively. The variation in the increase of thermal conductivity with volume fraction at higher temperatures is greater than that at lower temperatures. Further, the variation in the increase of thermal conductivity with temperature at higher volume fractions is more than that at lower volume fractions. The effect of temperature on the Brownian motion of nanoparticles at higher volume fractions is more noticeable because of the presence of more nanoparticles. Figure 4 illustrates the thermal conductivities of SiO₂ and hybrid nanofluids of different volume proportions as functions of the volume fraction.

It can be observed that adding MWCNTs to SiO₂ nanoparticles to synthesize hybrid nanoparticles led to a noticeable increase in the effective thermal conductivity. This phenomenon is related to the higher thermal conductivity of carbon nanotubes in comparison to SiO₂ nanoparticles. Literature reports that the length to diameter ratio of nanoparticles is an integral parameter in controlling the thermal conductivity of nanofluids. Compared to spherical nanoparticles, in which the length to diameter ratio is 1, carbon nanotubes have a high length to diameter ratio of 100. It can be seen that by increasing the volume proportion of MWCNT to SiO₂ at the same volume fraction, thermal conductivity increased up to 1.8%.

Many theoretical and experimental studies have been conducted for the prediction of the effective thermal conductivity of nanofluids. Figure 5 illustrates a comparison between the experimentally measured thermal conductivities of SiO₂ nanoparticles in a glycerol base fluid with the values reported in a previous study. It is obvious that the experimental results agree well with reports in literature.
The small differences between the two sets of results can be explained in terms of the following factors. 1—The nanofluid preparation method. 2—The length of time between nanofluid preparation and conducting the experiment. 3—The type and amount of surfactant used for the stabilization of the nanofluid. 4—The accuracy of the measurement device used. In Figure 6, a comparison between the experimental results and the values predicted by several classical models at 50 °C is presented. We investigated the accuracy of these models in predicting the thermal conductivity of nanofluids. The first commercial model is the Maxwell model, which was proposed to predict the thermal and electrical conductivities of solid–liquid suspensions. Hamilton-Crosser expanded Maxwell’s model to take into account the effect of nanoparticle shape. Later, Yu and Choi introduced a correlation for calculating the thermal conductivity of nanofluids. Patel et al. proposed a thermal conductivity correlation for metallic and oxide nanofluids at different volume fractions and temperatures.

Comparing the theoretical models with the obtained experimental results illustrates the fact that the classic models (Maxwell and Hamilton-Crosser) predict the effective thermal conductivity of the nanofluids to be lower than the experimental results because they do not take into account the effect of the size of nanoparticles, nanoparticle distribution, and the interfacial layer at the solid–liquid interface. However, the thermal conductivity predicted by the model proposed by Yu and Choi is more in line with the experimental results at concentrations less than 1%; as the concentration increases, the accuracy of the prediction model decreases. The model proposed by Patel et al. predicts thermal conductivities higher than the experimental results.

Because the proposed models could not predict the thermal conductivities of the tested hybrid nanofluids precisely, a new correlation for the prediction of hybrid nanofluid conductivity is proposed. Different parameters, including the thermal conductivities of the base fluid and nanoparticles, volume proportion, volume concentration, and temperature are taken into account in this correlation.

\[
\frac{k_{nf}}{k_{bf}} = \left[ 1 + 0.214\left( \omega_1 \frac{k_{np1}}{k_{nf}} + \omega_2 \frac{k_{np2}}{k_{nf}} \right) 0.25 \varphi^{0.475} \left( \frac{T}{20} \right)^{0.48} \right]
\]  

(1)

In this correlation, \(\omega_1\) and \(\omega_2\) refer to the volume proportion of nanoparticles 1 and 2, respectively, in the hybrid nanofluid. The maximum deviation of the proposed correlation occurs at a volume fraction of 2%. Figure 7 shows the comparison between the proposed prediction model and the experimental results.

### 3.2. Viscosity of MWCNT-SiO₂ Hybrid Nanofluids

The resistance of a fluid against flowing is defined as viscosity, which is one of the most critical factors in selecting suitable working fluids for different applications. To obtain an insight into the rheological behavior of nanofluids, in the present study, we focused on analyzing the viscosity of SiO₂, SiO₂/MWCNT hybrid nanofluids, and SiO₂ nanofluid in a glycerol base fluid. The viscosities of nanofluids with different volume fractions of 0.5%, 1%, 1.5%, and 2% are measured in the temperature range of 20 °C to 50 °C. The viscosity of the base fluid at different temperatures is compared with literature reports to verify...
The accuracy of our experiments. We found that the maximum deviation is less than 5% in the temperature range of 20–50 °C.

In Figure 9, the viscosities of silica and hybrid nanofluids at a volume fraction of 2% are presented as functions of temperature. According to this plot, as the temperature rises, the viscosity of the nanofluid decreases. This could be explained by the fact that the viscosity of the base fluid decreases with an increase in the temperature. The viscosity of a liquid is a function of the underlying intermolecular attractive forces. When the temperature increases, these forces reduce, resulting in a reduction in the viscosity of the base fluid. A similar trend was reported with respect to the viscosity of the nanofluid with increasing temperature. It can be observed that the hybrid nanofluid with a volume proportion of 90-10 has higher viscosity at different temperatures. Upon increasing the temperature, the difference between the viscosities of the nanofluid and base fluid decreases; the differences between their viscosities are 1.27 and 0.157 Pa·s at 20 °C and 50 °C, respectively.

Figure 10 illustrates the ratio of the viscosities of the nanofluids and glycerol base fluid as a function of concentration. The experimental results show that the viscosity ratio increases as the volume fraction increases because the number of nanoparticles coming into contact with the base fluid increases. The total surface area in contact with the base fluid will increase, resulting in more resistance to the movement of the base fluid molecules and therefore the viscosity of the nanofluid rises. The minimum and maximum enhancements in the viscosity of glycerol at 50 °C by dispersing nanoparticles belong to SiO₂ at volume fraction of 0.5% by 13.1%, and SiO₂/MWCNT hybrid nanofluid at volume proportion of 90-10 and volume fraction of 2% by 105.4%, respectively.

It is obvious from Figure 10 that the viscosities of SiO₂/MWCNT hybrid nanofluids are higher than that of the SiO₂ nanofluid. At low volume fractions, their viscosities are close to each other. However, upon increasing the volume fraction, the viscosity of the nanofluid with higher volume proportion of MWCNT to SiO₂ increases. Because of the dense structure of MWCNTs, a greater number of clusters of hybrid nanostructures are formed in the base fluid compared to spherical SiO₂ nanoparticles; therefore, by increasing the volume proportion of MWCNT in the hybrid nanofluid, the viscosity increases.

The entangled structure of MWCNTs increases surface interactions when MWCNTs are dispersed in the base fluid. The higher resistive force offered by the clusters of MWCNTs and particle–particle interactions in the carrier fluid lead to an increase in the viscosity. The spherical structure of silica particles allows more comfortable movement inside the fluid and between its layers. To verify the accuracy of the experimental results, they are compared with those reported in literature. In Figure 11, the experimental ratios of the viscosities of silica nanofluid and glycerol base fluid are compared with the results presented by Shanker et al. They measured the viscosity of SiO₂ (35 nm diameter) nanoparticles suspended in a stabilized-glycerol base fluid using sodium dodecyl benzene sulfonate (SDBS) as the surfactant in the temperature range of 30–80 °C and volume fraction in the range of 0.1–1%. They reported that increasing the concentration of SiO₂ nanoparticles led to an increase in the viscosity of the nanofluid. We found that there is a good agreement between our experimental results and Shanker et al.’s data at various volume fractions.
Experimental Investigation of Thermal Conductivity and Viscosity of SiO$_2$/MWCNT Hybrid Nanofluid

Figure 12. The comparison of experimental data with the prediction of well-known models.

However, there exist several empirical correlations to predict the effective viscosity of nanofluids. Some of the well-known classical models are the Einstein, Brinkman, and Batchelor models. Wang et al. proposed a model to calculate the viscosity of nanofluids. Corcione suggested a model to calculate the viscosity of nanofluids in the nanoparticle diameter, volume fraction, and temperature ranges of 25–200 nm, 0.01%–7.1%, and 20–50°C, respectively. They used the curve-fitting method based on experimental data points to extract the model.

These models predict nanofluid viscosities lesser than the experimental results because these models are developed for low-concentration nanofluids. In future studies, other parameters, including the amount of the surfactant, pH, temperature of the medium, shape and size of the nanoparticles, and clustering should be considered for more accurate theoretical prediction. The proposed model in this study, as described in Figure 13, exhibits good conformity with the experimental results,

\[ \frac{\mu_{nf}}{\mu_{bf}} = (1 + a\varphi + b\varphi^2)e^{c(1/dT_{max})} \]  

Figure 13 illustrates that the results predicted by the proposed model are close to the experimental results and the maximum relative deviation is about 4%.

4. CONCLUSION

In this experimental study, hybrid nanoparticles are synthesized using the wet chemical method. Initially, the surfaces of carbon nanotubes are functionalized with carboxylic groups (–COOH), which enhance interactions between SiO$_2$ nanoparticles and the surface of MWCNTs; later, these surfaces are coated with SiO$_2$ nanoparticles to yield composite SiO$_2$/MWCNT powders of volume proportions of 90-10 and 95-5. Nanofluids with four different volume fractions ranging from 0.5% to 2% in two volume proportions (90-10 and 95-5) are synthesized using the two-step method. GA is used as the dispersant. The thermal conductivities and viscosities of the nanofluids are measured using a KD2 pro thermal properties analyzer and falling ball viscometer, respectively. The effective thermal conductivity and viscosity of the hybrid nanofluids are compared with those of the glycerol base fluid. The experimental results show that

- With increasing temperature and nanoparticle volume fraction, the thermal conductivity of the hybrid nanofluid increases because of increasing Brownian motion and nanoparticle clustering.
- At a volume fraction of 2%, the thermal conductivity of the hybrid nanofluid (90-10) increased by 8.3% upon increasing the temperature from 20°C to 50°C.
- At a temperature of 50°C, the thermal conductivity of the hybrid nanofluid (90-10) increased by 7.7% upon increasing the volume fraction from 0.5% to 2%.
- The thermal conductivity of the nanofluids increased by 1.8% upon increasing the volume proportion of MWCNT to SiO$_2$ from 0 to 10.
- By increasing the temperature from 20°C to 50°C, the rate of increasing thermal conductivity of nanofluid with higher volume fraction is greater.
- Upon increasing the nanoparticle volume fraction from 0.5% to 2%, the viscosities of the hybrid nanofluids increased by 105.4% because of the increase in the total surface area of the nanoparticles in contact with the base fluid.
- Upon increasing the temperature from 20°C to 50°C, the viscosities of the hybrid nanofluids decreased by 140.6% because of the reduction in the intermolecular attractive forces.
- Upon increasing the volume proportion of MWCNT to SiO$_2$ from 0 to 10, the viscosities of the hybrid nanofluid increased by 14.7%.
- The measured thermal conductivity is not in good agreement with the values predicted by theoretical models; therefore, a new thermal conductivity model based on the experimental results is proposed.
- The measured values for the viscosity of hybrid nanofluids are much higher than those predicted by theoretical models; therefore, a new viscosity model is proposed for the prediction of hybrid nanofluid viscosity.
The new models proposed for the prediction of thermal conductivity and viscosity are in good agreement with the experimental results.

**NOMENCLATURE**

- \( a \)  Coefficient in Eq. (2)
- \( b \)  Coefficient in Eq. (2)
- \( C \)  Centigrade degree
- \( c \)  Coefficient in Eq. (2)
- \( d \)  Coefficient in Eq. (2)
- \( d_f \)  Equivalent diameter of the base fluid molecule, (m)
- \( d_p \)  Diameter of the nanoparticle (m)
- \( g \)  Gram
- \( K \)  Kelvin degree
- \( k \)  Thermal conductivity (W/mK)
- \( M \)  Molecular weight (kg mol\(^{-1}\))
- \( N \)  Avogadro number = 6.022 × 10\(^{23}\) mol\(^{-1}\)
- \( q \)  Heat power (W)
- \( Pa \)  Pascal
- \( T \)  Temperature (K)
- \( t \)  Time (s)
- \( W \)  Watt.

**Greek Symbols**

- \( \mu \)  Dynamic viscosity (Pa - s)
- \( \Phi \)  Volume fraction
- \( \omega \)  Volume proportion
- \( \rho_{bf} \)  Mass density of the base fluid calculated at temperature \( T_0 = 293 \) K.

**Subscripts**

- \( bf \)  Base Fluid
- \( nf \)  Nanofluid
- \( p \)  Nanoparticle.

**References and Notes**


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