# Influences of Temperature, Concentration and Shear Rate on Rheological Behavior of Nanofluid: An Experimental Study with $Al_2O_3$-MWCNT/10W40 Hybrid Nano-Lubricant

***Hemmat Esfe, Mohammad****+

*Department of mechanical Engineering, Imam Hossein University, Tehran, I.R. IRAN*

***Rostamian, Hadi***

*Department of chemical Engineering, Semnan University, Semnan, I.R. IRAN*

**ABSTRACT:** *In this experimental study, the rheological behavior of $Al_2O_3$-MWCNT (90%:10%)/10W40 hybrid nano-lubricant has been determined at the temperature range of 5°C to 55°C. $Al_2O_3$ nanoparticles (average size of 50 nm) and MWCNTs (inner and outer diameter of 2-6 nm and 5-20 nm, respectively) were dispersed in engine oil (10W40) to prepare 0.05%, 0.1%, 0.25%, 0.5%, 0.75% and 1% solid volume fractions. For each sample, dynamic viscosity was measured at shear rates ranging from 666.5 $s^{-1}$ to 13330 s-1 with an uncertainty of about 0.6%. The findings insinuated that at the most range of temperature and solid volume fraction the nano-lubricant, as well as the base oil, are non-Newtonian fluids. Thus, by curve fitting the indexes of power law and consistency were calculated. Eventually, the correlations indicated a very well compromise with experimental data.*

**KEYWORDS:** *Hybrid nano-lubricant; $Al_2O_3$-MWCNT; Dynamic viscosity; Rheological behavior; New correlation.*

## INTRODUCTION

Increasing heat transfer efficiency is one of the interesting issues that is considered by engineers, recently. However, several empirical studies were performed to survey thermo-physical characteristics of nanofluids and nano- lubricants. Also, most of the researches had tested the effects of temperature, concentration and nanoparticle size on thermal conductivity and dynamic viscosity. According to the studies, thermal conductivity can augment by enhancing concentration and temperature and using smaller nanoparticles [1-8]. On the other extreme, dynamic viscosity increased by enhancing concentration and nanoparticle diameter and decreasing temperature [9-10]. Beside the experimental studies, the results were extracted by artificial intelligence, whether thermal

* To whom correspondence should be addressed.
+ E-mail: mhemmatesfe@ihu.ac.ir
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conductivity [6, 11-15] or dynamic viscosity [16-18]. Fluids such as nanofluids have various states which can affect their applications such as engineering of materials science, physiology, and geophysics. Employing rheological behavior is a way to determine the states, therefore the rheological behavior evaluation is important. Several types of research have been performed to investigate the rheological behavior of different nanofluids [19-27]. *Gallego et al.* [26] investigated behavior of $Fe_2O_3$/EG nanofluid. The results indicated that the nanofluid is a non-Newtonian fluid with shear thinning behavior. *Abareshi et al.* [27] showed that α-$Fe_2O_3$/glycerol with diameter size of 26 nm has shear thinning behavior. At high concentration of $Fe_3O_4$/deionized water nanofluid with diameter size about 10 nm is a non-Newtonian, while it is a Newtonian fluid at low concentration. Some other studies are listed in Table 1.

The effects due to different rheological behaviors on nanofluid applications is an obvious point in heat transfer. Literature survey discloses that the rheological behavior of $Al_2O_3$-MWCNT (90%-10%)/10W40 hybrid nano-lubricant has not been taken into account by any experimental or modeling work. Therefore, in this study, the dynamic viscosity of the hybrid nano-lubricant was measured through varying temperatures and solid volume fractions and a new correlation was suggested to predict the dynamic viscosity data.

## EXPERIMENTAL SECTION

### *Nanoparticles*

In these experiments, engine oil (10W40) is chosen as the base fluid, $Al_2O_3$ nanoparticle and Multi-Walled Carbon NanoTube (MWCNT) are consumed to prepare $Al_2O_3$-MWCNT/10W40 hybrid nano-lubricant. The specifications of 10W40, $Al_2O_3$ and MWCNT are reported in Tables 2 and 3, respectively.

### *Preparing nanofluid*

By Eq. (1), the needed weights of $Al_2O_3$ nanoparticle and MWCNTs with proportional of 90% $Al_2O_3$ to 10% MWCNTs were calculated. 1%, 0.75%, 0.5%,0.25%, 0.1% and 0.05% solid volume fraction of the particles were measured.

$$\varphi\% = \frac{\left(\frac{w}{\rho}\right)_{MWCNT} + \left(\frac{w}{\rho}\right)_{Al_2O_3}}{\left(\frac{w}{\rho}\right)_{MWCNT} + \left(\frac{w}{\rho}\right)_{Al_2O_3} + \left(\frac{w}{\rho}\right)_{10W40}} \quad (1)$$

Where the density is defined by ρ, φ is nano-lubricant solid volume fraction and w is the particle’s weight. The weighted particles were blended with 10W40, then for 2h, the mixture was stirred by a magnetic stirrer. For decomposing the particle agglomeration, by utilizing ultrasonic agitation from Kimia Nano Danesh (KND) Company of Iran, the suspension by power of 1200W and frequency of 20 kHz was sonicated for 6-7h. The particles of $Al_2O_3$ and MWCNT, the 10W40 and nanofluid samples are presented in Fig. 1.

### *Measuring viscosity*

Dynamic viscosity of $Al_2O_3$-MWCNT/10W40 hybrid nano-lubricant was measured at solid volume fractions of 0.05%, 0.1%, 0.25%, 0.5%, 0.75% and 1. At temperature range of 5°C up to 55°C, CAP 2000+ Viscometer was utilized for collecting viscosity data. The viscometer has accuracy and repeatability of ±2.0% and ±0.5%, respectively and the viscometer is supplied from Brookfield Engineering Laboratories, Inc.

## RESULT AND DISCUSSION

### *The nano-lubricant rheological behavior*

For a Newtonian fluid, the shear stress against shear rate has linear relation like a straight line. But about non-Newtonian fluid, there is a different situation; the shear stress versus shear rate may increase, decreases or with an initial shear rate alters linearly.

According to the following equations, the apparent viscosity decreases with enhancing the shear rate. The apparent viscosity for fluid with power law is given in Eq. (3):

$$\tau = m\dot{\gamma}^n \quad (2)$$

$$\mu = m\dot{\gamma}^{n-1} \quad (3)$$

Where $\mu$ is the apparent viscosity, $n$ is the index of the power law, $m$ is index of consistency and shear rate and the shear stress are defined by τ and $\dot{\gamma}$, respectively.

To determine the base fluid and the nano-lubricant rheological behaviors, the viscosity of 10W40 and apparent viscosity of $Al_2O_3$-MWCNT/10W40 hybrid nano-lubricant against shear rate are depicted in Fig. 2. As can be seen, viscosities alter nonlinearly by shear rate. This indicates the non-Newtonian behaviors of both base oil and nano-lubricant.

***Table 1: Summary of the rheological studies.***

| Ref. | Nanofluid | Rheological behavior | Shear rate range ($s^{-1}$) | Size | Conc. (vol.%) |
|---|---|---|---|---|---|
| [20] | MWCNT-$Al_2O_3$ | Shear thinning | 10-200 | 10-30 nm | 10-30 |
| [25] | COOH functionalized MWCNTs-$SiO_2$ /EG-water | Shear thinning | 0.612 - 122.3 | 20-30 nm<br>Inner diameter 5-15 nm | 0.0625 - 2 |
| [27] | $Fe_2O_3$-glycerol | Shear thinning | 0.01 - 264 | 26 nm | 0.25-0.8 |
| [21] | $Al_2O_3$/EG-water | Bingham plastic | 3 - 74 | 50 nm | 0.1-1.5 |
| [28] | $TiO_2$/Water | Shear thinning | 10 - 1000 | 7-20 nm | 0.5-0.12 |
| [29] | Fe–Ni/paraffin | Shear thinning Bingham plastic | 1-100 | <15 | 2–12 wt% |
| [30] | $SiO_2$/ethanol | Newtonian | 0-50000 | 35,94,190 | 1.1-7 |
| [31] | | | 10-1000 | 10-100 | 0.4-3.1 |
| [32] | Graphite/water | Shear thinning | 1-100 | 3-4 | 1-4 |
| [33] | MWCNT/water | low Conc.: Newtonian<br>High Conc.: shear thinning | 0-200 | 20-30 | 0.24-1.43 |

***Table 2: Specification of 10W40.***

| Property | Value |
|---|---|
| Kinematic viscosity @ 100 °C | 14.81 cSt |
| Viscosity Index (VI) | 160 |
| Minimum flash point | 232 °C |
| Minimum pour point | -24 °C |
| Density @ 15 °C | 873 ($kg/m^3$) |

***Table 3: Physicochemical specification of $Al_2O_3$ and multi-walled carbon nanotube nanoparticles.***

| Parameter | Value | |
|---|---|---|
| | $Al_2O_3$ | multi-walled carbon nanotube |
| Color | white | Black |
| Purity | 99.9% | > 95 wt% (carbon nanotubes) (from TGA & TEM) |
| SSA | 35 $m^2/g$ | > 233 $m^2/g$ (BET) |
| Diameter | 50 nm | 5-20 nm (from HRTEM, Raman) |
| pH value | 7 | - |


*Fig. 1: Photograph of $Al_2O_3$ and MWCNT particles, 10W40 and nano-lubricant samples.*

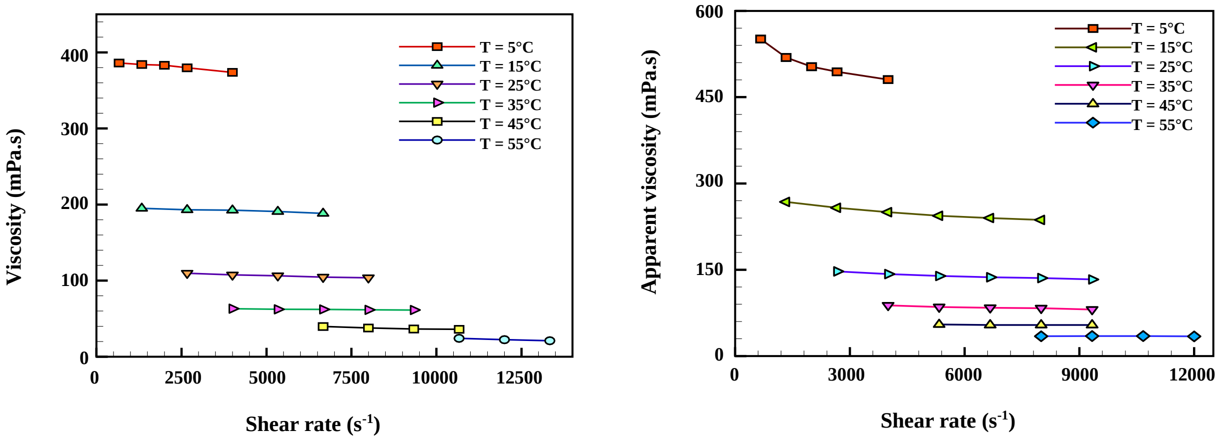


*Fig. 2: Viscosity vs. shear rate at different temperatures for 10W40 and nano-lubricant with 1% solid volume fraction.*

Fig. 2 illustrates at a temperature of 5°C by small shear rate enhancing, the viscosities reduce more than other temperatures.

Fig 3 shows nonlinearity changes of shear stress against shear rate for 10W40 and 1% solid volume fraction of nano-lubricant. For a better understanding of

***Table 4: The values of power law index.***

| T (°C) | Solid volume fraction (vol.%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 0.05 | 0.1 | 0.25 | 0.5 | 0.75 | 1 |
| 5 | 0.9832 | 0.9148 | 0.9017 | 0.9128 | 0.9106 | 0.9103 | 0.9237 |
| 15 | 0.9806 | 0.8884 | 0.8738 | 0.8901 | 0.8995 | 0.9201 | 0.9293 |
| 25 | 0.9488 | 0.8909 | 0.4227 | 0.8615 | 0.891 | 0.9098 | 0.9219 |
| 35 | 0.9671 | 0.8836 | 0.8894 | 0.856 | 0.8985 | 0.8933 | 0.9068 |
| 45 | 0.7855 | 0.8225 | 0.9624 | 0.9674 | 1.0063 | 0.9864 | 0.975 |
| 55 | 0.3829 | 0.6531 | 0.8455 | 0.8582 | 1.079 | 1.0205 | 0.9894 |

***Table 5: The values of consistency index.***

| T (°C) | Solid volume fraction (vol. %) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 0.05 | 0.1 | 0.25 | 0.5 | 0.75 | 1 |
| 5 | 0.4324 | 0.7898 | 0.9115 | 0.9355 | 0.9697 | 0.9792 | 0.9015 |
| 15 | 0.2248 | 0.5137 | 0.5842 | 0.534 | 0.5754 | 0.4778 | 0.4476 |
| 25 | 0.1644 | 0.2869 | 0.9986 | 0.4007 | 0.3582 | 0.2993 | 0.2724 |
| 35 | 0.0828 | 0.1911 | 0.1895 | 0.2726 | 0.1959 | 0.2102 | 0.1907 |
| 45 | 0.2609 | 0.2158 | 0.0642 | 0.0647 | 0.0489 | 0.0599 | 0.0677 |
| 55 | 7.3745 | 0.6365 | 0.1107 | 0.1067 | 0.0158 | 0.0281 | 0.038 |

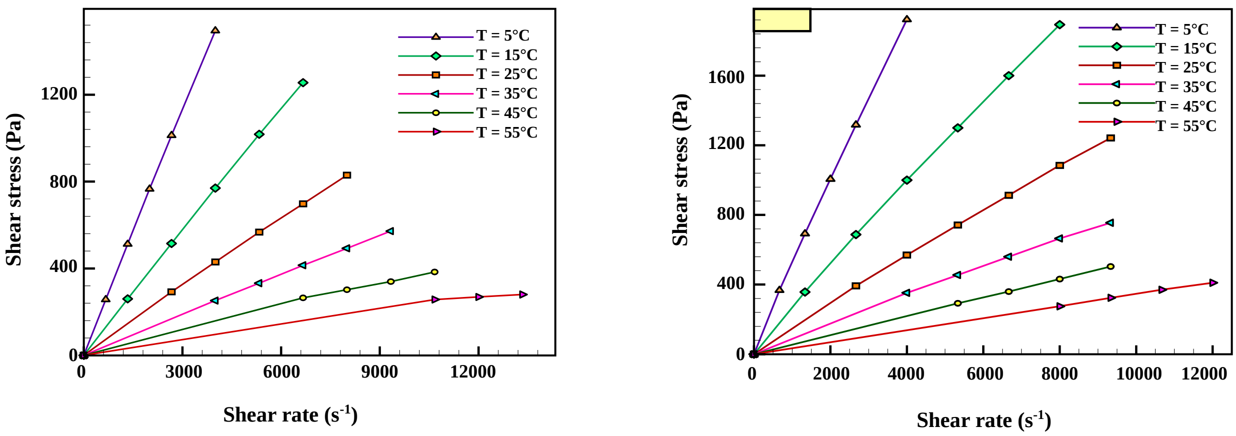


***Fig. 3: Shear stress vs. shear rate at different temperatures for 10W40 and nano-lubricant with 1% solid volume fraction.***

the non-Newtonian behavior, curve fitting was performed on viscosity data to derive the power law index and consistency index. The indexes are presented in Table 4 and Table 5, respectively.

According to Fig. 3 and Table 4, the base oil at higher temperatures is a non-Newtonian fluid, while at lower temperatures, the base oil is near to a Newtonian fluid. For solid volume fractions from 0.5% to 1 vol.%, increasing temperature leads to that nano-lubricant behavior closes to Newtonian fluid. The n values lower than 1 indicate that both base oil and nano-lubricant have a shear thinning behavior.

Fig. 4 demonstrates the power law index and consistency index against solid volume fraction for

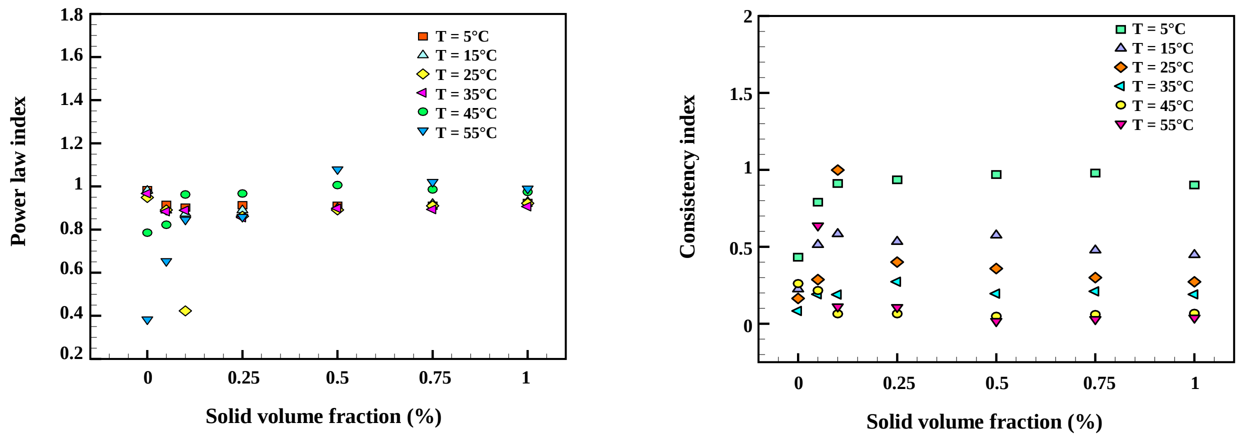


***Fig. 4: Power law index and consistency index vs. solid volume fraction for various temperatures.***

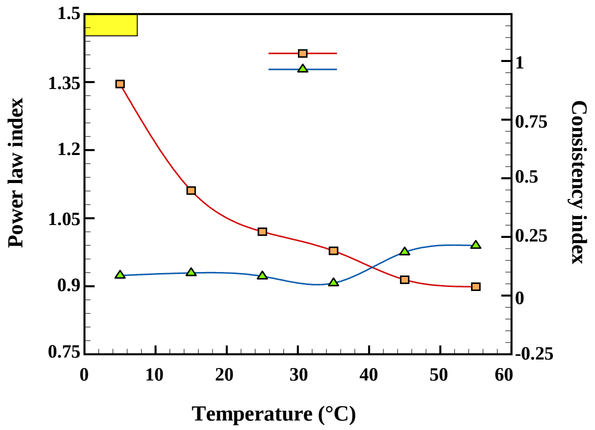


***Fig. 5: Power law and consistency indexes versus temperature for 1% solid volume fraction.***

different temperatures. At the temperature of 55°C, by adding nanoparticles the n value from 0.38 boosts to 1.079 then decreases. This states that the solid volume fraction increasing changes the nano-lubricant behavior from non-Newtonian to Newtonian.

The consistency index increases by enhancing solid volume fraction until 0.1 vol.%, then by adding nanoparticle it decreases very low.

At solid volume fraction of 1 vol.%, power law index and consistency index against temperature are depicted in Fig. 5. Due to temperature raising, the distances between molecules enhance, so viscosity diminishes then the consistency declines. Based on the figure, by increasing temperature, the power law index enhances gradually. This indicates that the behavior of $Al_2O_3$-MWCNT/10W40 hybrid nano-lubricant tends to Newtonian at higher temperatures.

***Proposed correlation***

For predicting the viscosities of $Al_2O_3$-MWCNT/10W40 hybrid nano-lubricant, a new correlation was introduced. This correlation was in terms of nano-lubricant concentration obtained by employing a curve fitting on experimental data. The general form of the new correlation is as follows:

$$\frac{\mu_{nf}}{\mu_{bf}} = a_0 + a_1\varphi^2 + a_2\varphi^3 + a_3\varphi^4 + a_4\varphi e^{\varphi} \tag{4}$$

Where $\mu$ is the dynamic viscosity and $\varphi$ is the nano-lubricant concentration (vol.%). In addition, the nano-lubricant and base oil define by the subscript of *nf* and *bf*, respectively. At each temperature, a relation is suggested and the relevant constant values of $a_0$, $a_1$, $a_2$, $a_3$, $a_4$, and $a_5$ are listed in Table 6.

To achieve the differences of correlation outputs from experimental data, the bellow equation [10] has been used:

$$\text{Dev}(\%) = \frac{\left(\frac{\mu_{nf}}{\mu_{bf}}\right)_{Exp} - \left(\frac{\mu_{nf}}{\mu_{bf}}\right)_{prop}}{\left(\frac{\mu_{nf}}{\mu_{bf}}\right)_{prop}} \times 100 \tag{5}$$

As can be seen in Fig. 6, the viscosity data are in good agreement with proposed viscosities obtained by the correlation. Most of the data fit on the equality line. The calculated deviations by Eq. (5) shown in Fig. 7 for various temperatures and volume concentrations.

***Table 6: Constant values of suggested correlation at various temperatures.***

| T (°C) | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $R^2$ |
|---|---|---|---|---|---|---|
| 5 | 0.9551 | -5.76 | 3.107 | -1.767 | 1.748 | 0.9873 |
| 15 | 1.116 | 10.21 | -13.1 | 6.896 | -1.407 | 0.9963 |
| 25 | 1.07 | -0.7867 | 0.6413 | -0.7079 | 0.4077 | 0.9936 |
| 35 | 1.063 | -6.976 | 4.753 | -2.756 | 1.954 | 0.9904 |
| 45 | 1.123 | 0.3286 | -1.709 | 0.7337 | 0.3328 | 0.9991 |
| 55 | 0.9851 | -7.464 | 6.131 | -3.721 | 2.002 | 0.9876 |

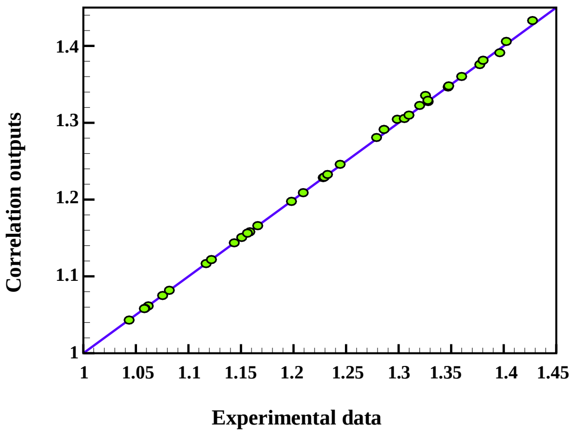


***Fig. 6: Comparison between correlation outputs and experimental data.***

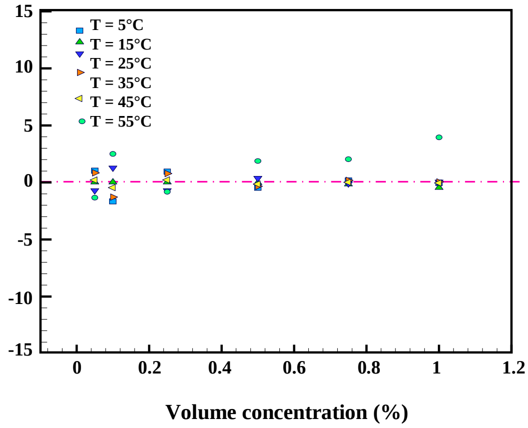


***Fig. 7: Measured margin of deviation for all data.***

The maximum value of deviation obtained about 0.36% at a solid volume fraction of 1 vol.% and temperature of 35°C.

Fig. 8 pictures the results of the correlation output in compare with experimental data. According to the figure, at all temperatures and nano-lubricant solid volume fractions, the correlation can predict the experimental data very well. Also, the accuracy of proposed correlation is decreased by increasing volume fraction.

## CONCLUSIONS

The dynamic viscosity of the nano-lubricant containing $Al_2O_3$ (50 nm) nanoparticles and MWCNTs (inner diameter of 2-6 nm and the outer diameter of 5-20 nm) with the proportional of 90%:10% dispersed in 10W40 engine oil was measured. The rheological behavior was determined at various temperatures up to 55°C and solid volume fractions of 0.05 to 1 vol.%. According to the results, the base oil and $Al_2O_3$-MWCNT/10W40 hybrid nano-lubricant were non-Newtonian fluids at the most range of temperature and solid volume fraction. Thereby, the power law index and consistency index were calculated for all temperatures and solid volume fractions. Using curve fitting, a new correlation in terms of nano-lubricant concentration was suggested to anticipate the viscosity data. The maximum deviation was calculated about 0.36% that indicates the correlation is an accurate one.

## Nomenclature

| | |
|---|---|
| T | Temperature, °C |
| w | Weight, g |

### *Greeks symbols*

| | |
|---|---|
| $\dot{\gamma}$ | Shear rate, $s^{-1}$ |
| μ | Dynamic viscosity, poise |
| ρ | Density, $kg/m^3$ |

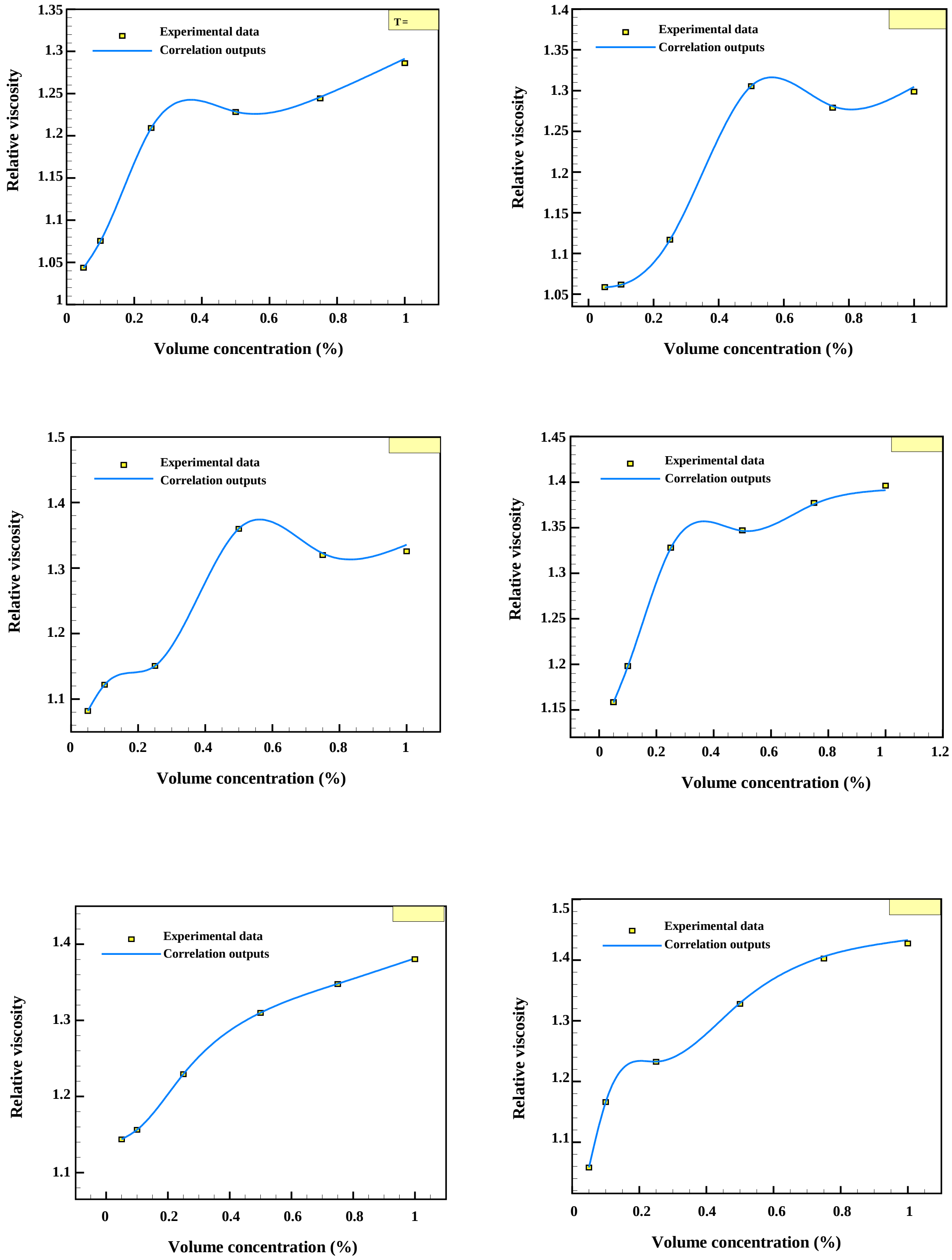


***Fig. 8: Regression results (proposed model) at different concentrations and temperatures.***

| | |
|---|---|
| $\tau$ | Shear stress, dyne/cm$^2$ |
| $\varphi$ | Nanoparticle volume fraction |

***Subscripts***

| | |
|---|---|
| nf | Nanofluid |
| bf | Base fluid |

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**REFERENCES**


[1] Hemmat Esfe M., Yan W.-M., Akbari M., Karimipour A., Hassani M., Experimental Study on Thermal Conductivity of DWCNT-ZnO/Water-EG Nanofluids, *Int. Commun. Heat Mass Transfer*, **68**: 248-251 (2015).

[2] Hemmat Esfe M., Saedodin S., Akbari M., Karimipour A., Afrand M., Wongwises S., Safaei M.R., Dahari M., Experimental Investigation and Development of New Correlations for Thermal Conductivity of CuO/EG–Water Nanofluid, *Int. Commun. Heat Mass Transfer*, **65**: 47-51 (2015).

[3] Hemmat Esfe M., Naderi A., Akbari M., Afrand M., Karimipour A., Evaluation of Thermal Conductivity of COOH-Functionalized MWCNTs/Water via Temperature and Solid Volume Fraction by Using Experimental Data and ANN Methods, *J. Therm. Anal. Calorim*, **121**(3): 1273-1278 (2015).

[4] Sarafraz M.M., Hormozi F., Nikkhah V.. Thermal Performance of a Counter-Current Double Pipe Heat Exchanger Working with COOH-CNT/Water Nanofluids, *Experimental Thermal and Fluid Science*, **78**: 41-49 (2016).

[5] Sarafraz M.M., Hormozi F., Peyghambarzadeh S.M., Thermal Performance and Efficiency of a Thermosyphon Heat Pipe Working with a Biologically Ecofriendly Nanofluid, *International Communications in Heat and Mass Transfer*, **57**: 297-303 (2014).

[6] Hemmat Esfe M., Saedodin S., Naderi A., Alirezaie A., Karimipour A., Wongwises S., Goodarzi M., bin Dahari M., Modeling of Thermal Conductivity of ZnO-EG Using Experimental Data and ANN Methods, *Int. Commun. Heat Mass Transfer*, **63**: 35-40 (2015).

[7] Sarafraz M.M., Hormozi F.. Experimental Study on the Thermal Performance and Efficiency of a Copper Made Thermosyphon Heat Pipe Charged with Alumina–Glycol Based Nanofluids, *Powder Technology*, **266**: 378-387 (2014).

[8] Sarafraz M.M., Hormozi F., Peyghambarzadeh S.M., Role of Nanofluid Fouling on Thermal Performance of a Thermosyphon: Are Nanofluids Reliable Working Fluid?. *Applied Thermal Engineering*, **82**: 212-224 (2015).

[9] Hemmat Esfe M., Saedodin S., Asadi A., An Empirical Investigation on the Dynamic Viscosity of Mg (OH) 2–Ethylene Glycol in Different Solid Concentrations and Proposing New Correlation Based on Experimental Data, *International Journal of Natural and Engineering Sciences*, **8**(3): 29-34 (2014).

[10] Hemmat Esfe M., Saedodin S., An Experimental Investigation and New Correlation of Viscosity of ZnO–EG Nanofluid at Various Temperatures and Different Solid Volume Fractions, *Exp. Thermal Fluid Sci.*, **55**: 1-5 (2014).

[11] Hemmat Esfe M., Wongwises S., Naderi A., Asadi A., Safaei M.R., Rostamian H., Dahari M., Karimipour A., Thermal Conductivity of Cu/TiO 2–Water/EG Hybrid Nanofluid: Experimental Data and Modeling Using Artificial Neural Network and Correlation, *Int. Commun. Heat Mass Transfer*, **66**: 100-104 (2015).

[12] Hemmat Esfe M., Rostamian H., Afrand M., Karimipour A., Hassani M., Modeling and Estimation of Thermal Conductivity of MgO–Water/EG (60: 40) by Artificial Neural Network and Correlation, *Int. Commun. Heat Mass Transfer*, **68**: 98-103 (2015).

[13] Hemmat Esfe M., Motahari K., Sanatizadeh E., Afrand M., Rostamian H., Hassani M., Estimation of Thermal Conductivity of CNTs-Water in Low Temperature by Artificial Neural Network and Correlation, *Int. Commun. Heat Mass Transfer*, **76**: 376-381 (2015).

[14] Hemmat Esfe M., Afrand M., Yan W.-M., Akbari M., Applicability of Artificial Neural Network and Nonlinear Regression to Predict Thermal Conductivity Modeling of $Al_2O_3$–Water Nanofluids Using Experimental Data, *Int. Commun. Heat Mass Transfer*, **66**: 246-249 (2015).

[15] Hemmat Esfe M., Afrand M., Wongwises S., Naderi A., Asadi A., Rostami S., Akbari M., Applications of Feedforward Multilayer Perceptron Artificial Neural Networks and Empirical Correlation for Prediction of Thermal Conductivity of Mg (OH) 2–EG Using Experimental Data, *Int. Commun. Heat Mass Transfer*, **67**: 46-50 (2015).

[16] Hemmat Esfe M., Saedodin S., Sina N., Afrand M., Rostami S., Designing an Artificial Neural Network to Predict Thermal Conductivity and Dynamic Viscosity of Ferromagnetic Nanofluid, *Int. Commun. Heat Mass Transfer*, **68**: 50-57(2015).

[17] Hemmat Esfe M., Ahangar M.R.H., Rejvani M., Toghraie D., Hajmohammad M.H., Designing an Artificial Neural Network to Predict Dynamic Viscosity of Aqueous Nanofluid of $TiO_2$ Using Experimental Data, *Int. Commun. Heat Mass Transfer*, **75**:192-196(2016).

[18] Atashrouz S., Pazuki G., Alimoradi Y., Estimation of the Viscosity of Nine Nanofluids Using a Hybrid GMDH-Type Neural Network System, *Fluid Phase Equilibria*, **372**: 43-48 (2014).

[19] Kulkarni D.P., Das D.K., Chukwu G.A., Temperature Dependent Rheological Property of Copper Oxide Nanoparticles Suspension (Nanofluid), *J. Nanosci. Nanotechnol.*, **6**(4); 1150-1154 (2006).

[20] Lu K., Rheological Behavior of Carbon Nanotube-Alumina Nanoparticle Dispersion Systems, *Powder Technol*., **177**(3): 154-161 (2007).

[21] Kole M., Dey T., Viscosity of Alumina Nanoparticles Dispersed in Car Engine Coolant, *Exp. Thermal Fluid Sci.*, **34**(6): 677-683 (2010).

[22] Chen H., Ding Y., Lapkin A., Fan X., Rheological Behaviour of Ethylene Glycol-Titanate Nanotube Nanofluids, *J. Nanopart. Res.*, **11**(6): 1513-1520 (2009).

[23] Cabaleiro D., Pastoriza-Gallego M.J., Gracia-Fernández C., Piñeiro M.M., Lugo L., Rheological and Volumetric Properties of $TiO_2$-ethylene Glycol Nanofluids, *Nanoscale Res. Lett.*, **8**(1): 1-13 (2013).

[24] Pötschke P., Fornes T., Paul D., Rheological Behavior of Multiwalled Carbon Nanotube/ Polycarbonate Composites, *Polymer*,**43**(11): 3247-3255 (2002).

[25] Eshgarf H., Afrand M., An Experimental Study on Rheological Behavior of Non-Newtonian Hybrid Nano-Coolant for Application in Cooling and Heating Systems, *Exp. Thermal Fluid Sci.*, **76**:*221-227* (2016).

[26] Pastoriza-Gallego M.J., Lugo L., Legido J.L., Piñeiro M.M., Rheological Non-Newtonian Behaviour of Ethylene Glycol-Based $Fe_2O_3$ Nanofluids, *Nanoscale Res. Lett.*, **6**(1): 1-7 (2011).

[27] Abareshi M., Sajjadi S.H., Zebarjad S.M., Goharshadi E.K., Fabrication, Characterization, and Measurement of Viscosity of $\alpha$-$Fe_2O_3$-glycerol Nanofluids, *J. Mol. Liq.*, **163**(1): 27-32 (2011).

[28] Tseng W.J., Lin K.-C., Rheology and Colloidal Structure of Aqueous $TiO_2$ Nanoparticle Suspensions, *Mater. Sci. Eng.*, **355**(1): 186-192 (2003).

[29] Katiyar A., Singh A., Shukla P., Nandi T., Rheological Behavior of Magnetic Nanofluids Containing Spherical Nanoparticles of Fe–Ni, *Powder Technol.*, **224**: 86-89 (2012).

[30] Chevalier J., Tillement O., Ayela F., Rheological Properties of Nanofluids Flowing Through Microchannels, *Appl. Phys. Lett.*, **91**(23): 23-31(2007).

[31] Chevalier J., Tillement O., Ayela F., Structure and Rheology of $SiO_2$ Nanoparticle Suspensions under Very High Shear Rates, *Phys. Rev. E*, **80**(5): 5-14 (2009).

[32] Duan F., Wong T.F., Crivoi A., Dynamic Viscosity Measurement in Non-Newtonian Graphite Nanofluids, *Nanoscale Res. Lett.*, **7**(1): 1-6 (2012).

[33] Phuoc T.X., Massoudi M., R Chen.-H., Viscosity and Thermal Conductivity of Nanofluids Containing Multi-Walled Carbon Nanotubes Stabilized by Chitosan, *Int. J. Therm. Sci.*, **50**(1): 12-18 (2011).