Experimental Studies and Analytical Analysis of Thermophysical Properties of Ethylene Glycol–Water-Based Nanofluids Dispersed with Multi-walled Carbon Nanotubes

Abhishek Dosodia1 · Srinivas Vadapalli2 · Amitabh Kumar Jain3 · Saratchandra Babu Mukkamala4 · Bhanu Teja Sanduru5

Received: 8 August 2022 / Accepted: 22 September 2022 / Published online: 5 October 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
The present study investigates the thermal conductivity and dynamic viscosity of ethylene glycol–water solutions dispersed with oxidized multi-walled carbon nanotubes. The physico-thermal properties and Mouromtseff number (Mo) were used to evaluate the heat transfer properties of the nanofluids. Ethylene glycol–water mixtures were chosen as base fluids, and the volume fraction of ethylene glycol varied from 100 % to 0 % (pure water). Oxidized multi-walled carbon nanotubes in weight percentages of 0.0625, 0.125, 0.25, and 0.5 were dispersed in ethylene glycol–water mixtures to achieve the best stability. The stability of the nanofluids was monitored by UV–Vis spectroscopy for 2 months. The dispersion of multi-walled carbon nanotubes in the base fluids resulted in a significant improvement in thermal conductivity. To derive correlations for thermal conductivity and dynamic viscosity, 1 500 data points were collected for all possible combinations of temperature, weight percent of multi-walled carbon nanotubes, and ethylene glycol content. The Mouromtseff number (Mo) showed that dilute nanofluids at low concentrations are the most effective heat transfer medium in turbulent flow.

Keywords Ethylene glycol–water mixtures · Mouromtseff number · Oxidized multi-walled carbon nanotubes · Thermophysical properties

Nomenclature

\[ C_p \quad \text{Specific heat (kJ·kg}^{-1}·\text{K}^{-1}) \]
\[ k \quad \text{Thermal conductivity (W·m}^{-1}·\text{K}^{-1}) \]
\[ Mo \quad \text{Mouromtseff number, } \left[ \frac{k^3\rho^3\tau_p^3}{\mu^2} \right]. \]

* Srinivas Vadapalli
svas1973@yahoo.com; svadapal@gitam.edu

Extended author information available on the last page of the article
N  Spindle speed of rheometer
P  Power of the instrument
R  Radiation and interfacial effects
T  Temperature °C
U  Uncertainty in measurement

Roman Letters
α  Volume percentage of ethylene glycol in water
β  Weight fraction of nanoparticles
μ  Dynamic viscosity (centipoise, cP)
ρ  Density of the fluid (kg·m⁻³)
ϕ  Weight fraction of MWCNTs

Subscripts
nf  Nanofluid
base  Base fluids

Abbreviations
DM water  Demineralized water
EG  Ethylene glycol
MWCNTs  Multi-walled carbon nanotubes
UV–Vis spectroscopy  Ultraviolet–Visible spectroscopy
% wt  Weight percentage

1 Introduction

Nanofluids are a relatively new technological development in recent decades. Several studies have shown that nanofluids can be used for various applications, such as thermofluids, lubricating oils, engine cooling, and solar thermal energy. The enhancement of thermal conductivity of nanofluids over the corresponding base fluid has been highlighted in the prior art [1–30], with all researchers noting an improvement in thermal properties.

Multi-walled carbon nanotubes (MWCNTs) are pure carbon polymers, which have the advantage that their surface can be modified to achieve stable dispersion in any fluid using the existing knowledge of carbon chemistry. The surface functionalization can improve the stability of the nanofluid, allowing for optimal thermal management. Multi-walled carbon nanotubes (MWCNTs) are excellent thermal conductors with thermal conductivity of 1500 W·m⁻¹·K⁻¹. A phenomenon called "ballistic conduction" occurs in MWCNTs, making them ideal materials for dispersion in base fluids for thermal management.

An organic compound, ethylene glycol with the formula (CH₂OH)₂, is miscible with water and other organic liquids to form mixtures for thermal management. Glycols offer tuneable properties by dilution with water, allowing thermophysical
properties to be altered depending on the application. Glycols are mainly used for two reasons: as antifreeze in coolants by admixing water in a volume fraction of 10 to 50% and as solar thermal fluid by admixing water in a fraction of 80, 90, and 100%.

1.1 Nanofluid Stability

Nanoparticles in the nanofluid can cluster together and hinder heat transfer in thermal systems. In addition, insufficient stability of the nanofluid can lead to changes in thermophysical properties such as thermal conductivity, viscosity, and specific heat. Since the enhancement of thermal conductivity is proportional to the stability of the nanomaterials dispersed in the fluid, any loss of stability would cause the nanofluids to lose their potential benefits. Pristine MWCNTs are highly hydrophobic and cannot be dispersed in polar fluids. Due to their hydrophobicity, the nanomaterials would form clusters in the fluids, causing them to settle in the liquid medium and lose their properties. Surface modification by surfactants via non-covalent functionalization is the most common approach researchers use to blend nanomaterials into base fluids. However, these surfactants increase the tendency of the fluids to foam, resulting in poor heat transfer performance.

Researchers [4, 6, 7, 21, 24, 29, 30] have highlighted covalent functionalization as one of the best options for nanofluids for thermal applications because it is convenient and can produce foam-free dispersions after a thorough evaluation of surface modification approaches. The modification of MWCNT was investigated by oxidative treatments with mild acids. The oxidative surface modification of MWNTs generates functional groups on their surface that increase their solubility in water and ethylene glycol-based coolants.

Researchers commonly use UV–Vis spectroscopy with wavelengths from 200 nm to 1 000 nm to study the stability of nanofluids. Due to its simplicity and efficiency, this approach is used to test the stability of nanofluids. UV–Visual spectroscopy establishes a relationship between light absorption and wavelength for each substance. This method estimates the stability of nanomaterials over time using Beer’s law and Lambert’s law, which states that concentration of particles in the solution is proportional to the rate of absorption of light through it. Therefore, this approach is advantageous to obtain quantitative results related to the stability of the nanofluid. In this method, the absorbance of a nanofluid sample is compared to the absorbance of a reference sample, the base fluid, to measure the dispersion stability of the nanomaterials. The difference in the absorbance of the base fluid and the nanofluid is proportional to the concentration of the nanoparticles. Any change in concentration due to agglomeration and resulting settling of the nanomaterials would result in a decrease in absorbance, indicating poor stability of the nanomaterials in the medium.
1.2 Present Work

The uniqueness of the current study is multi-layered. First, the preparation of nanofluids dispersed with oxidized multi-walled carbon nanotubes, followed by the study of the stability of the prepared nanofluids over 2 months using UV–Visible spectroscopy. Then, the dynamic viscosity, thermal conductivity, and specific heat of the nanofluids are determined. Finally, the heat transfer performance is indirectly evaluated using the Mouromtseff number (Mo).

In most previous studies, the amount of ethylene glycol in water was limited to 50 % by volume. In the current study, the properties of water–ethylene glycol are investigated, varying the water fraction between 100 %, 80 %, 60 %, 40 %, 20 % and 0 % (pure ethylene glycol). This variation in water content causes the boiling points to vary from 100 °C to 194 °C. In the present study, surfactant is not used to stabilize MWCNTs in liquids because it forms foam that affects the properties. Instead, MWCNTs are oxidized to achieve high stability in EG–water combinations, and the oxidized MWCNTs are mixed at 0.5 wt%, 0.25 wt%, 0.125 wt%, and 0.0625 wt%. Extensive correlations for thermal conductivity and dynamic viscosity were proposed, with weight percent of MWCNTs, percentage of water, and temperature as the variables.

2 Materials and Methods

U.S.-based Cheaptubes Inc. supplied multi-walled carbon nanotubes produced utilizing the CVD technology. MWCNTs are 30 nm to 50 nm in diameter and 3 µm to 15 µm in length. All other chemicals purchased were of analytical grade.

2.1 Purification and Oxidation of MWCNTs

MWCNTs were purified and then oxidized in a three-step process. MWCNTs were first calcined in air at 575 °C for 45 min to remove the carbon content from the amorphous phase (soot). In the second step, MWCNTs were refluxed in five-molar hydrochloric acid for 4 h to remove all impurities accumulated during the CVD process to produce MWCNTs. In the third step, the HCl-treated MWCNTs were oxidized with a mixture of 4 mol of HNO₃ and 4 mol of H₂SO₄ (volume ratio 1:3) for 3 h. The residue was washed with demineralized water until it reached a pH of seven and then dried overnight in a 60 °C oven.

2.2 Characterizations of Nanomaterials

The structure of the carbon nanotubes was studied using a transmission electron microscope (JEOL–2010, 200 kV). Figure 1a shows the presence of impurities such as metal particles and carbon black that entangle and cluster the MWCNTs.
The purified CNTs in Fig. 1b show that the MWCNTs have been disentangled by the oxidative treatment, revealing their open tips.

An FTIR spectrometer instantaneously collects data with high spectral resolution over a different spectral wavelength with respect to the percent transmission of light through the substance. The treated MWCNTs were characterized using FTIR spectroscopy to identify functional groups on their surface. Figure 2 shows the spectrum of untreated and oxidized MWCNTs. Line ‘a’ contains no visible peaks, indicating that the carbon nanotubes are pristine.

The modified MWCNTs, as seen in line b, display a stretch between 4000 and 3200 cm\(^{-1}\) representing oxalate groups (OH\(^-\)) and stretch between 1700 and 1600 cm\(^{-1}\) for carboxylate groups (CO\(^2-\)).
1500 cm\(^{-1}\) with a peak at 1651 cm\(^{-1}\) indicating carbonyl groups. All these groups are hydrophilic in nature and make the MWCNTs stable in all polar solvents, including ethylene glycol–water mixtures. The evaluation of stability by UV–Vis spectroscopy will be discussed in the next section.

### 2.3 Base Fluids and Nanofluids Preparation

In the present work, the properties of six base fluids as shown in Table 1 were evaluated. In these base fluids, oxidized multi-walled carbon nanotubes were dispersed in 0.5 wt%, 0.25 wt%, 0.125 wt%, and 0.0625 wt% using an ultrasonic probe. The fluids were sonicated for thirty minutes after mixing the MWCNTs to achieve uniform nanomaterials dispersion.

### 2.4 Stability of Nanofluids

The UV–Vis spectra of the samples were collected for 2 months to evaluate the stability of the nanofluids. The UV–Vis absorption spectra of all nanofluids dispersed with oxidized MWCNTs were the same over 2 months, indicating that the stability of the fluid had not changed. On the other hand, the absorbance of fluids containing pure MWCNTs decreased within the first 3 days after synthesis of the nanofluid, indicating agglomeration of MWCNTs leading to poor stability. Figure 3 shows the UV–Vis spectra of nanofluids containing 0.5 wt% surface-modified MWCNTs dispersed in pure DM water and DM water–ethylene glycol mixtures. The highest amount of 0.5 wt% is used to determine stability, since good stability at this percentage automatically implies the best stability at all weight percentages. In Fig. 3, a slight variation can be seen in the spectra of the nanofluids between 200 nm and 450 nm. This may be due to the changes in stability over time. However, as seen in Fig. 5, the peak absorbance, a critical indicator for determining the stability of the nanofluid does not change significantly.

Figure 4 shows the change in absorbance with wavelength for the case of nanofluids with unoxidized MWCNTs. From Fig. 4, it can be seen that the slope line for nanofluids with unoxidized CNTs is sharp, indicating a rapid decrease in the absorption of the fluid due to the precipitation of MWCNTs. The maximum absorbance of the different fluids studied for 2 months is shown in Fig. 5. Absorbance variations of nanofluids containing oxidized multi-walled carbon

| S. No | Composition                                      |
|-------|--------------------------------------------------|
| 1     | De mineralized (DM) water                        |
| 2     | Ethylene glycol—20 % + DM water—80 %             |
| 3     | Ethylene glycol—40 % + DM water—60 %             |
| 4     | Ethylene glycol—60 % + DM water—40 %             |
| 5     | Ethylene glycol—80 % + DM water—20 %             |
| 6     | Ethylene glycol—100 %                            |
nanotubes (MWCNTs) are shown in Fig. 5a. The values remain the same over the 2 months, indicating low precipitation of MWCNTs and good stability. In contrast to the nanofluids with oxidized MWCNTs, the fluids dispersed with pristine MWCNTs show precipitation leading to a sharp decrease in absorption, as shown in Fig. 5b.
2.5 Assessment of Thermal Conductivity and Dynamic Viscosity

Testing the thermal conductivity of liquids is more difficult than testing solids because heat is transferred by convection in the liquid during the measurement. With the TPS 500 model, the hot disk technique uses a transient, plane source technique that is extremely effective for estimating the thermal conductivity of liquids because it eliminates the measurement error caused by convection. The sensor is also held vertically to reduce the likelihood of air pockets causing turbulence that affects measurement accuracy. These features make this instrument particularly suitable for measuring the thermal conductivity of nanofluids. The Kapton sensor 7577 was used since its shorter measurement duration reduces the likelihood of errors due to convection.

Kapton sensor 7577 comprises polyimide (Kapton) sandwiched between two thin films to support and electrically insulate the sensor. Gradual joule heating is created by applying current progressively to the sensor of the hot disk, which is placed upright in the liquid sample under test. This causes a fluctuating temperature field in the sample and sensor. The resistance thermometer measures temperature by recording the rate at which the resistance of a metal sensor increases with time. The thermal properties of the sample are determined by studying its temperature response, using the model created for the idealized sensor with specified
geometry as a boundary condition for the heat conduction problem in the sample. 10 mL of the sample was poured into the liquid hot disk sample holder, and the sensor was placed vertically to minimize the risk of air entrapment. The sample was then carefully pumped back and forth through the sample holder chamber to ensure that all potential air bubbles exited the system. Each set of measurements goes through five iterative tests for better accuracy. The measurement duration varied as 5 s, 10 s, and 15 s, and the heating power was 20 mW in all tests. These short measurement times and low heating power minimize the development of convection when testing liquids. The average of the measurements from these trials was reported. A minimum interval of 15 min is maintained between successive observations to ensure that thermal equilibrium is reached.

Dynamic viscosity is measured with the Anton Paar MCR 302 rheometer. The instrument uses the principal changes in shear deformation of the fluid under conditions of applied torque, which are detected by an encoder and converted to dynamic viscosity using standard equations. It includes an air bearing with active temperature management, a normal force sensor, and a high-resolution optical encoder that enables rheological measurements even at the smallest torques. This air bearing ensures the experimental results with minimum deviation. The entire system is integrated with RheoCompass™ software, which enables rapid conversion to results. The current study uses a cone and plate system that requires only a small sample to generate the torque to deform the liquid under test. This system is best suited for dispersions with a particle size less than µm. First, 3 mL of the test samples is taken, of which 2 mL is added to the system and the gap between the cone and plate is fixed. The temperature of the sample was set and controlled using a Peltier system. The instrument is then allowed to run and report the value. Later, the remaining 1 mL was also added to the system and the experiment was repeated. If the deviation between two successive determinations exceeds the limits of determinability, the experiment is repeated until the deviation is within the limits.

The samples listed in Table 1 were taken, and measurements were made to determine thermal conductivity and dynamic viscosity at temperatures from 30 °C to near boiling point. Five repeatable experiments were performed at each temperature, and the average value was reported.

2.6 Estimation of Density and Specific Heat

Pak and Cho [31], in their work, have estimated the density and specific heat of nanofluids by considering the principles of conservation of mass and energy. The density can be derived by applying the principle of conservation of mass of two species from the following relation.

\[ \rho_{nf} = \varnothing \rho_{base} + (1 - \varnothing) \rho_{MWCNTs}, \]  

(1)

Similarly, the specific heat of nanofluids can be derived from Eq. 2 using the law of conservation of energy for two species.
The density and specific heat values of the present analysis are calculated using the above equations.

\[
C_{\text{Pmt}} = \frac{\phi \left( \rho C_P \right)_{\text{MWCNTs}} + (1 - \phi) \left( \rho C_P \right)_{\text{base}}}{\phi (\rho)_{\text{MWCNTs}} + (1 - \phi) (\rho)_{\text{base}}}. \tag{2}
\]

2.7 Uncertainty Analysis

The uncertainties in the measurement of the variables during the experiment must be investigated to determine the confidence level of the results obtained. The technique proposed by Beckwith et al. [32] is used to determine the uncertainties of the experimental parameters. The uncertainty in measuring dynamic viscosity with an Anton Paar viscometer depends on the input voltage, current, spindle speed, and temperature. Prasher et al. [20] point out that when measuring thermal conductivity using the hot disk technique, the uncertainty depends on several factors, such as the input power, temperature, radiation effects, thickness, and thermal mass of the insulating layer of the sensor which will result in interfacial thermal resistance. The combined effect of radiation and interfacial thermal resistance on the thermal conductivity was predicted to be 3% to 4%. The list of variables affecting thermal conductivity and dynamic viscosity and their uncertainties are given in Table 2.

The uncertainty in thermal conductivity is calculated using

\[
\frac{U_k}{k} = \sqrt{\left(\frac{U_P}{P}\right)^2 + \left(\frac{U_R}{R}\right)^2 + \left(\frac{U_T}{T}\right)^2} = \sqrt{(0.1)^2 + (3)^2 + (0.1)^2} = 3\%.
\]

\[
\frac{U_\mu}{\mu} = \sqrt{\left(\frac{U_P}{P}\right)^2 + \left(\frac{U_T}{T}\right)^2 + \left(\frac{U_N}{N}\right)^2} = \sqrt{(0.1)^2 + (0.1)^2 + (0.5)^2} = 0.5\%.
\]

| S. No | Variables                                      | Uncertainty % |
|-------|-----------------------------------------------|---------------|
| 1     | Temperature, T                                | 0.1           |
| 2     | Power, P                                       | 0.1           |
| 3     | Radiation and interfacial effects, R [20]     | 3             |
| 4     | Spindle speed of rheometer, N                 | 0.5           |
| 5     | Thermal conductivity, k                       | 3             |
| 6     | Dynamic viscosity, \(\mu\)                   | 0.5           |
3 Results and Discussion

3.1 Thermal Conductivity Enhancement

The results show that the higher the percentage of MWCNTs in the base fluid, the higher the thermal conductivity of the nanofluid, as shown in the graph in Fig. 6. Compared to equivalent base fluids, the thermal conductivity of the nanofluid increased significantly at all volume percentages of water.

Compared to all other fluids, the fluid with 80% ethylene glycol and 20% water exhibited the most significant improvement in thermal conductivity. Pure ethylene glycol, on the other hand, showed only a small increase in thermal conductivity. It is also important to note how temperature affects the improvement of thermal conductivity. At higher temperatures, the improvement in thermal conductivity profound. The highest percentage improvements are 18%, 24%, and 26% for pure ethylene glycol, ethylene glycol–water combination (80:20), and ethylene glycol–water mixture (60:40), respectively. Significant increases in thermal conductivity were also observed for other ratios. The data of thermal
Table 3  The data of thermal conductivity for different test fluids

| Temperature | Thermal conductivity, k (W·m⁻¹·K) |
|-------------|------------------------------------|
|             | Base fluid 0.0625 % MWCNTs 0.125 % MWCNTs 0.25 % MWCNTs 0.5 % MWCNTs |
| Water-based nanofluids | | |
| 30          | 0.612 0.615 0.632 0.647 0.661 |
| 35          | 0.619 0.631 0.647 0.664 0.679 |
| 40          | 0.625 0.640 0.656 0.684 0.703 |
| 45          | 0.632 0.653 0.670 0.702 0.719 |
| 50          | 0.638 0.667 0.683 0.716 0.736 |
| 55          | 0.644 0.678 0.695 0.731 0.749 |
| 60          | 0.649 0.691 0.709 0.745 0.763 |
| 65          | 0.654 0.703 0.721 0.757 0.775 |
| 70          | 0.659 0.715 0.733 0.770 0.788 |
| 75          | 0.663 0.729 0.747 0.784 0.803 |
| 80          | 0.667 0.742 0.761 0.798 0.818 |
| 85          | 0.671 0.751 0.771 0.809 0.829 |
| Ethylene glycol–water (20:80)-based nanofluids | | |
| 30          | 0.524 0.531 0.545 0.559 0.574 |
| 35          | 0.528 0.541 0.555 0.571 0.586 |
| 40          | 0.532 0.547 0.561 0.577 0.592 |
| 45          | 0.535 0.556 0.570 0.586 0.599 |
| 50          | 0.538 0.564 0.579 0.596 0.604 |
| 55          | 0.541 0.573 0.589 0.606 0.615 |
| 60          | 0.543 0.582 0.598 0.616 0.624 |
| 65          | 0.546 0.590 0.605 0.623 0.632 |
| 70          | 0.548 0.598 0.614 0.632 0.641 |
| 75          | 0.550 0.608 0.623 0.643 0.652 |
| 80          | 0.552 0.618 0.633 0.653 0.662 |
| 85          | 0.553 0.625 0.640 0.660 0.669 |
| 90          | 0.554 0.633 0.649 0.670 0.678 |
| Ethylene glycol–water (40:60)-based nanofluids | | |
| 30          | 0.445 0.449 0.461 0.483 0.493 |
| 35          | 0.446 0.457 0.469 0.491 0.501 |
| 40          | 0.447 0.462 0.474 0.498 0.506 |
| 45          | 0.448 0.465 0.478 0.502 0.510 |
| 50          | 0.450 0.470 0.483 0.507 0.516 |
| 55          | 0.452 0.476 0.487 0.513 0.522 |
| 60          | 0.453 0.482 0.494 0.519 0.528 |
| 65          | 0.454 0.487 0.499 0.524 0.533 |
| 70          | 0.456 0.491 0.502 0.528 0.540 |
| 75          | 0.458 0.496 0.508 0.534 0.547 |
| 80          | 0.461 0.502 0.514 0.540 0.554 |
| 85          | 0.463 0.508 0.520 0.547 0.559 |
Table 3 (continued)

| Temperature | Thermal conductivity, k (W·m⁻¹·K) |
|-------------|-----------------------------------|
|             | Base fluid | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
| 90          | 0.464      | 0.512           | 0.524           | 0.551           | 0.564         |
| 95          | 0.467      | 0.516           | 0.530           | 0.556           | 0.568         |

Ethylene glycol–water (60:40)-based nanofluids

| Temperature | Base fluid | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
|-------------|------------|-----------------|----------------|---------------|---------------|
| 30          | 0.377      | 0.390           | 0.400           | 0.410           | 0.416         |
| 35          | 0.376      | 0.392           | 0.402           | 0.412           | 0.420         |
| 40          | 0.375      | 0.394           | 0.404           | 0.414           | 0.422         |
| 45          | 0.374      | 0.397           | 0.406           | 0.416           | 0.424         |
| 50          | 0.372      | 0.399           | 0.409           | 0.420           | 0.427         |
| 55          | 0.371      | 0.402           | 0.412           | 0.423           | 0.430         |
| 60          | 0.370      | 0.404           | 0.414           | 0.425           | 0.432         |
| 65          | 0.369      | 0.405           | 0.416           | 0.427           | 0.434         |
| 70          | 0.366      | 0.408           | 0.418           | 0.429           | 0.436         |
| 75          | 0.365      | 0.411           | 0.421           | 0.432           | 0.439         |
| 80          | 0.363      | 0.415           | 0.425           | 0.435           | 0.443         |
| 85          | 0.361      | 0.417           | 0.426           | 0.437           | 0.444         |
| 90          | 0.359      | 0.417           | 0.428           | 0.439           | 0.446         |
| 95          | 0.358      | 0.419           | 0.429           | 0.442           | 0.448         |

Ethylene glycol–water (80:20)-based nanofluids

| Temperature | Base fluid | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
|-------------|------------|-----------------|----------------|---------------|---------------|
| 30          | 0.322      | 0.326           | 0.335           | 0.340           | 0.345         |
| 35          | 0.319      | 0.328           | 0.336           | 0.341           | 0.347         |
| 40          | 0.317      | 0.329           | 0.337           | 0.343           | 0.348         |
| 45          | 0.314      | 0.331           | 0.338           | 0.343           | 0.348         |
| 50          | 0.312      | 0.332           | 0.338           | 0.343           | 0.348         |
| 55          | 0.308      | 0.333           | 0.339           | 0.343           | 0.348         |
| 60          | 0.306      | 0.333           | 0.339           | 0.344           | 0.349         |
| 65          | 0.304      | 0.333           | 0.340           | 0.345           | 0.351         |
| 70          | 0.300      | 0.333           | 0.342           | 0.347           | 0.352         |
| 75          | 0.298      | 0.333           | 0.341           | 0.346           | 0.352         |
| 80          | 0.296      | 0.330           | 0.339           | 0.346           | 0.351         |
| 85          | 0.292      | 0.327           | 0.336           | 0.343           | 0.350         |
| 90          | 0.288      | 0.324           | 0.333           | 0.340           | 0.347         |
| 95          | 0.286      | 0.320           | 0.330           | 0.337           | 0.344         |
| 100         | 0.283      | 0.317           | 0.327           | 0.334           | 0.341         |
| 105         | 0.280      | 0.314           | 0.324           | 0.331           | 0.338         |

Ethylene glycol (100 %)-based nanofluids

| Temperature | Base fluid | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
|-------------|------------|-----------------|----------------|---------------|---------------|
| 30          | 0.276      | 0.283           | 0.287           | 0.290           | 0.293         |
| 35          | 0.272      | 0.283           | 0.287           | 0.291           | 0.293         |
| 40          | 0.269      | 0.283           | 0.287           | 0.290           | 0.293         |
| 45          | 0.265      | 0.283           | 0.288           | 0.291           | 0.294         |
| 50          | 0.262      | 0.283           | 0.287           | 0.290           | 0.293         |
conductivity for different test fluids with respect to normalized temperature are given in Table 3.

### Table 3 (continued)

| Temperature | Thermal conductivity, k (W·m⁻¹·K) |
|-------------|-----------------------------------|
|             | Base fluid | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
| 55          | 0.258      | 0.282           | 0.287           | 0.290           | 0.292         |
| 60          | 0.253      | 0.281           | 0.285           | 0.289           | 0.291         |
| 65          | 0.250      | 0.280           | 0.283           | 0.286           | 0.289         |
| 70          | 0.246      | 0.277           | 0.282           | 0.285           | 0.287         |
| 75          | 0.243      | 0.277           | 0.281           | 0.284           | 0.287         |
| 80          | 0.238      | 0.275           | 0.279           | 0.282           | 0.285         |
| 85          | 0.234      | 0.273           | 0.276           | 0.280           | 0.282         |
| 90          | 0.231      | 0.271           | 0.275           | 0.278           | 0.281         |
| 95          | 0.228      | 0.269           | 0.273           | 0.276           | 0.279         |
| 100         | 0.223      | 0.265           | 0.269           | 0.272           | 0.275         |
| 105         | 0.218      | 0.261           | 0.265           | 0.268           | 0.271         |
| 110         | 0.212      | 0.257           | 0.261           | 0.263           | 0.266         |
| 120         | 0.210      | 0.254           | 0.259           | 0.260           | 0.263         |
| 125         | 0.207      | 0.252           | 0.256           | 0.259           | 0.262         |
| 130         | 0.202      | 0.247           | 0.251           | 0.254           | 0.257         |
| 140         | 0.197      | 0.244           | 0.247           | 0.250           | 0.253         |
| 150         | 0.192      | 0.239           | 0.240           | 0.246           | 0.248         |
| 155         | 0.186      | 0.234           | 0.234           | 0.240           | 0.242         |
| 160         | 0.180      | 0.225           | 0.229           | 0.233           | 0.235         |
| 165         | 0.174      | 0.220           | 0.223           | 0.225           | 0.227         |
| 170         | 0.171      | 0.217           | 0.221           | 0.223           | 0.225         |
| 175         | 0.170      | 0.215           | 0.217           | 0.221           | 0.223         |

### 3.2 Variation of Dynamic Viscosity

Figure 7 shows the temperature dependence of dynamic viscosity of different nanofluids with different weight percents of MWCNTs.

Figure 7 depicts the variation of dynamic viscosity of water and ethylene glycol–water mixtures (20:80, 40:60, 60:20, 80:20) and 100 % ethylene glycol at temperatures between 30 °C and 180 °C. The difference in the maximum temperature is explained by the lowering of the boiling point due to the admixture of water. The obvious increase in dynamic viscosity with MWCNT dispersion is a standard feature of nanofluids. When compared to base fluids, the dynamic viscosity of nanofluids is found to be significantly higher at lower temperatures. Several studies have demonstrated that at higher temperatures, the effect of temperature on the viscosity...
of nanofluids containing MWCNTs is minimal. The data of dynamic viscosity for different test fluids with respect to normalized temperature are given in Table 4.

3.3 Correlation to Forecast Thermal Conductivity and Dynamic Viscosity

In the literature, several researchers discuss the improvement of thermal conductivity. However, the experimental data show enormous discrepancies. Therefore, a proper mathematical model is needed to predict the thermal conductivity and dynamic viscosity of nanofluids. The experimental data on thermal conductivity and dynamic viscosity are analyzed separately to generate regression equations to evaluate the properties. In the current study, the statistical tool Minitab is used to construct the non-linear mathematical model. The predictor variables are thermal conductivity and dynamic viscosity. The response variables are temperature, ethylene glycol content, and MWCNT concentration. Since the regression modeling is an iterative process, several iterations are performed, and finally, a non-linear regression model that can predict the data with the least error is selected. Since thermal
Table 4  The data of dynamic viscosity for different test fluids

| Temperature | Dynamic viscosity, \( \mu \) (cP) | Pure water | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
|-------------|-----------------------------------|------------|----------------|----------------|----------------|----------------|
| Water-based nanofluids |
| 30          | 0.654                             | 0.717      | 0.799          | 0.858          | 0.937          |
| 35          | 0.577                             | 0.630      | 0.713          | 0.759          | 0.832          |
| 40          | 0.518                             | 0.583      | 0.637          | 0.693          | 0.751          |
| 45          | 0.462                             | 0.515      | 0.575          | 0.625          | 0.684          |
| 50          | 0.416                             | 0.465      | 0.519          | 0.567          | 0.624          |
| 55          | 0.350                             | 0.419      | 0.480          | 0.508          | 0.561          |
| 60          | 0.314                             | 0.375      | 0.427          | 0.471          | 0.524          |
| 65          | 0.294                             | 0.347      | 0.403          | 0.443          | 0.483          |
| 70          | 0.287                             | 0.320      | 0.365          | 0.402          | 0.445          |
| 75          | 0.284                             | 0.306      | 0.335          | 0.364          | 0.405          |
| 80          | 0.270                             | 0.297      | 0.314          | 0.341          | 0.376          |
| 85          | 0.265                             | 0.291      | 0.309          | 0.332          | 0.341          |
| 90          | 0.262                             | 0.285      | 0.302          | 0.317          | 0.315          |
| Ethylene glycol–water (20:80)-based nanofluids |
| 30          | 0.847                             | 0.943      | 1.047          | 1.124          | 1.312          |
| 35          | 0.785                             | 0.856      | 0.934          | 1.014          | 1.131          |
| 40          | 0.723                             | 0.810      | 0.890          | 0.970          | 1.064          |
| 45          | 0.655                             | 0.752      | 0.835          | 0.934          | 0.991          |
| 50          | 0.611                             | 0.692      | 0.780          | 0.889          | 0.928          |
| 55          | 0.571                             | 0.632      | 0.717          | 0.814          | 0.855          |
| 60          | 0.526                             | 0.574      | 0.648          | 0.743          | 0.813          |
| 65          | 0.489                             | 0.547      | 0.609          | 0.674          | 0.728          |
| 70          | 0.437                             | 0.513      | 0.573          | 0.619          | 0.676          |
| 75          | 0.410                             | 0.491      | 0.516          | 0.571          | 0.617          |
| 80          | 0.403                             | 0.462      | 0.492          | 0.517          | 0.562          |
| 85          | 0.358                             | 0.434      | 0.450          | 0.451          | 0.494          |
| 90          | 0.339                             | 0.393      | 0.384          | 0.391          | 0.434          |
| Ethylene glycol—water (40:60)-based nanofluids |
| 30          | 1.887                             | 1.985      | 2.136          | 2.259          | 2.530          |
| 35          | 1.619                             | 1.676      | 1.777          | 1.980          | 2.093          |
| 40          | 1.321                             | 1.430      | 1.521          | 1.719          | 1.825          |
| 45          | 1.080                             | 1.198      | 1.316          | 1.519          | 1.648          |
| 50          | 0.945                             | 1.082      | 1.194          | 1.344          | 1.476          |
|                    | Ethylene glycol—water (40:60) | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
|--------------------|-------------------------------|----------------|----------------|----------------|----------------|
|                    |                               |                |                |                |                |
| 55                 | 0.887                    | 1.007          | 1.092          | 1.203          | 1.343          |
| 60                 | 0.790                    | 0.919          | 1.027          | 1.106          | 1.197          |
| 65                 | 0.692                    | 0.786          | 0.927          | 0.995          | 1.087          |
| 70                 | 0.624                    | 0.706          | 0.833          | 0.785          | 0.997          |
| 75                 | 0.593                    | 0.676          | 0.775          | 0.715          | 0.887          |
| 80                 | 0.530                    | 0.633          | 0.605          | 0.694          | 0.721          |
| 85                 | 0.496                    | 0.518          | 0.557          | 0.627          | 0.687          |
| 90                 | 0.458                    | 0.492          | 0.518          | 0.587          | 0.602          |
| 95                 | 0.437                    | 0.485          | 0.497          | 0.502          | 0.552          |

|                    | Ethylene glycol—water (60:40) | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
|--------------------|-------------------------------|----------------|----------------|----------------|----------------|
|                    |                               |                |                |                |                |
| Ethylene glycol—water (60:40)-based nanofluids |
| 30                 | 2.839                    | 3.263          | 3.539          | 3.640          | 3.937          |
| 35                 | 2.264                    | 2.338          | 2.965          | 3.060          | 3.338          |
| 40                 | 1.855                    | 2.064          | 2.386          | 2.609          | 2.876          |
| 45                 | 1.602                    | 1.751          | 2.062          | 2.236          | 2.526          |
| 50                 | 1.342                    | 1.477          | 1.748          | 1.996          | 2.258          |
| 55                 | 1.104                    | 1.277          | 1.431          | 1.681          | 2.043          |
| 60                 | 0.958                    | 1.143          | 1.246          | 1.480          | 1.869          |
| 65                 | 0.884                    | 1.060          | 1.166          | 1.405          | 1.707          |
| 70                 | 0.825                    | 0.996          | 1.090          | 1.309          | 1.524          |
| 75                 | 0.797                    | 0.964          | 1.026          | 1.241          | 1.376          |
| 80                 | 0.722                    | 0.917          | 0.998          | 1.195          | 1.304          |
| 85                 | 0.673                    | 0.817          | 0.963          | 1.151          | 1.240          |
| 90                 | 0.628                    | 0.788          | 0.932          | 1.070          | 1.194          |
| 95                 | 0.581                    | 0.720          | 0.841          | 0.958          | 1.017          |

|                    | Ethylene glycol—water (80:20) | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
|--------------------|-------------------------------|----------------|----------------|----------------|----------------|
|                    |                               |                |                |                |                |
| Ethylene glycol—water (80:20)-based nanofluids |
| 30                 | 7.436                    | 7.4357         | 7.931          | 8.306          | 8.998          |
| 35                 | 6.391                    | 6.3907         | 6.808          | 7.131          | 7.725          |
| 40                 | 5.460                    | 5.4603         | 5.811          | 6.086          | 6.593          |
| 45                 | 4.626                    | 4.6261         | 4.918          | 5.151          | 5.580          |
| 50                 | 3.912                    | 4.039          | 4.422          | 4.722          | 4.966          |
| 55                 | 3.492                    | 3.672          | 4.187          | 4.368          | 4.638          |
| 60                 | 2.716                    | 3.056          | 3.299          | 3.524          | 3.758          |
| 65                 | 2.340                    | 2.681          | 2.867          | 3.257          | 3.477          |
| 70                 | 2.134                    | 2.346          | 2.555          | 2.929          | 3.138          |
### Table 4 (continued)

| Ethylene glycol–water (80:20) | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
|-------------------------------|------------------|-----------------|---------------|--------------|
| 75                            | 1.664            | 1.776           | 1.997         | 2.284        | 2.526        |
| 80                            | 1.487            | 1.656           | 1.753         | 2.046        | 2.261        |
| 85                            | 1.359            | 1.567           | 1.667         | 1.883        | 2.080        |
| 90                            | 1.262            | 1.459           | 1.552         | 1.805        | 1.969        |
| 95                            | 1.142            | 1.297           | 1.430         | 1.656        | 1.762        |
| 100                           | 1.107            | 1.206           | 1.336         | 1.511        | 1.632        |
| 105                           | 1.051            | 1.165           | 1.288         | 1.403        | 1.552        |
| 110                           | 0.965            | 1.116           | 1.144         | 1.246        | 1.378        |
| 115                           | 0.933            | 1.049           | 1.097         | 1.104        | 1.280        |
| 120                           | 0.904            | 0.993           | 1.038         | 1.056        | 1.169        |

| Ethylene glycol (100 %)-based nanofluids | 0.0625 % MWCNTs | 0.125 % MWCNTs | 0.25 % MWCNTs | 0.5 % MWCNTs |
|------------------------------------------|-----------------|-----------------|---------------|--------------|
| 30                                       | 10.137          | 10.410          | 10.675        | 11.180       | 12.151       |
| 35                                       | 9.117           | 9.363           | 9.601         | 10.055       | 10.933       |
| 40                                       | 8.169           | 8.390           | 8.603         | 9.010        | 9.800        |
| 45                                       | 7.277           | 7.473           | 7.866         | 8.957        | 9.733        |
| 50                                       | 6.885           | 7.315           | 7.746         | 8.908        | 9.621        |
| 55                                       | 5.801           | 6.163           | 6.526         | 7.505        | 8.105        |
| 60                                       | 5.129           | 5.449           | 5.771         | 6.636        | 7.167        |
| 65                                       | 4.327           | 4.597           | 4.868         | 5.598        | 6.046        |
| 70                                       | 3.812           | 4.050           | 4.288         | 4.932        | 5.326        |
| 75                                       | 3.364           | 3.574           | 3.785         | 4.353        | 4.701        |
| 80                                       | 2.986           | 3.172           | 3.359         | 3.863        | 4.172        |
| 85                                       | 2.680           | 2.847           | 3.015         | 3.467        | 3.745        |
| 90                                       | 2.462           | 2.616           | 2.770         | 3.186        | 3.441        |
| 95                                       | 2.184           | 2.320           | 2.457         | 2.825        | 3.051        |
| 100                                      | 1.965           | 2.088           | 2.211         | 2.543        | 2.746        |
| 105                                      | 1.744           | 1.853           | 1.963         | 2.257        | 2.438        |
| 110                                      | 1.644           | 1.746           | 1.850         | 2.127        | 2.297        |
| 115                                      | 1.547           | 1.643           | 1.740         | 2.001        | 2.161        |
| 120                                      | 1.399           | 1.486           | 1.574         | 1.810        | 1.955        |
| 125                                      | 1.301           | 1.382           | 1.464         | 1.683        | 1.818        |
| 130                                      | 1.225           | 1.301           | 1.378         | 1.585        | 1.712        |
| 135                                      | 1.134           | 1.205           | 1.276         | 1.467        | 1.585        |
| 140                                      | 1.053           | 1.119           | 1.185         | 1.363        | 1.472        |
| 145                                      | 1.010           | 1.073           | 1.137         | 1.307        | 1.412        |
| 150                                      | 0.950           | 1.009           | 1.069         | 1.229        | 1.328        |
| 155                                      | 0.891           | 0.947           | 1.003         | 1.153        | 1.246        |
| 160                                      | 0.842           | 0.895           | 0.948         | 1.090        | 1.177        |
conductivity, dynamic viscosity, and temperature are variables with units, they are normalized as $k_{nf}/k_b, \mu_{nf}/\mu_b,$ and $\left(1 + \frac{T}{T_{max}}\right)$ to reduce the bias. Originally, the non-linear model resulted in a very high prediction error. Therefore, all variables are logarithmically transformed and a linear model is fitted. This linear model is later transformed into a non-linear model in the form of equations shown below.

$$\frac{k_{nf}}{k_b} = 0.978 \left[ \left(1 + \frac{T}{T_{max}}\right)^{0.108} (1 + \phi)^{0.27} (1 + \alpha)^{0.013} \right], \quad (3)$$

$$\frac{\mu_{nf}}{\mu_b} = 1.065 \left[ \left(1 + \frac{T}{T_{max}}\right)^{-0.03} (1 + \phi)^{0.4388} (1 + \alpha)^{-0.072} \right], \quad (4)$$

The validation of Eqs. 3 and 4 is shown in Fig. 8. The equations predict the dynamic viscosity and thermal conductivity of ethylene glycol–water-based fluids with ethylene glycol volume percentages from 0 % to 100 % in the temperature range of 50 to 190 °C and MWCNT weight percentages from 0.0625 wt% to 0.5 wt%. The proposed Eq. 3 has an overall average deviation of 3.8 % and a standard deviation of 4.3 %. The data were fitted by Eq. 4 with an average deviation of 2.8 % and a standard deviation of 3.3 %. Furthermore, both equations are close to the experimental data with a maximum deviation of ± 10 %.

### 3.4 Mouromtseff Number for Indirect Evaluation of Heat Transfer Performance

The Mouromtseff number (Mo) can be used as a "performance index" to compare the heat transfer performance of different fluids. For a given shape and velocity, the convective heat transfer coefficient ‘h’ can be expressed as proportional to the Mouromtseff number (Mo). Simons [22] was the first to use the Mouromtseff number to demonstrate the usefulness of various liquid coolants for cooling electronic devices. The Mouromtseff number of nanofluids accounts for the improvement in thermal conductivity and the increase in viscosity with the dispersion of nanomaterials. While the improvement in thermal conductivity is a good sign, an increase in viscosity would lead to increased pumping power in heat transfer processes.
The Mouromtseff number for the case of a fully developed internal flow is given by the equation

$$Mo = \frac{k \rho c_p}{\mu}.$$

The significance of the Mouromtseff number lies in the condition that for a given flow through a given geometry at a given velocity, the higher the Mouromtseff number (Mo), the greater the capacity of the fluid to carry heat. The values of a, b, c, and d are suitable for a given heat transfer mode with a known heat transfer correlation. Since the Nusselt number is a constant at both constant wall temperature and constant heat flux, Vajjha and Das [25] suggest that the following equation applies to a fully developed internal laminar flow.

$$\frac{Mo_{nf}}{Mo_{base}} = \frac{h_{nf}}{h_{base}} = \frac{k_{nf}}{k_{base}}.$$

For the case of turbulent flow inside a tube, they proposed that

$$\frac{Mo_{nf}}{Mo_{base}} \approx \frac{h_{nf}}{h_{base}} \text{ and } Mo_{nf} \propto h_{nf} = \frac{k^{0.5} \rho^{0.5} c_p^{0.5}}{\mu^{0.3}}.$$
Further, they proposed the following expression for the Mouromtseff number for turbulent flow

\[
Mo_{\text{base}} \propto h_{\text{base}} = \frac{k^{0.6} \rho^{0.8} \epsilon^{0.4}}{\mu^{0.4}}.
\]  

Using the method proposed by Vajjha and Das [25], the ratio of \( \frac{Mo_{\text{nf}}}{Mo_{\text{base}}} \) for laminar and turbulent flow conditions can be calculated, and the effect of mixing MWCNTs in ethylene glycol–water mixtures on heat transfer performance can be determined. It can be assumed that the ratio \( \frac{Mo_{\text{nf}}}{Mo_{\text{base}}} \) indicates the relative heat transfer performance of the nanofluid. Figure 9 shows the relative heat transfer rate \( \frac{Mo_{\text{nf}}}{Mo_{\text{base}}} \) varying with temperature for different types of nanofluids in both laminar and turbulent flow. For the base fluid, the ratio \( \frac{Mo_{\text{nf}}}{Mo_{\text{base}}} \) is taken as unity. For the nanofluids, the relative heat transfer rate \( \frac{Mo_{\text{nf}}}{Mo_{\text{base}}} \) remains greater than 1, which means that the performance of the nanofluids under laminar conditions is more remarkable than that of the base fluid compared to turbulent conditions.

The plots in Fig. 9 show that the effect of temperature on relative heat transfer is significant under laminar flow conditions. As the temperature increases, the relative heat transfer rate increases, indicating that nanofluids are very effective at higher

![Figure 9](image-url)
compared to lower temperatures. It is also observed that for fluids containing 0.125, 0.25, and 0.5 wt% MWCNTs, the relative heat transfer does not increase as much, indicating an optimum weight percentage above which the heat transfer does not increase significantly.

In the case of turbulent flow, it is observed that an optimum concentration of 0.1 % MWCNTs gives the best results for water and ethylene glycol–water mixtures (20–80); above this, heat transfer decreases. Increasing the volume percentage of ethylene glycol increases the viscosity of the fluid, so a lower weight percentage is required, and the best results are obtained at 0.125 wt%. It appears that for turbulent flow, only dilute nanofluids with low concentration can provide the best results in terms of heat transfer performance. This pattern is observed for all nanofluid types studied. The explanation for the lower performance is that inertial effects dominate the Brownian motion of the nanofluids in a turbulent regime. Therefore, the improvement in heat transfer is insignificant at higher weight percentages.

4 Conclusions

The conclusions from the results are as follows.

1. Stability analysis using UV–Vis spectroscopy shows that nanofluids dispersed with pure MWCNTS exhibit poor stability characterized by a sharp decrease in absorbance. However, for nanofluids dispersed with oxidized MWCNTs, the change in absorbance is minimal, indicating excellent stability.
2. Thermal conductivity increased by 10 % to 25 % in water and all ethylene glycol–water ratios when oxidized MWCNTs were dispersed in solution. Nanofluids have a higher viscosity between 50 °C and 70 °C. In comparison, the viscosity rise at higher temperatures is insignificant.
3. A simplified correlation in terms of weight percent, temperature, and ethylene glycol content is proposed to predict the thermal conductivity and viscosity, which works for all possible combinations of ethylene glycol–water mixtures.
4. An indirect evaluation of the relative heat transfer rate using the Mouromtseff (Mo) number was performed. The analysis shows that in both laminar and turbulent regimes, there is an optimal weight percentage of MWCNTs up to which significant heat transfer enhancement occurs.
5. Beyond this optimal weight percentage, deterioration of heat transfer was observed. This deterioration in heat transfer can be attributed to the dominance of inertial effects under turbulent flow conditions.

Acknowledgements The authors gratefully acknowledge the support received from Hindustan Petroleum Corporation Ltd., Corporate R&D for conducting the tests. The authors acknowledge the assistance from the central university, Hyderabad, in characterization.

Author Contributions AD and VS have conceptualized the research, investigated, curated the data, and prepared the manuscript. AKJ has done the data validation and reviewed the manuscript. MSB reviewed the manuscript. SBT has collected resources and validated the data.
Funding The authors received no funding from any sources.

Data Availability The data and relevant material are stored in Mendeley database.

Declarations

Conflict of interest The authors declare no potential competing interest with respect to the research, authorship, and/or publication of this article.

References

1. A.R.I. Ali, B. Salam, SN Appl. Sci. 2, 1636 (2020). https://doi.org/10.1007/s42452-020-03427-1
2. A.R. Alizadeh Jajarm, H.R. Goshayeshi, K. Bashirinezhad, Nanoscale Microscale Thermophys. Eng. 26(2–3) 95–111 (2022). https://doi.org/10.1080/15567265.2022.2072790
3. M.J. Assael, W.A. Wakeham, Int. J. Thermophys. (2019). https://doi.org/10.1007/s10765-019-2520-6
4. M.J. Assael, I.N. Metaxa, D. Christofilos, C. Lioutas, Int. J. Thermophys. 26, 647–664 (2005)
5. D. Wen, Y. Ding, Int. J. Heat Mass Transf. 47, 24 (2004)
6. Y. Ding, H. Alias, D. Wen, R.A. Williams, Int. J. Heat Mass Transf. 49, 240–250 (2006)
7. F. Aviles, J.V. Cauich, L. Moo-Tah, A. May-Pat, R. Vargos-Coronado, Carbon (2009). https://doi.org/10.1016/j.carbon.2009.06.044
8. G.K. Poongavanam, V. Ramalingam, Int. J. Therm. Sci. 136, 15 (2019). https://doi.org/10.1016/j.ijthermalsci.2018.10.007
9. M. Hemmat Esfe, Arab. J. Sci. Eng. 46, 5957 (2021). https://doi.org/10.1007/s13369-020-05091-4
10. M. Hemmat Esfe, S. Saedodin, O. Mahian, S. Wongwises, Int. Commun. Heat Mass Transf. 58, 138–146 (2014)
11. I.D. Rosca, F. Watari, M. Uo, T. Akasaka, Carbon (2005). https://doi.org/10.1016/j.carbon.2005.06.019
12. H. Khani, O. Moradi, J. Nanostruct. Chem. (2013). https://doi.org/10.1186/2193-8865-3-73
13. G.A. Longo, C. Zilio, Int. J. Thermophys. (2013). https://doi.org/10.1007/s10765-013-1478-z
14. L. Godson, M. Mohan-Lal, S. Wongwises, J. Nanoscale Microscale Thermophys. Eng. (2010). https://doi.org/10.1080/15567265.2010.500319
15. L. Vaisman, H.D. Wagner, G. Marom, Adv. Colloid Interface Sci. (2006). https://doi.org/10.1016/j.cis.2006.11.007
16. S. Mukherjee, S.R. Panda, P.C. Mishra, Int. J. Thermophys. 41, 162 (2020). https://doi.org/10.1007/s10765-020-02745-1
17. M. Baratpour, A. Karimpour, M. Afraand, S. Wongwises, Int. Commun. Heat Mass Transf. 74, 108–113 (2016). https://doi.org/10.1016/j.icheatmasstransfer.2016.02.008
18. P. Ganesh Kumar, D. Sakhthivadivel, M. Meikandand, V.S. Vigneswaran, R. Velraj, Heliyon (2019). https://doi.org/10.1016/j.heliyon.2019.e02385
19. P. Kanti, K.V. Sharma, K.M. Yashawanth, M. Jamei, Z. Said, Sol. Energy Mater Sol. Cells 234, 111423 (2022). https://doi.org/10.1016/j.solmat.2021.111423
20. Q. Zheng, S. Kaur, C. Damas, R.S. Prasher, Int. J. Heat Mass Transf. 151, 119331 (2020). https://doi.org/10.1016/j.ijheatmasstransfer.2020.119331
21. Q. He, S. Zeng, S. Wang, Appl. Therm. Eng. 88, 165–171 (2015). https://doi.org/10.1016/j.applthermaleng.2014.09.053
22. Q.H. Yang, P.X. Hou, S. Bai, C. Liu, H.M. Cheng, Carbon (2002). https://doi.org/10.1016/S0008-6223(01)00075-6
23. R.E. Simons, Electron. Cool. 12, 10 (2006)
24. R. Agarwal, K. Verma, N. Agrawal, R. Singh, Exp. Therm. Fluid Sci. (2016). https://doi.org/10.1016/j.expthermflusci.2016.08.007
25. R.S. Vajjha, D.K. Das, Int. J. Heat Mass Transf. (2012). https://doi.org/10.1016/j.ijheatmasstransfer.2012.03.048
26. S. Halelfadl, T. Maré, P. Estellé, Exp. Therm. Fluid Sci (2014). https://doi.org/10.1016/j.expthermfusci.2013.11.010
27. I. Wole-oso, E.C. Okonkwo, S. Abbasoglu, Int. J. Thermophys. 41, 157 (2020). https://doi.org/10.1007/s10765-020-02737-1
28. X. Zhang, H. Gu, M. Fujii, Int. J. Thermophys. (2006). https://doi.org/10.1007/s10765-006-0054-1
29. Y. Yang, Z.G. Zhang, E.A. Grulke, W.B. Anderson, Int. J. Heat Mass Transf. (2005). https://doi.org/10.1016/j.ijheatmasstransfer.2004.09.038
30. H. Zhang, H.M. Cheng, H.X. Li, J. Phys. Chem. B (2006). https://doi.org/10.1021/jp060193y
31. B. Pak, Y. Cho., Exp. Heat Transf. II(2)151–170 (1998). https://doi.org/10.1080/089161598089465
32. T.G. Beckwith, R.D. Marangoni, J.H. Lienhard (1990), in Mechanical Measurements (5th edn.). (New York, Addison-Wesley Publishing company)

Publisher's Note  Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

Authors and Affiliations

Abhishek Dosodia¹ · Srinivas Vadapalli² · Amitabh Kumar Jain³ · Saratchandra Babu Mukkamala⁴ · Bhanu Teja Sanduru⁵

¹ Quality Control, Hindustan Petroleum Corporation Ltd., Visakhapatnam, India
² Department of Mechanical Engineering, GITAM (Deemed to Be University), Visakhapatnam, India
³ Product Development and OEM Business, Hindustan Petroleum Corporation Ltd., Mumbai, India
⁴ Department of Chemistry, GITAM (Deemed to Be University), Visakhapatnam, India
⁵ GLWEC College of Engineering, Hyderabad, India