Journal of Thermal Analysis and Calorimetry (2022) 147:7099–7132
https://doi.org/10.1007/s10973-021-10993-y

Statistical study and a complete overview of nanofluid viscosity correlations: a new look

A. Barkhordar[1] · R. Ghasemiasl[1] · T. Armaghani[2]

Received: 7 April 2021 / Accepted: 7 July 2021 / Published online: 22 August 2021

Abstract
Nanofluids are considered the top candidates to replace surface cooling systems, making it essential to study the effect of nanoparticles on thermophysical properties of the base fluid when it is added. Viscosity is a crucial factor in heat transfer, especially convection heat transfer. In most of the studies published, the correlations obtained from experiments were performed without examining statistical tests, and the effect of different parameters, including temperature, volume (mass) fraction, etc., on the viscosity of nanofluid in the proposed correlations was not specified. Moreover, some correlations it was shown that the elimination of one of the parameters had no effect on the response of that correlation. For statistical analysis, analysis of variance and sensitivity analysis were used to determine the relationship of the correlation with its variable parameters. The results showed that approximately 27.2% of the correlations presented for the ethylene glycol-based nanofluid and 27.7% of the correlations presented for the water-based nanofluid are reliable. Finally, as until now, no accurate correlation has been provided for the viscosity in a wide temperature and volume fraction range. According to the R-square statistical index, viscosity models were obtained in this study with an accuracy of 97.01% and 96.08% for water- and ethylene glycol-based nanofluids, regardless of the nanoparticle type. Also, the RMSE value was improved by 35.82% and 49.84% compared to the best correlation presented by the researchers for estimating the viscosity of water-based nanofluid and ethylene glycol-based nanofluid, respectively.

Keywords Nanofluid viscosity · Statistical analysis · Monte Carlo method

Nomenclature

T	Temperature (°C or K)
φ	Concentration (%)
μ	Dynamic viscosity (mPa.s)
d	Diameter (nm)
$\dot{\gamma}$	Shear rate (s^{-1})
N	Number of data
θ	Dimensionless temperature
a, b	Constant values

Subscripts

bf	Base fluid
nf	Nanofluid
p	Particles
max	Maximum
min	Minimum
o	Reference value
exp	Experimental data
pre	Predicted data
w	Mass concentration

✉ R. Ghasemiasl
ghasemiasl@yahoo.co.in

✉ T. Armaghani
armaghani.taher@yahoo.com

[1] Department of Mechanical Engineering, West Tehran Branch, Islamic Azad University, Tehran, Iran

[2] Department of Mechanical Engineering, Mahdishahr Branch, Islamic Azad University, Mahdishar, Iran

Introduction

One of the perspectives for solving conservation equations for nanofluids is the single-phase method. In this method, the thermophysical properties of the nanofluid replace the thermophysical properties of the base fluid [1–3]. The single-phase model is used by some investigations [4–7]. This shows the impact of thermophysical properties of the nanofluid, especially its viscosity, on heat transfer. [8–10]

Among the thermophysical properties of nanofluids, viscosity indicates fluid resistance. Therefore, viscosity has determined the performance of energy and heating systems. [11–13]

In industrial equipment and scientific research, where heat transfer is in the forms of forced convection and natural convection, the viscosity of nanofluids plays a crucial role in determining the flow regime, pumping power, pressure drop, and workability of systems [14–17].

The first viscosity model for suspensions containing metal particles was introduced by Einstein in 1906 [18]. Later on, viscosity models proposed by Brinkman [19], Batchelor [20], and other equations started to be used to model the heat transfer of nanofluids. However, these correlations each have weaknesses, including the inability to estimate the viscosity of nanofluids in a wide range of temperatures and concentrations used in heat transfer.

In the experiments conducted by Duangthongsuk and Wongwises [21] on the behavior of TiO_2 and water nanofluid, they presented a correlation by applying the effects of base fluid viscosity and volume fraction variables on the viscosity model. In their model, nanofluid's temperatures and volume fraction ranged between 15 to 35 °C and 0.2 to 2%, respectively.

In an experimental test performed by Esfe and Saedodin [22] on the viscosity of ZnO nanofluid with ethylene glycol-based fluid at a temperature between 25 and 50 °C and a volume fraction of 0.25 to 5%, the viscosity model with the variables of temperature and volume fraction and the viscosity of the base fluid presented that the ratio of mean variation of the model data compared to other the experimental values was less than 2%.

Sharifpur et al. [23] also introduced a viscosity model based on the data derived from experiments using Al_2O_3 and glycerin nanofluid with an accuracy of 0.9495. In their viscosity model, in addition to the variables of temperature and volume fraction and the viscosity of the base fluid, the effect of the thickness of the nanoparticles is also taken into account. It is used for nanofluids in the temperature range of 20 to 70 °C and volume fraction of 0 to 5%, and diameter of nanoparticles about 19 to 160 nm. But Aberoumand et al. [24] presented a viscosity model for oil-silver nanofluid that depends only on the variables of volume fraction and viscosity of the base fluid and is valid for nanofluids at temperatures between 25 and 60 °C and volume fraction of 0 to 2%.

In an experimental study performed by Akbari et al. [25] on Si O_2 and ethylene glycol nanofluids in the temperature range of 30 to 50 °C and volume fraction of 0.5 to 3%, using temperature and volume fraction components and the viscosity of the base fluid proposed a viscosity model for the nanofluid. Li and Zuo [26] had proposed a viscosity model for a nanofluid including TiO_2 nanoparticles and a mixture of water-based fluid and ethylene glycol at a temperature between 20 to 50 °C and a volume fraction of 0.25 to 1%.

Yu et al. [27] also proposed a new viscosity model based on the data derived from experiments using multi-walled carbon nanotubes [MWCNT] and water nanofluids. In their model, in addition to the role of temperature, mass fraction, and base fluid viscosity, the effect of shear rate on viscosity variations is also considered. This model is valid in a temperature range of 275 to 283 Kelvin, and mass fraction range of 0.1 to 0.6 percent, and a shear rate of 10 to 1000 s^{-1}. According to the experiment performed by Yan et al. [28] on a hybrid nanofluid with multi-walled carbon nanotube [MWCNT] nanoparticles and TiO_2 with a base fluid of ethylene glycol at 25 to 55 °C and a volume fraction of 0.05 to 1%, the viscosity model with volume fraction and non-dimensional temperature components has been presented with an accuracy of 0.995.

Figure 1 is plotted to know the year of publication of the evaluated correlations in the present study. Therefore, it can be concluded that researchers have considered the study and presentation of models for the viscosity of nanofluids in recent years.

Figure 2 is plotted to indicate the temperature range at which the viscosity models are valid. The correlations separated according to the temperature range they cover in different temperature ranges that differ by 10 degrees. (Temperature difference of less than five °C in the classification has been neglected.)

According to Fig. 2, 21.4 and 23.2% of the temperature range cover 30 and 40°, respectively, and only 23.2% of the correlations in the 50° temperature range can estimate the viscosity of the nanofluid.

Similar to the temperature diagram, the viscosity models were separated into 1% by volume (mass) fraction intervals

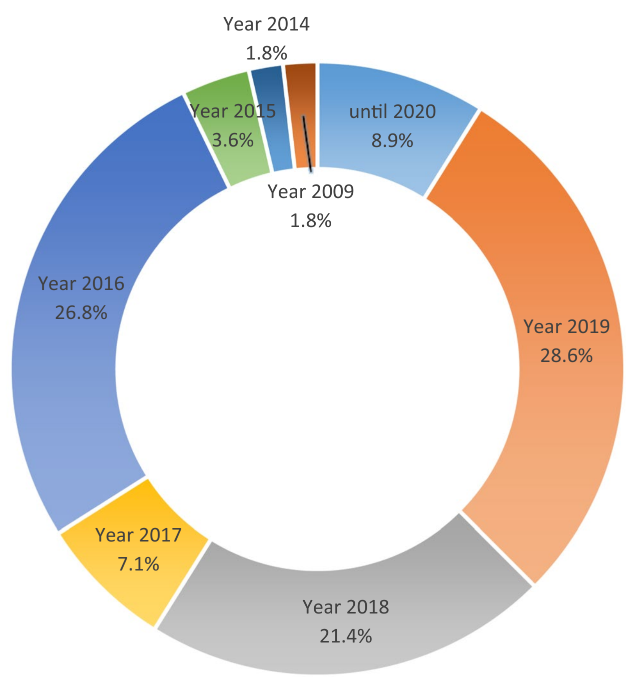

Fig. 1 Year of publication of evaluated correlations in articles

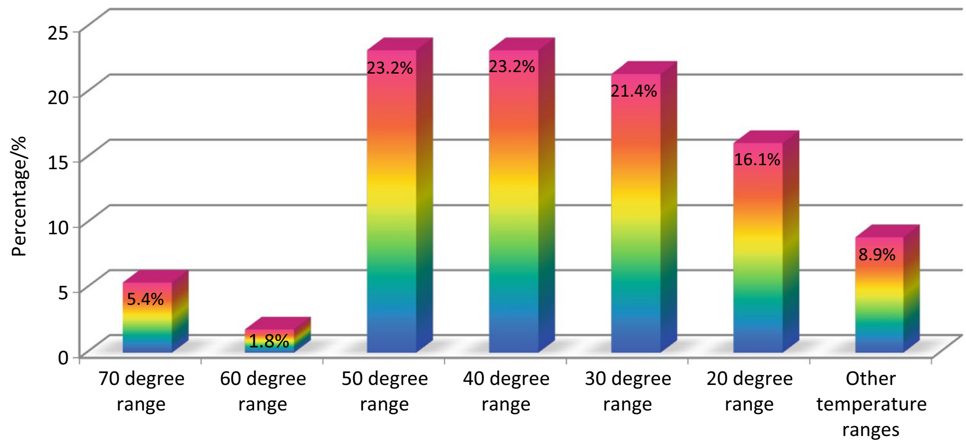

Fig. 2 The temperature ranges are covered by the viscosity models

relative to the concentration range in which they are valid, and Fig. 3 shows that only 19.6% of the correlations can cover the concentration range of 2 percent.

As the authors worked on the thermal conductivity of nanofluid based on present studies and introduced a new general model named MAG. [29] So this study must be done about nanofluid viscosity.

In this study, the correlations presented for the viscosity of nanofluids were wholly reviewed and investigated thoroughly in terms of compliance with the physics and viscosity of nanofluids. In the following, the relationship between viscosity and variables of temperature and volume (mass) fraction of nanofluids was evaluated according to the statistical test of variance. Moreover, all the correlations presented for nanofluid viscosity were investigated with the sensitivity analysis test to identify the variable with the most significant effect on the viscosity model. Finally, two general models for water-based nanofluids and ethylene glycol were presented to predict the viscosity behavior of nanofluids.

Strategy

Analysis of variance

Statistics is a broad field of mathematics that studies how data collection, summary, and conclusion are studied. Here, the status of variables related to the viscosity of nanofluid investigated using statistical science based on probability theory and mathematics.

ANOVA test or analysis of variance is a subset of statistical science, which analyzes and compares the means of different statistical groups and determines the effect of independent variables on the dependent variable. This method has been introduced by the famous statistician and geneticist "R. Fisher."[30]

This method tries to estimate the differences between several statistical populations. In other words, using the mean index in statistical populations, we will be able to express the characteristics of the population; thus, if the mean of one group is different from other groups in society, we conclude that the statistical populations are not the same. In the one-way analysis of variance, the null hypothesis indicates that

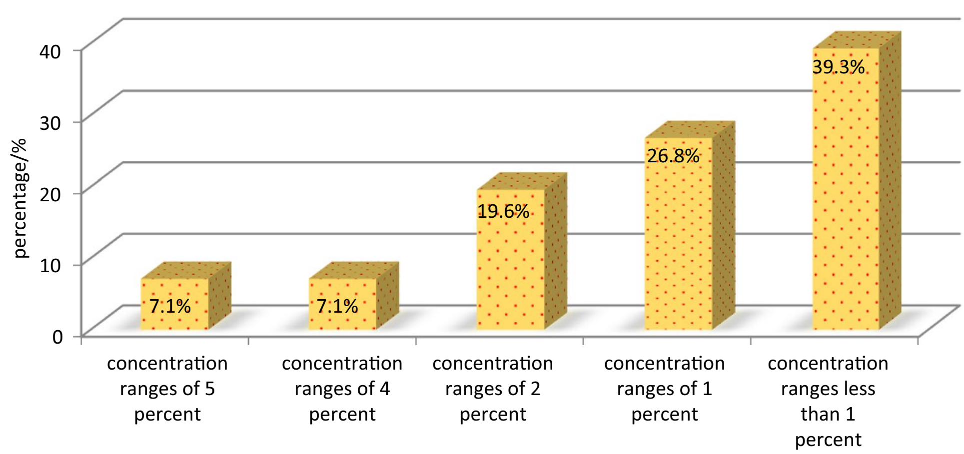

Fig. 3 The concentration ranges are covered by the viscosity models

the mean of the experimental groups is equal to each other. The opposite assumption is that at least one of the means is different from the others; if the null hypothesis is confirmed, it will be accepted that there is no difference between the means of the groups, and the variable has no role in the correlation. Therefore, to better understand the correspondence of variables on nanofluid viscosity, it is necessary to perform variance analysis. [31]

Thus, by groups that will be created in terms of temperature and concentration variables for each equation and with the help of a one-way ANOVA test, the results presented in Table 1 are obtained.

In some of the correlations proposed by researchers due to the lack of attention to the response power of the correlation in the temperature range affecting the viscosity of nanofluids and also because the appropriate relationship is not used in correlations to express the relationship between temperature and viscosity of nanofluid and the correlation are not able to predict the nanofluid viscosity at sensitive temperature and do not express the role and importance of temperature variables in nanofluid viscosity models.

One of the issues that researchers had not been considered in presenting correlations is the effect of terms on the viscosity model. For example, Dalkılıça et al. [32] presented Eq. (1) for nanofluid viscosity by experimental investigation of the viscosity of a hybrid nanofluid containing graphene and SiO_2 nanoparticles in a water-based nanofluid in the temperature range of 15 to 60 °C and a volume fraction of 0.001 to 0.02%.

$$\mu_{nf} = \left[1.00527 \times \left(T^{0.00035}\right) \times (1+\varphi)^{9.36265} \times \left(\frac{\varphi_{w,G}}{\varphi_{w,SiO_2}}\right)^{-0.028935}\right]\mu_{bf} \quad (1)$$

In the case, where $\varphi = 1$ and other components are a constant value, if the lower and upper-temperature limits are set in Eq. (1), the range of viscosity changes will be less than 0.04%. Therefore, Eq. (1) is not dependent on temperature, but the researcher had given in the equation, and this is not considered significant by the researcher.

In addition to the temperature variable, the concentration variable also has an undeniable role in the viscosity models of nanofluids. So that with increasing the concentration of nanofluid, the viscosity of nanofluid increases significantly; therefore, in most viscosity models, the prominent role of the concentration variable was considered by researchers. However, in some correlations recently published by researchers, the correlations have been measured in the range of inappropriate volume (mass) fractions and only at low concentrations. On the other hands, due to the use of irrational relationships to express the relationship between the viscosity of nanofluid and the concentration of nanoparticles, viscosity models cannot respond commensurately with the expected concentration range in heat transfer.

By conducting experimental tests on nanofluids of Al_2O_3 and ethylene glycol, Li et al. [33] presented the new viscosity model in compliance with the trend of temperature variation from 25 to 60 °C and a mass fraction of 0 to 2% in Eq. (2).

$$\mu_{nf} = -334.9\varphi_w^{4.044}\left(\frac{1}{T}\right)^{10.03} + 296.8\left(\frac{1}{T}\right)^{0.7795} - 6.841 \quad (2)$$

Concentration variable in term $-334.9\varphi_w^{4.044}\left(\frac{1}{T}\right)^{10.03}$ less than 0.01% affects the nanofluid viscosity. Therefore, the viscosity model of Li et al. does not have the expected dependence on the concentration variable.

By evaluating the correlations presented for nanofluid viscosity, the situation of temperature and volume (mass) fraction variables in the correlations is determined. The results showed if there is a significant relationship between variables and nanofluid viscosity.

Therefore, it is necessary to consider the effects of variables on the viscosity models of nanofluids in the temperature range and volume (mass) fraction of heat transfer.

Physical analysis of correlations

Viscosity models at different dimensions in this part of the research are studied. First, the structure of the proposed correlations to calculate the viscosity has been examined and then evaluated for analyzing complex, heterogeneous, or ambiguous components. Meanwhile, in another section, based on the experimental studies of researchers in the temperature range and volume (mass) fraction, the data extracted from the correlations are evaluated. Also, the accuracy of the experimental model for the case where the concentration of nanofluid is considered zero with the viscosity of base fluid has been investigated. Finally, the correlations have been measured in terms of the laws governing the physics of nanofluids and the changes due to an increase or decrease in temperature and concentration of nanofluids.

According to Table 1 of the Term section, in most of the experimental relations studied for calculating viscosity, it is observed that mathematical expressions and terms do not interfere with the calculation of the viscosity of nanofluids. Thus, these expressions have only caused the complexity and inefficiency of empirical relations, which increases the possibility of errors in the viscosity calculations of nanofluids.

Table 1 Experimental correlation of nanofluid viscosity and their analysis

No.	Author	Material Nano-particle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] *P*-Value For T	*P*-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
1	Li et al. [40]	SiO_2 (liquid paraffin)	$\mu_{nf} = \left[6.8376 + 15.2522\varphi_w + 0.038779\varphi_w T - 2.63029\varphi_w^2\right]\mu_{bf}$	25 °C < T_{nf} < 70 °C	1.000	0.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable
				20 ~ 45 nm				✓	
				$0.005 < \varphi < 5$ Wt				✓	
2	Li et al. [33]	Al_2O_3 (EG)	$\mu_{nf} = -334.9\varphi_w^{4.044}\left(\frac{1}{T}\right)^{10.03} + 296.8\left(\frac{1}{T}\right)^{0.7795} - 6.841$	25 °C < T_{nf} < 60 °C	0.000	1.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the concentration variable
				20 nm				✓	
				$0 < \varphi < 2$ Wt				✓	
3	Sahoo and Kumar [41]	Al_2O_3, SiO_2, CuO (Water)	$\mu_{nf} = \left[0.955 - 0.00271 \times T + 1.858 \times \frac{\varphi}{100} + \left(705 \times \frac{\varphi}{100}\right)^{1.223}\right]\mu_{bf}$	35 °C < T_{nf} < 50 °C	1.000	0.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable
				30 ~ 50 nm				✓	
				$0.01 < \varphi < 0.1$ Vol				✓	
4	Yan et al. [28]	MWCNT/TiO_2 80–20%) Hybrid (EG)	$\mu_{nf} = [0.90463 + 280.20104\varphi + 0.257340 + 368.05239\theta\varphi$ $-28643.68399\varphi^2 - 0.012051\theta^2 - 1968.73612\varphi^2\theta$ $-235.04729\theta^2\varphi + 2.09629 \times 10^6\varphi^3 - 0.099694\theta^3]\mu_{bf}$	25 °C < T_{nf} < 55 °C	0.000	0.983	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the concentration variable. The correlation has multiple terms. *(θ is the dimensionless temperature)*
				30 nm					
				$0.05 < \varphi < 1$ Vol				✓	
5	Tian et al. [42]	Cu/MWCNT (water/EG) [70–30]	$\mu_{nf} = [0.50013 + 0.019722T + 4.23827\varphi - 0.099694T\varphi]\mu_{bf}$	20 °C < T_{nf} < 60 °C	0.000	0.000	Acceptable	✓	
				–				✓	
				$0.025 < \varphi < 0.25$ Vol				✓	

Table 1 (continued)

No.	Author	Material Nano-particle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] P-Value For T	P-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
6	Li et al. [43]	SWCNT (water)	$\mu_{nf} = 0.001732 - 0.000046T + 4.832 \times 10^{-7}T^2 + 0.0259\varphi - 1.262\varphi^2 - 0.000305T\varphi$	5 °C < T_{nf} < 50 °C	0.978	0.682	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable. The correlation has multiple terms
				20 nm				✓	
				0 < φ < 0.5 Vol				✓	
7	Esfe and Esfandeh [39]	MWCNT / ZnO [20–80] Hybrid (5W30)	$\mu_{nf} = 458.77 - 23.13T - 0.01\dot{\gamma} - 3.16\varphi T + 5.82 \times 10^{-4}T\dot{\gamma} + 0.44T^2 + 2.48 \times 10^{-7}\dot{\gamma}^2 + 9.6 \times 10^{-5}\varphi T\dot{\gamma} + 0.02\varphi T^2 - 8.37 \times 10^{-6}T^2\dot{\gamma} + 71.26\varphi^3 - 2.81 \times 10^{-3}T^3$	5 °C < T_{nf} < 55 °C	0.000	0.000	Acceptable	✓	The variation trend of the viscosity model is not consistent with the increase in the volume fraction of the nanofluid. The correlation has multiple terms
				–					
				0.05 < φ < 1 Vol					
8	Ganesh Kumar et al. 219 [44]	MWCNTs water / solar glycol) [70–30]	$\mu_{nf} = \left[0.8834\varphi_w^2 + 0.3903\varphi_w + 1.0077\right]\mu_{bf}$	30 °C < T_{nf} < 50 °C	–	1.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the concentration variable
				30–50 nm				✓	
				0.15 < φ < 0.45 Wt				✓	
9	Asadi and Pourfattah [45]	ZnO / MgO Hybrid (Oil)	$\mu_{nf} = a + b\varphi$	15 °C < T_{nf} < 55 °C	0.000	0.000	Acceptable	✓	*(a, b are dependent on temperature)*
				35 ~ 45 nm ZnO					
				40 nm MgO				✓	
				0.125 < φ < 1.5 Vol				✓	

Table 1 (continued)

No.	Author	Material Nano-particle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] P-Value For T	ANOVA[1] [Variances] P-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
10	Shahsavar et al. [46]	Fe_3O_4 (Paraffin)	$\mu_{nf} = a_{04} + a_{14}\left(b_{2233}\right) + a_{24}\left(b_{1311}\right) + a_{34}\left(b_{2233}\right)^2 + a_{44}\left(b_{1311}\right)^2 + a_{54}\left(b_{2233}\right)\left(b_{1311}\right)$	20 °C < T_{nf} < 90 °C	0.999	1.000	Rejected	✓	*According to the statistical variance analysis, the viscosity model does not have the expected dependence on the variables of temperature and concentration. (Constants are dependent on temperature)*
				20 nm				✓	
				0.5 < φ < 3 Vol				✓	
11	Esfe et al. [38]	MWCNT/Al_2O_3 30– 70%) (5W50)	$\mu_{nf} = 688.46 + 347.09\varphi - 33.12T - 0.04\dot{\gamma} - 7.36\varphi T - 0.0087\varphi\dot{\gamma} + 0.0014T\dot{\gamma} - 305.24\varphi^2 + 0.61T^2 + 1.49\times10^{-6}\dot{\gamma}^2 + 0.0001\varphi T\dot{\gamma} + 0.46\varphi^2 T + 0.0014\varphi^2\dot{\gamma} + 0.065\varphi T^2 + 1.87\times10^{-7}\varphi\dot{\gamma}^2 - 7.25\times10^{-6}T^2\dot{\gamma} - 7.33\times10^{-8}T\dot{\gamma}^2 + 169.62\varphi^3 - 0.0043T^3 + 0.00000000011\dot{\gamma}^3$	5 °C < T_{nf} < 55 °C	0.000	0.000	Acceptable	✓	The correlation has multiple terms
				5 ~ 15 nm					
				0.05 < φ < 1 Vol				✓	
12	Alarifi et al. 219 [34]	MWCNT / TiO_2 [80–20%] (Oil)	$\mu_{nf} = 2.936T + \frac{2e^4}{1.68+T-1.68\varphi} - 448.8 - \tan((1.68\varphi) - 1.68)$	25 °C < T_{nf} < 50 °C	0.000	0.000	Acceptable	✓	The correlation has an irrelevant function
				-					
				0.25 < φ < 2 Vol				✓	
13	Li et al. [47]	Cu (EG)	$\mu_{nf} = \left[1.045 + 2.105\varphi_w - 5.015\varphi_w^2\right]\mu_{bf}$	20 °C < T_{nf} < 60 °C	-	1.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the concentration variable
				50 nm				✓	
				1 < φ < 3.8 Wt				✓	

Table 1 (continued)

No.	Author	Material Nanoparticle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] *P*-Value For T	*P*-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
14	Ruhani et al. [35]	Si O_2 (EG / Water) [30-70]	$\mu_{nf} = [2.030 - \left(931.616 \times \varphi^{0.9305} \times 5.4597 \times T^{-3.4574}\right) - \exp\left(-0.0028 \times \varphi^{2.1421} \times T^{1.0133}\right)^2]\mu_{bf}$	25 °C < T_{nf} < 50 °C 20–30 nm 0.1 < φ < 1.5 Vol	1.000	0.000	Rejected	✓ ✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable. The correlation has a complex term
15	Esfe et al. [37]	MWCNT / ZnO [10%—90%] Hybrid (10W40)	$\mu_{nf} = 679.78306 + 259.62463\varphi - 33.64131T - 0.045393\dot{\gamma} - 6.0695 \times \varphi T - 0.00031841\varphi\dot{\gamma} + 0.00129007T\dot{\gamma} - 236.23287\varphi^2 + 0.65796T^2 + 2.31776E - 06\dot{\gamma}^2 + 1.55167\varphi^2 T + 0.049805\varphi T^2 - 9.63258E - 8T\dot{\gamma}^2 + 94.57115\varphi^3 - 0.0051586T^3 + 0.0000000001\dot{\gamma}^3$	5 °C < T_{nf} < 55 °C 5 ~ 15 nm 0.05 < φ < 1 Vol	0.000	1.000	Rejected	✓ ✓	According to the results of the statistical test of variance, the correlation is not dependent on the concentration variable. The correlation has multiple terms
16	Esfe et al. [48]	MWCNTs / Ti O_2 [20%—80%] Hybrid (Water / EG) [70%—30%]	$\mu_{nf} = 6.35 + 2.56\varphi - 0.24T - 0.068\varphi T + 0.905\varphi^2 + 0.0027T^2$	10 °C < T_{nf} < 50 °C 5 ~ 15 nm 0.05 < φ < 0.85 Vol	0.000	0.001	Acceptable	✓ ✓	
17	Yu et al. [27]	MWCNT (water)	$\mu_{nf} = \left[1 - 1634\varphi + 8T\varphi + (10T - 2190)\varphi\exp\left(-\frac{\dot{\gamma}}{60}\right)\right]\mu_{bf}$	275 K ≤ T_{nf} ≤ 283 K 8 ~ 15 nm 0 ≤ φ ≤ 0.2381 Vol	1.000	0.000	Rejected	✓ ✓ ✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable
18	Soman et al. [49]	BMImBr ionic liquid (Water)	$\mu_{nf} = -3.4807 + 0.0304T + 0.4674\varphi_w + 0.0005T\varphi_w - 0.1233\varphi_w^2 - 0.000052T^2$	296 K ≤ T_{nf} ≤ 336 K 20 ~ 30 nm 0.1 ≤ $\varphi_{.}$ ≤ 0.6 Wt	1.000	0.000	Rejected	✓ ✓ ✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable

Table 1 (continued)

No.	Author	Material Nano-particle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] *P*-Value For T	*P*-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
19	Ruhani et al. [50]	ZnO / Ag [50–50%] Hybrid (water)	$\mu_{nf} = \left[a_0 + a_1\varphi + a_2\varphi^2 + a_3\varphi^3\right]\mu_{bf}$	25 °C < T_{nf} < 50 °C	0.999	0.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable. *(a_0, a_1, a_2, a_3 are dependent on temperature)*
				10 ~ 30 nm ZnO 0 nm Ag				✓	
				0.125 ≤ φ 2 Vol				✓	
20	Huminic et al. [36]	La_2O_3 lanthanum oxide (water)	$\mu_n f = a_1 + a_2T + a_3\varphi + a_4T^2 + a_5T\varphi + a_6\varphi^2 + a_7T^3 + a_8T^2\varphi + a_9T\varphi^2 + a_{10}0\varphi^3 + a_{11}1T^3\varphi + a_{12}2T^2\varphi^2 + a_{13}3T\varphi^3 + a_{14}4\varphi^4$	293 K. T_{nf} 323 K	1.000	0.961	Rejected		According to the statistical variance analysis, the viscosity model does not have the expected dependence on the variables of temperature and concentration. Given the zero concentration in the correlation, the value of the viscosity of the base fluid is not correctly predicted. The correlation has multiple terms
				60 ~ 70 nm diameter and 500 ~ 700 nm length					
				0 < < 0.03 Vol				✓	
21	Elcioglu et al. [51]	Al_2O_3 (water)	μ_{nf} = 1.00973 - 0.0148T + 34.2292φ+0.0041d_p − 0.3458$T\varphi$	20 °C < T_{nf} < 50 °C	1.000	0.999	Rejected	✓	*According to the statistical variance analysis, the viscosity model does not have the expected dependence on the variables of temperature and concentration. (ANOVA [d_p]: 0.986) (d_p: nanoparticles diameter)*
				10 ~ 30 nm				✓	
				0.01 < < 0.03 Vol				✓	

Table 1 (continued)

No.	Author	Material Nano-particle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] *P*-Value For T	*P*-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
22	Li and Zou [26]	TiO_2 (EG / water) [20-80]	$\mu_{nf} = 0.838\varphi^{0.188}T^{0.089}\mu_{bf}^{1.1}$	20 °C < T_{nf} < 60 °C	0.220	0.000	Acceptable	✓	
				15 nm				✓	
				0.025 < < 0.1 Vol				✓	
23	Ghasemi and Karimipour [52]	CuO (liquid paraffin)	$\mu_{nf} = \left[a_1T^{b_1} + a_2\varphi_w^{b_2} + a_3\varphi_w^{b_3}.T^{b_4} + a_4\right]\mu_{bf}$	20 °C < Tnf < 60 °C		0.998	Rejected	✓	According to the statistical variance analysis, the viscosity model does not have the expected dependence on the variables of temperature and concentration
				15 ~ 30 nm				✓	
				0.25 < < 6 Wt				✓	
24	Dalkılıça et al. [32]	SiO_2 / Graphite Hybrid (water)	$\mu_{nf} = \left[1.00527 \times \left(T^{0.00035}\right) \times (1+\varphi)^{9.36265} \times \left(\frac{\varphi_{w,G}}{\varphi_{w,SiO_2}}\right)^{-0.028935}\right]\mu_{bf}$	15 °C < T_{nf} < 60 °C	0.998	0.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable
				SiO_2 7 nm Graphite 6 ~ 10 nm				✓	
				0.001 < < 0.02 Vol				✓	
25	Moldoveanu et al. [53]	Al_2O_3, SiO_2 Hybrid and Separately (Water)	$Al_2O_3 : \mu_{nf} = \left[4135\varphi^2 - 91.72\varphi + 2.06\right]\mu_{bf}$ $SiO_2 : \mu_{nf} = \left[-769\varphi^2 + 42\varphi + 1.1\right]\mu_{bf}$	10 °C < T_{nf} < 60 °C	–	0.000	Acceptable	✓	
				Al_2O_3 43 nm SiO_2 20 nm					
				1 < < 5 Al_2O_3 1 < < 3 SiO_2 Vol				✓	
26	Moldoveanu et al. [54]	Al_2O_3, TiO_2 Hybrid and Separately (Water)	$Al_2O_3 : \mu_{nf} = \left[0.6152\varphi^2 - 1.5449\varphi + 2.3792\right]\mu_{bf}$ $TiO_2 : \mu_{nf} = [0.2302 - 0.3202\varphi + 1.5056]\mu_{bf}$	25 °C	–	0.000	Acceptable	✓	
				Al_2O_3 43 nm TiO_2 30 nm				✓	
				1 < . < 5 Al_2O_3 1 < < 3 TiO_2 Vol				✓	

Table 1 (continued)

No.	Author	Material Nanoparticle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] *P*-Value For T	*P*-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
27	Saeedi et al. [55]	CeO_2 (EG)	$\mu_{nf} = \left[781.4 \times T^{-2.117} \times \varphi^{0.2722} + \frac{0.05776}{T^{-0.7819} \times \varphi^{-0.04009}} + 0.511 \times \varphi^2 - 0.1779 \times \varphi^3\right]\mu_{bf}$	25 °C < T_{nf} < 50 °C	0.000	0.000	Acceptable	✓	
				10 ~ 30 nm				✓	
				0.05 < < 1.2 Vol				✓	
28	Karimipour et al. [56]	CuO (Paraffin)	$\mu_{nf} = \left[a_1 + a_2 T.\varphi_w + a_3\varphi_w\right]\mu_{bf}$	25 °C < T_{nf} < 100 °C	0.371	0.000	Acceptable	✓	
				15 ~ 30 nm					
				0.25 < < 6 Wt				✓	
29	Alrashed et al. [57]	MWCNT / COOH (water)	$\mu_{nf} = 0.00215 - (0.00020 \times [\ln(T - 1) - \ln(\varphi)])$	20 °C < T_{nf} < 50 °C	0.997	0.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable
				9 ~ 15 Diamond 3 ~ 5 MWCNTs				✓	
				0 < < 0.2 Vol				✓	
30	Khodadadi et al. [58]	MgO (Water)	$\mu_{nf} = \left[a_1 + a_2 e^{\varphi^{b_1}} + a_3 e^{T^{b_2}} + a_4 T\right]\mu_{bf}$	25 °C < T_{nf} < 60 °C	0.000	0.000	Acceptable	✓	The correlation has complex terms
				20 nm					
				0.07 < < 1.25 Vol				✓	
31	Esfe amd Arani [59]	MWCNT / SiO_2 (40—60) Hybrid (Oil) [5W50]	$\mu_{nf} = [1.047 + 0.19\varphi + 0.0011T - 1.51 \times 10^{-5}\dot{\gamma} - 1.88 \times 10^{-7}T\dot{\gamma} + 9.974\varphi^2 + 1.5 \times 10^{-9}\dot{\gamma}^2]\mu_{bf}$	5 °C < T_{nf} < 55 °C	1.000	0.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable
				5 ~ 30 nm				✓	
				0 < < 1 Vol				✓	
32	Esfe et al. [60]	MWCNT / [10%—90%] Hybrid (10w40)	$\mu_{nf} = 697.4317382 + 431.879068\varphi - 33.39840555T - 0.041346927\dot{\gamma} - 10.77912341\varphi T - 0.006913725\varphi\dot{\gamma} + 0.001487159T\dot{\gamma} - 334.024913\varphi^2 + 0.623341666T^2 + 0.00000133838\dot{\gamma}^2 + 0.000149409\varphi T\dot{\gamma} + 2.908513579\varphi^2 T + 0.076573024\varphi T^2 - 0.00000120931T\dot{\gamma}^2 + 121.11947\varphi^3 - 0.004802059T^3$	5 °C < T_{nf} < 55 °C	0.000	0.000	Acceptable	✓	The correlation has multiple terms
				-					
				0.05 < < 1 Vol				✓	

Table 1 (continued)

No.	Author	Material Nanoparticle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] *P*-Value For T	*P*-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
33	Abdul Hamid et al. [61]	TiO_2 / SiO_2 Hybrid (Water/EG) [20–80, 40–60, 50–50, 60–40 80–20]	$\mu_{nf} = \left[1.42(1+R)^{-0.1063}\left(\frac{T}{80}\right)^{0.2321}\right]\mu_{bf}$	30 °C < T_{nf} < 80 °C	0.000	–	Acceptable	✓	*(R is ratio of TiO_2 to SiO_2)*
				50 nm TiO_2 22 nm SiO_2				✓	
				1.0 Vol				✓	
34	Akbari et al. [25]	SiO_2 (EG)	$\mu_{nf} = [-24.81 + 3.23T^{0.08014}\exp\left(1.838\varphi^{0.002334}\right) -0.0006779T^2 + 0.024\varphi^3]\mu_{bf}$	30 °C < T_{nf} < 50 °C	0.000	0.000	Acceptable	✓	The correlation has complex terms
				25 nm					
				1 < < 3 Vol				✓	
35	Nabil et al. [62]	TiO_2 / SiO_2 Hybrid (Water / EG) [60-40]	$\mu_{nf} = \left[37\left(0.1 + \frac{\varphi}{100}\right)^{1.59}\left(0.1 + \frac{T}{80}\right)^{0.31}\right]\mu_{bf}$	30 °C < T_{nf} < 80 °C	0.000	0.000	Acceptable	✓	
				30 ~ 50 nm TiO_2 22 nm SiO_2				✓	
				0.5 < < 3 Vol				✓	
36	Zyła and Fal [63]	SiO_2 (EG)	$\mu_{nf} = [1 + 15.39\varphi]\mu_{bf}$	298.15 K	–	0.999	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the concentration variable
				7 ~ 14 nm				✓	
				0 < < 0.26 Vol				✓	
37	Amani et al. [64]	Fe2O4 Magnetic field (Water)	$\mu_{nf} = \left[a_1(1+\varphi)^{a_2}T^{a_3}B^{a_4}\right]\mu_{bf}$	20 °C < T_{nf} < 60 °C	1.000	0.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable. *(Constant parameters are dependent on magnetic field)*
				20 nm				✓	
				0.25 < < 3 Vol				✓	

Table 1 (continued)

No.	Author	Material Nano-particle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] *P*-Value For T	Analysis: ANOVA[1] [Variances] *P*-Value For φ	Analysis: Statistical Status[5]	Analysis: Data[2] Term[3] Trend[4]	Overall conclusion
38	Soltani and Akbari [65]	MgO / MWCNT Hybrid (EG)	$\mu_{nf} = \left[\left[0.191\varphi + 0.240\left(T^{-0.342}\varphi^{-0.473}\right)\right]exp\left(1.45T^{0.120}\varphi^{0.158}\right)\right]\mu_{bf}$	30 °C < T_{nf} < 60 °C	0.516	0.000	Accept-able	✓	The variation trend of the viscosity model is not consistent with the increase in the volume fraction of the nanofluid. The correlation has complex terms
				5 ~ 20 nm MWCNT 40 nm MgO					
				0 < < 1 Vol					
39	Aberoumand et al. [24]	Ag (Oil)	$\mu_{nf} = \left[1.15 + 1.061\varphi - 0.5442\varphi^2 + 0.1181\varphi^3\right]\mu_{bf}$	25 °C < T_{nf} < 60 °C	–	0.000	Accept-able	✓	
				20 nm				✓	
				0 < < 2 Vol				✓	
40	Ilhan et al. [66]	Hexagonal boron nitride [hBN] (water / EG)		25 °C	–	0.000	Accept-able	✓	
				70 nm				✓	
				0.03 < < 3 Vol				✓	
41	Esfe et al. [67]	TiO_2 (water)	$\mu_{nf} = [1.431 - 0.01864T + 0.6073\varphi_w + 0.01334T^2 + 0.02586T\varphi_w + 0.3092\varphi_w^2 + 0.006043T^3 + 0.005644T^2\varphi_w + 0.03323T\varphi_w^2 + 0.08318\varphi_w^3]\mu_{bf}$	280 K T_{nf} 350 K	0.000	0.000	Accept-able	✓	The correlation has multiple terms
				–					
				1 < < 3.5 Wt				✓	
42	Toghraie et al. [68]	Fe_3O_4 (water(	$\mu_{nf} = \left[1.01 + \left(0.007165T^{1.171}\varphi^{1.509}\right) \times \exp(-0.00719T\varphi)\right]\mu_{bf}$	20 °C < T_{nf} < 55 °C	0.609	0.000	Accept-able	✓	
				20–30 nm				✓	
				0.01 < < 3 Vol				✓	
43	Abdolbaqi et al. [69]	SiO_2 (BioGly-col/water) [20–80%] [30–70%]	$\mu_{nf} = \left[0.906exp\left(10.975\varphi + 0.169\frac{T}{80}\right)\right]\mu_{bf}$	30 °C < T_{nf} < 80 °C	0.819	0.000	Acept-able	✓	
				22 nm				✓	
				0.5 < < 2 Vol				✓	

Table 1 (continued)

No.	Author	Material Nanoparticle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] P-Value For T	P-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
44	Syam Sundar et al. [70]	Nanodiamond [ND] (water)	$\mu_{nf} = 1.097\mu_{bf}\left[(1+\varphi)^{0.632}\left(\frac{T_{min}}{T_{max}}\right)^{0.056}\right]$	293 K T_{nf} 333 K	1.000	0.970	Rejected	✓	According to the statistical variance analysis, the viscosity model does not have the expected dependence on the variables of temperature and concentration
				5 ~ 10 nm				✓	
				0 < < 1 Vol				✓	
45	Mostafizur et al. [71]	SiO_2 (methanol)	$\mu_{nf} = 0.2861\varphi^2 + 0.4752\varphi + 1.056$	5 °C < T_{nf} < 25 °C	–	0.000	Acceptable	✓	
				5–15 nm				✓	
				0.005 < < 0.15 Vol				✓	
46	Asadi and Asadi [72]	MWCNT / ZnO (Oil)	$\mu_{nf} = 796.8 + 76.26\varphi + 12.88T + 0.7695\varphi T + \frac{-169.9T - 16.53\varphi T}{\sqrt{T}}$	5 °C < T_{nf} < 55 °C	0.000	1.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the concentration variable
				30 nm				✓	
				0.125 < < 1 Vol				✓	
47	Adio et al. [73]	MgO (EG)	$\mu_{nf} = \left[1 + a_o\phi + a_1\left(\frac{T}{T_o}\right)\varphi + a_2\left(\frac{d_p}{h}\right)\varphi + a_3\left(\frac{T}{T_o}\right)\varphi + a_4\left(\left(\frac{d_p}{h}\right)\varphi\right)^2 + a_5\left(\left(\frac{T}{T_o}\right)\varphi\right)^2 + a_6\varphi^2 + a_7\left(\frac{T}{T_o}\right)^2\varphi^{\frac{1}{3}}\right]\mu_{bf}$	20 °C < T_{nf} < 70 °C	0.000	0.000	Acceptable	✓	*(a is constant, h is the thickness of the capping layer (nanolayer))*
				~21, ~105 and ~125 nm				✓	
				0 < < 5 Vol				✓	
48	Esfe et al. [74]	(Oil)	$\mu_{nf} = \left[1.402 - 0.08407\varphi + 0.2916\varphi^2 - 0.05465\varphi^3\right]\mu_{bf} 5°C$ $\mu_{nf} = \left[1.392 - 0.1682\varphi + 0.5401\varphi^2 - 0.1553\varphi^3\right]\mu_{bf} 25°C$ $\mu_{nf} = \left[1.438 + 0.1002\varphi + 0.2995\varphi^2 - 0.08701\varphi^3\right]\mu_{bf} 45°C$ $\mu_{nf} = \left[1.053 + 0.4609\varphi - 0.2516\varphi^2 + 0.1286\varphi^3\right]\mu_{bf} 65°C$	5 °C < T_{nf} < 65 °C	0.000	0.000	Acceptable	✓	The correlation has multiple terms
				20 nm					
				0.25 < < 2 Vol				✓	

Table 1 (continued)

No.	Author	Material Nano-particle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] P-Value For T	P-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
49	Baratpour et al. [75]	SWCNTs (EG)	$\mu_{nf} = \left[1.089 + \left[-7.722 \times 10^{-9}\left(T/\varphi\right)^2 + 1.1917T^{0.298}\varphi^{0.4777}\right] \times exp\left(19457T^{-0.453}\varphi^{3.219}\right)\right]\mu_{bf}$	30 °C < T_{nf} < 60 °C	0.220	0.000	Acceptable	✓	The correlation has complex terms
				–					
				0.0125 < < 0.1 Vol				✓	
50	Afrand et al. [76]	SiO_2 / MWCNT Hybrid (Oil) [SAE40]	$\mu_{nf} = \left[a_o + a_1\varphi + a_2\varphi^2 + a_3\varphi^3 + a_4\varphi^4\right]\mu_{bf}$	25 °C < T_{nf} < 60 °C	0.995	0.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable. *(a is dependent on temperature)*
				5 ~ 15 nm				✓	
				0 < < 1 Vol				✓	
51	Abdolbaqi et al. [77]	TiO_2 (BioGlycol/water) [20%—80%] [30%—70%]	$\mu_{nf} = \left[0.918exp\left(14.696\varphi + 0.161\frac{T}{80}\right)\right]\mu_{bf}$	30 °C < T_{nf} < 80 °C	0.813	0.000	Acceptable	✓	
				15 nm				✓	
				0.5 < < 2 Vol				✓	
52	Dalkilic et al. [78]	Graphite (Water)	$\mu_{nf} = 1.1686\mu_{bf} + 1.3764 \times 10^{-4}\varphi - 1.8027 \times 10^{-4}$	20 °C < T_{nf} < 60 °C	–	0.945	Acceptable	✓	
				6 ~ 10 nm				✓	
				0 < < 2 Vol				✓	
53	Li et al. [79]	SiC (EG)	$\mu_{nf} = \left[1.07879 + 0.45546\varphi + 0.4051\varphi^2 - 0.2871\varphi^3\right]\mu_{bf}$	25 °C < T_{nf} < 60 °C	–	0.000	Acceptable	✓	
				30 nm				✓	
				0.2 < < 1 Vol				✓	
54	Sharifpur et al. [23]	Al_2O_3 (glycerol)	$\mu_{nf} = \left[1 + \Re[\eta].\left[\left(\frac{T}{T_o}\right)^{a_1}.\varphi^{a_2}.\left(\frac{d_p}{h}\right)^{a_3}\right]\right]\mu_{bf}$	20 °C < T_{nf} < 70 °C	0.997	0.000	Rejected	✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable. *(is the systemparameter, [η] is the intrinsic viscosity,,, are correlation coefficients)*

Table 1 (continued)

No.	Author	Material Nanoparticle (Base Fluid)	Correlation	Range of temperature Nanoparticle diameter concentration	Analysis: ANOVA[1] [Variances] P-Value For T	ANOVA[1] [Variances] P-Value For φ	Statistical Status[5]	Data[2] Term[3] Trend[4]	Overall conclusion
55	Esfe and Saedodin [22]	ZnO (EG)	$\mu_{nf} = \left[0.9118Exp\left(5.94\varphi - 0.00001359T^2\right) + 0.0303Ln(T)\right]\mu_{bf}$	19~160 nm 0< <5 Vol 25 °C < T_{nf} < 50 °C	1.000	0.000	Rejected	✓ ✓ ✓	According to the results of the statistical test of variance, the correlation is not dependent on the temperature variable. The correlation has complex terms
56	Duangthongsuk and Wongwises [21]	TiO_2 (water)	$\mu_{nf} = \left[\left(a_1 + a_2\varphi + a_3\varphi^2\right)\right]\mu_{bf}$	18 nm 0.25< <5 Vol 15 °C < T_{nf} < 35 °C 21 nm 0.2< <2 Vol	–	0.345	Acceptable	✓ ✓ ✓ ✓	*(a, b and c are constant values and dependent on temperature)*

Variances analysis[1]: Results of variance analysis determine the dependence of the correlation on the variable.✓ According to the type of physical evaluation, the correlation is reliable in this case

Data[2]: By considering the concentration of zero in the correlation, the ability of the correlation to estimate the viscosity of the base fluid is investigated. : According to the type of physical evaluation, the correlation, in this case, is not reliable

Terms[3]: correlations with multiple or irrational terms are identified

Trends[4]: According to the physical laws governing the viscosity of nanofluids, the decreasing or increasing trend of viscosity is evaluated according to changes in temperature and concentration

Statistical[5]: Results of physical evaluations of correlations

Given the above, Alarifi et al. [34] studied the viscosity of hybrid nanofluids, which are composed of a mixture of MWCNT and TiO_2 nanoparticles in oil, and they presented a new model by Eq. (3) for the viscosity of the nanofluid by examining the effects of temperature and concentration on the viscosity of the nanofluid. According to the equation, a trigonometric ratio has been used to express the relationship between concentration and viscosity. Therefore, a disproportionate function in relationships is not necessary and can only cause problems in calculations.

$$\mu_{\mathrm{nf}} = 2.936T + \frac{2e^4}{1.68 + T - (1.68\varphi)} - 448.8 - \tan((1.68\varphi) - 1.68) \tag{3}$$

Based on an experimental test on the viscosity behavior of SiO_2 nanoparticles dispersed in a mixture of water and ethylene glycol, Ruhani et al.[35] proposed a viscosity model in Eq. (4), valid in the temperature range of 25 to 50 °C and a volume fraction of 0.1 to 1.5%. The temperature variable in the viscosity model is both in the position of the power function and is powered by the exponential function in terms of position. Therefore, using such functions one after the other is not justified and causes the calculations to be complex.

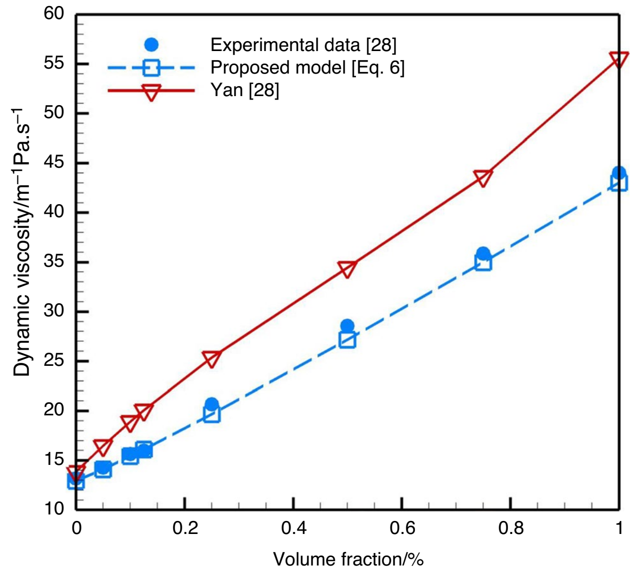

Fig. 4 Comparison of the results of Yan et al.'s correlation [28] and the currently proposed correlation with experimental data

$$\mu_{\mathrm{nf}} = \left[2.030 - \left(931.616 \times \varphi^{0.9305} \times 5.4597 \times T^{-3.4574}\right) - \exp\left(-0.0028 \times \varphi^{2.1421} \times T^{1.0133}\right)^2\right]\mu_{\mathrm{bf}} \tag{4}$$

Yan et al. [28] have presented Eq. (5) for the hybrid nanofluid of MWCNT and TiO_2 in ethylene glycol in the temperature range of 25 to 55 °C and at the volume fraction between 0.05 and 1%;

$$\begin{aligned}\mu_{\mathrm{nf}} = [&0.90463 + 280.20104\varphi + 0.257340\theta + 368.05239\theta\varphi \\ &-28643.68399\varphi^2 - 0.012051\theta^2 - 1968.73612\varphi^2\theta \\ &-235.047290\theta^2\varphi + 2.09629 \times 10^6\varphi^3 - 0.099694\theta^3]\mu_{\mathrm{bf}}\end{aligned} \tag{5}$$

Equation (5) has many terms that entering the equation for subsequent heat transfer calculations may be associated with many errors. On the other hands, by reducing the terms of the equation with increasing the accuracy, the equation becomes easier to use. Therefore, Eq. (5) can be presented more simply as Eq. (6).

$$\mu_{\mathrm{nf}} = \left(0.0029741 + \varphi^{1.07982}\right) \times \left(T^{-1.25573}\right) \times 311157 \tag{6}$$

Equation (6) has been obtained by the nonlinear regression method from experimental data of Yan et al. [28] for hybrid nanofluid viscosity.

According to Fig. 4, the proposed model in Eq. (6), while having higher accuracy than Eq. (5), has a simpler form compared to Eq. (5). Figure (4) plotted at a volume fraction of 0 to 1% and a temperature of 30 °C for nanofluids.

$$\begin{aligned}\mu_{\mathrm{nf}} = &a_1 + a_2T + a_3\varphi + a_4T^2 + a_5T\varphi + a_6\varphi^2 + a_7T^3 + a_8T^2\varphi + a_9T\varphi^2 \\ &+ a_{10}\varphi^3 + a_{11}T^3\varphi + a_{12}T^2\varphi^2 + a_{13}T\varphi^3 + a_{14}\varphi^4\end{aligned} \tag{7}$$

Huminic et al. [36] proposed Eq. (7) for La_2O_3 and water nanofluids in the temperature range of 293 to 323 K and a volume fraction between 0 and 0.03%.

According to Eq. (7), there are many components in the correlation that are similar to Eq. (5), and the experimental data provided by Huminic et al. are used, and Eq. (8) is presented as follows.

$$\mu_{\mathrm{nf}} = \left(0.458474 + \varphi^{1.10104}\right) \times \left(\frac{T}{323}\right)^{-0.636006} \times 1.5773 \tag{8}$$

According to Fig. 5, Eq. (8), simplicity has accuracy more than 2% more than Eq. (7).

A closer look reveals similar cases in which researchers try to present complex correlations; however, using the same experimental data, simple and sometimes linear equations can be given with much higher accuracy than the desired equations, so Eqs. (6) and (8) can replace Eqs. (5) and (7).

While the models proposed for nanofluid viscosity by Esfe et al. [37, 38] presented in Eq. (9) and (10), there are several terms in the viscosity model; therefore, the presence

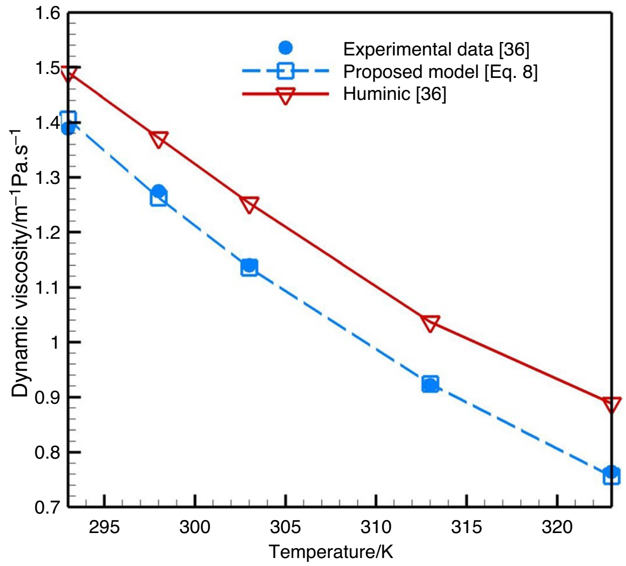

Fig. 5 Comparison of the results of Huminic et al.'s [36] correlation and the proposed correlation with experimental data

of multiple terms in the equations is not necessary and makes the equations more complex, and these multiple components in viscosity calculation will lead to increased computational error.

concentration independently and directly affect the nanofluid viscosity, so that with increasing temperature, the viscosity of nanofluid decreases, and by adding nanoparticles to the base fluid, the viscosity of nanofluid increases. Therefore, at this stage, the variation trend of viscosity values at different temperatures and concentrations according to the physical laws governing nanofluid viscosity is investigated. The results of this analysis are presented in Table 1 of the Trend section.

According to the presented issue, in the viscosity model proposed by Esfe and Esfandeh [39] for the viscosity of nanofluids, including oil and hybrid particles, the variation trend of viscosity values with increasing concentration is contrary to the physical laws governing nanofluid viscosity.

Table 1 exhibits the correlations presented for nanofluid viscosity by various researchers from 2009 to 2020, along with statistical analysis and physical analysis. Statistical analysis of ANOVA test was performed, and terms related to physical examination [Data, Term, Trend] entirely have been presented for each experimental equation.

In addition, the validity range of the equations and the overall conclusion have been presented by the correlation evaluation.

$$\begin{aligned}\mu_{\mathrm{nf}} = {} & 679.7806 + 259.62463\varphi - 33.64131T - 0.045393\dot{\gamma} - 6.0695 \times \varphi T \\ & -0.00031841\varphi\dot{\gamma} + 0.00129007T\dot{\gamma} - 236.23287\varphi^2 + 0.65796T^2 + 2.31776E - 06\dot{\gamma}^2 \\ & +1.55167\varphi^2 T + 0.049085\varphi T^2 - 9.63258E - 8T\dot{\gamma}^2 + 94.57115\varphi^3 \\ & -0.0051586T^3 + 0.0000000001\dot{\gamma}^3\end{aligned} \tag{9}$$

$$\begin{aligned}\mu_{\mathrm{nf}} = {} & 688.46 + 347.09\varphi - 33.12T - 0.04\dot{\gamma} - 7.36\varphi T - 0.0087\varphi\dot{\gamma} + 0.0014T\dot{\gamma} \\ & -305.24\varphi^2 + 0.61T^2 + 1.49 \times 10^{-6}\dot{\gamma}^2 + 0.0001\varphi T\dot{\gamma} + 0.46\varphi^2 T + 0.0014\varphi^2\dot{\gamma} \\ & + 0.065\varphi T^2 + 1.87 \times 10^{-7}\varphi\dot{\gamma}^2 - 7.25 \times 10^{-6}T^2\dot{\gamma} - 7.33 \times 10^{-8}T\dot{\gamma}^2 + 169.62\varphi^3 \\ & -0.0043T^3 + 0.00000000011\dot{\gamma}^3\end{aligned} \tag{10}$$

In the continuation of reviewing the results and data extracted from viscosity models, it has been observed that sometimes the equations at zero concentration and in a certain range of temperature and concentration have an unusual response. The results of this analysis are presented in Table 1 of the Data section.

For example, Huminic et al. [36] presented the viscosity model for La_2O_3 and water nanofluids in the temperature range of 293–323 K and at a volume fraction between 0 and 0.03 contrary to the researcher claims, the correlation is not able to respond at zero concentration.

Finally, according to studies by researchers on the viscous behavior of nanofluids, variables of temperature and

Sensitivity analysis with Monte Carlo test

The sensitivity analysis method has been used to continue the statistical study process of relationships and know the position of variables in correlations. According to the general definition in statistics, sensitivity analysis is the study of the effectiveness of output variables from a set of assumed input variables in a statistical model.

As a result, the researcher can determine how changes in a component affect the model's output. Therefore, in the continuation of the statistical study article, the sensitivity analysis will give a deeper look at viscosity models with the

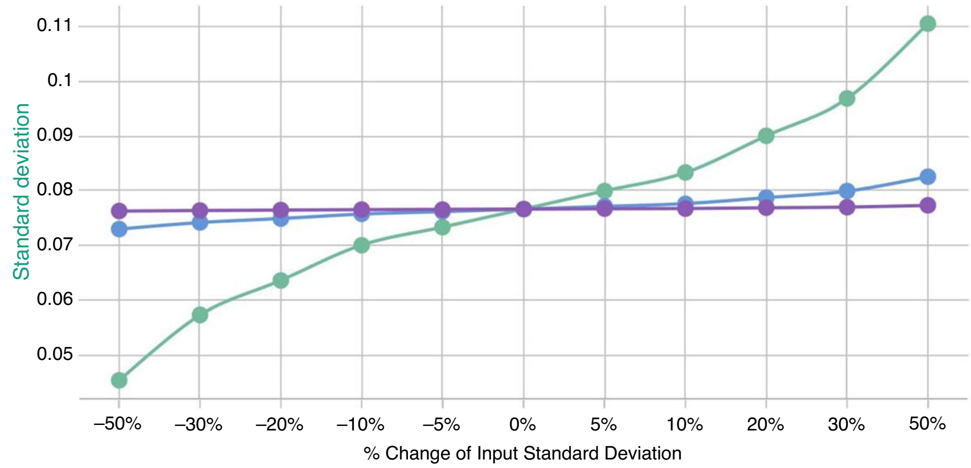

Fig. 6 Result of sensitivity analysis on the correlation proposed by Li and Zou [26]. (green color: base fluid viscosity variable/ blue color: volume fraction variable/ purple color: temperature variable)

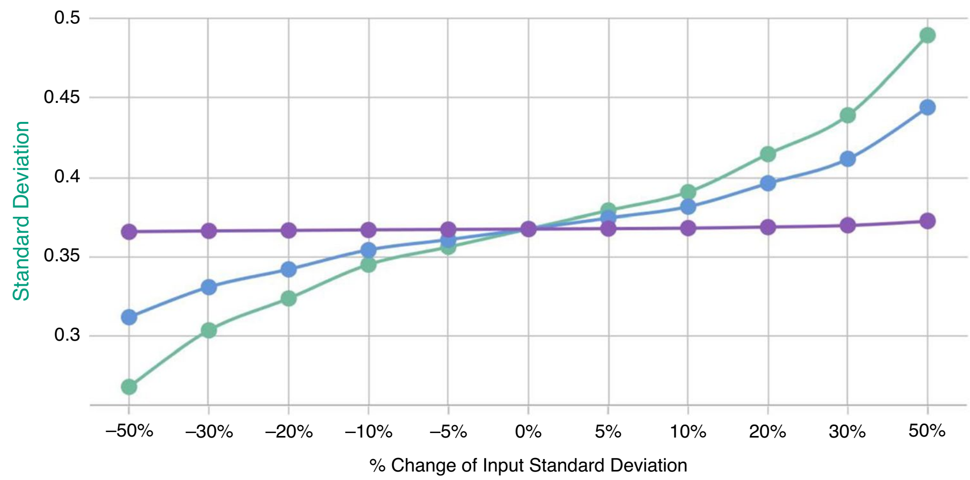

Fig. 7 Result of sensitivity analysis on the correlation proposed by Saeedi et al. [55]. (green color: base fluid viscosity variable/ blue color: volume fraction variable/ purple color: temperature variable)

variables of base fluid viscosity, temperature, and concentration. [80]

Therefore, to obtain a complete conclusion about the performance of viscosity models and the effectiveness of variables, only the correlations in which the variables have the expected dependence on the viscosity equations in terms of variance test are examined.

In the present study, to analyze viscosity models, also a method known as the Monte Carlo test is used.

Variables with little effect and little change on the equations are displayed as flat lines in the graph. So the more curved lines show the more dependence of the variable on the equation.

Li and Zou [26] introduced the viscosity model of Eq. (11) for nanofluids consisting of Al_2O_3 nanoparticles and water-based nanofluid, and Saeedi et al. [55] proposed the viscosity model of Eq. (12) for Ce O_2 nanoparticles dispersed in ethylene glycol.

$$\mu_{\mathrm{nf}} = 0.838\varphi^{0.188}T^{0.089}\mu_{\mathrm{bf}}^{1.1} \tag{12}$$

The test results in Figs. 6 and 7 show that the curvature of the green line is greater than that of the blue and purple lines, and the presence of the variable of the viscosity of the base fluid in correlation is more important than other variables. In addition, concentration and temperature, respectively, have an influential role in the equations.

Equation (13) presents Nabil et al. [62] viscosity model for the hybrid nanofluid of TiO_2 and SiO_2 in a mixture of water and ethylene glycol.

$$\mu_{\mathrm{nf}} = \left[37\left(0.1 + \frac{\varphi}{100}\right)^{1.59}\left(0.1 + \frac{T}{80}\right)^{0.31}\right]\mu_{\mathrm{bf}} \tag{13}$$

In Fig. 8, the green line has higher curvature than the blue and purple lines. Therefore, the sensitivity analysis results showed that the variables of base fluid viscosity,

$$\mu_{\mathrm{nf}} = \left[781.4 \times T^{-2.117} \times \varphi^{0.2722} + \frac{0.05776}{T^{-0.7819} \times \varphi^{-0.04009}} + 0.511 \times \varphi^2 - 0.1779 \times \varphi^3\right]\mu_{\mathrm{bf}} \tag{11}$$

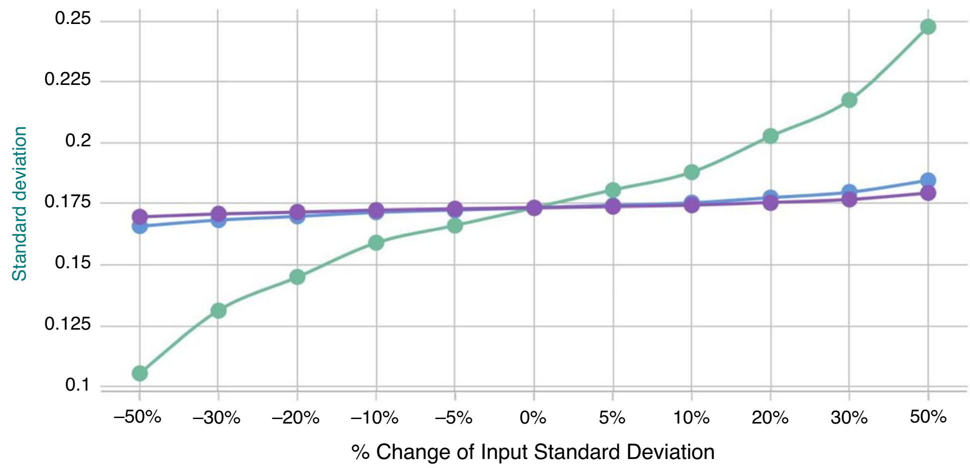

Fig. 8 Result of sensitivity analysis on the correlation proposed by Nabil et al. [62]. (green color: base fluid viscosity variable/ blue color: volume fraction variable/ purple color: temperature variable)

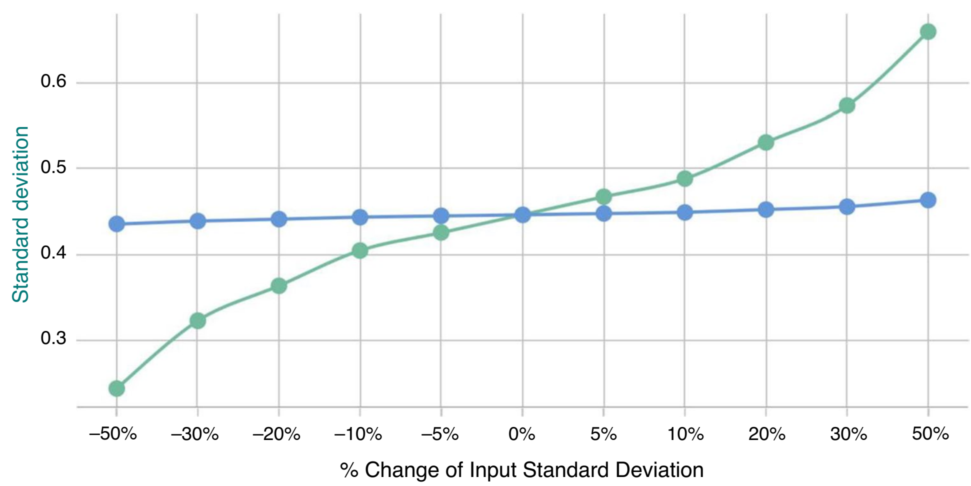

Fig. 9 Result of sensitivity analysis on the correlation proposed by Esfe et al. [48]. (green color: temperature variable/ blue color: concentration variable)

concentration, and temperature significantly affect Eq. (13), respectively.

The variables of base fluid viscosity, temperature, and concentration are available in the above viscosity equations. The variable of base fluid viscosity applies the value of the base fluid viscosity in proportion to the reference temperature in the viscosity model. Therefore, the dependence of the viscosity equations on the viscosity variable of the base fluid expresses the relationship of the equations on temperature. On the other hands, the sensitivity analysis results show that the variable of the base fluid viscosity has a more contribution in estimating the viscosity of nanofluid than other variables. Therefore, considering the mentioned conditions, it is concluded that the temperature factor indirectly has a more significant effect on viscosity equations than other variables.

Esfe et al. [48] have presented Eq. (14) for the viscosity of hybrid nanoparticles of MWCNT and Ti O_2 in a mixture of water-based nanofluid and ethylene glycol;

$$\mu_{\mathrm{nf}} = 6.35 + 2.56\varphi - 0.24T - 0.068\varphi T + 0.905\varphi^2 + 0.0027T^2 \tag{14}$$

According to the sensitivity analysis results presented in Fig. 9, the effect of the temperature is greater than the concentration in the equation because the curvature of the green line is more significant.

$$\begin{aligned}\mu_{\mathrm{nf}} = {} & 688.46 + 347.09\varphi - 33.12T - 0.04\dot{\gamma} - 7.36\varphi T - 0.0087\varphi\dot{\gamma} + 0.0014T\dot{\gamma} \\ & -305.24\varphi^2 + 0.61T^2 + 1.49\times10^{-6}\dot{\gamma}^2 + 0.0001\varphi T\dot{\gamma} + 0.46\varphi^2 T + 0.0014\varphi^2\dot{\gamma} \\ & + 0.065\varphi T^2 + 1.87\times10^{-7}\varphi\dot{\gamma}^2 - 7.25\times10^{-6}T^2\dot{\gamma} - 7.33\times10^{-8}T\dot{\gamma}^2 + 169.62\varphi^3 \\ & -0.0043T^3 + 0.00000000011\dot{\gamma}^3\end{aligned} \tag{15}$$

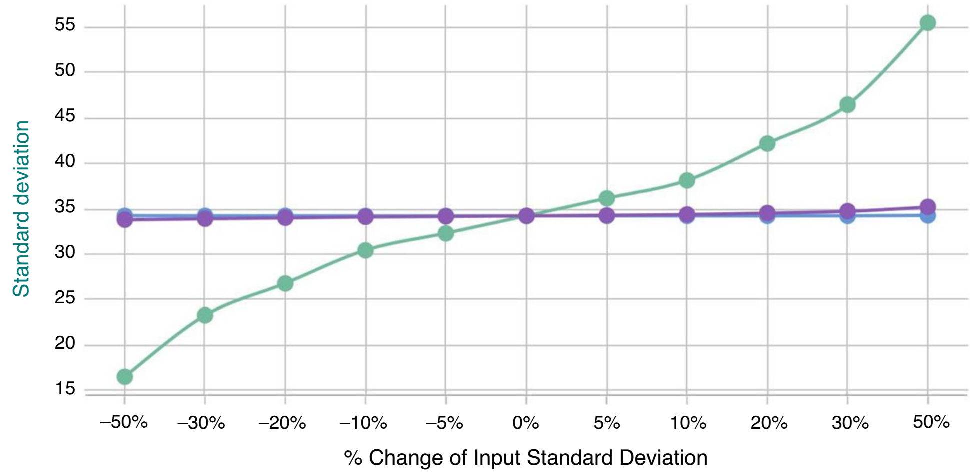

Fig. 10 Result of sensitivity analysis on the correlation proposed by Esfe et al. [37]. (green color: temperature variable/ blue color: volume fraction variable/purple color: variable of shear rate)

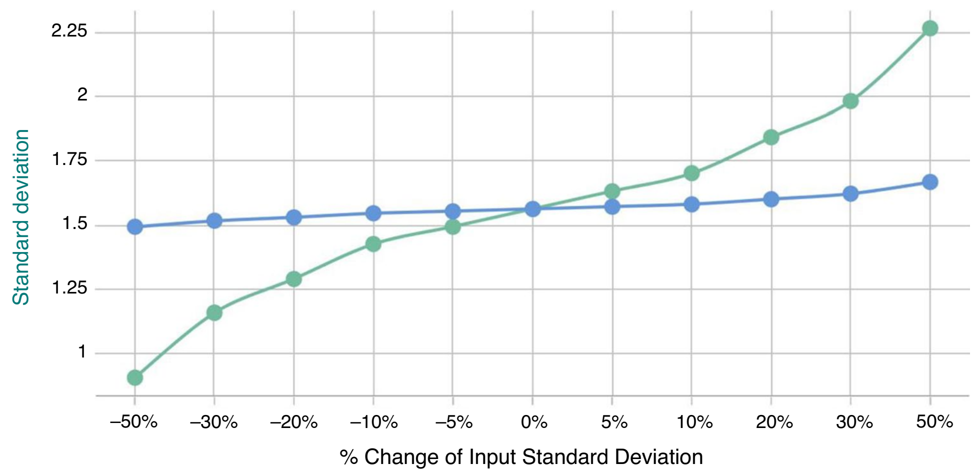

Fig. 11 Result of sensitivity analysis on the correlation proposed by Li et al. [79]. (green color: base fluid viscosity variable/ blue color: concentration variable)

Esfe et al. [38] presented the nanofluid viscosity model for the MWCNT and Al_2O_3 hybrid nanoparticles dispersed in oil in Eq. (15).

The sensitivity analysis results in Fig. 10 showed that the green line has higher curvature than the purple and blue lines, so the effect of the temperature is greater than the concentration in the equation.

According to the results and the role of temperature and concentration in Eq. (15), the shear rate of nanofluid is also effective in calculating the viscosity of nanofluid.

The results of sensitivity analysis of the previous two equations show that when the variable of base fluid viscosity is not present in the viscosity equations, conditions are created that the effect of temperature factor is directly applied in the viscosity equations, and thus, the temperature variable has a more influential role than other variables.

Equation (16) presents Li et al. [79] model for the viscosity of SiC and water nanofluids.

$$\mu_{\mathrm{nf}} = \left[1.07879 + 0.45546\varphi + 0.4051\varphi^2 - 0.2871\varphi^3\right]\mu_{\mathrm{bf}} \quad (16)$$

Based on the sensitivity test results in Fig. 11 and given the curvature of the green line, the viscosity of base fluid has a higher contribution to the concentration variable in calculating the viscosity of the nanofluid.

There is a base fluid viscosity variable μ_{bf} in most of the correlations reviewed here and in the known nanofluid viscosity models, and this factor determines the viscosity value of the base fluid relative to the reference temperature in the viscosity models, so the effects of temperature through the base fluid viscosity variable are considered in viscosity models. Therefore, the high dependence of the viscosity models on the variable of base fluid viscosity is due to the dependence of the viscosity models on temperature.

It is concluded that the effects of temperature are not directly considered in the correlations, and the μ_{bf} component is not an independent variable, which can cause problems.

Table 2 Status of statistical and physical analysis of all equations of Table 1

Viscosity correlations of nanofluids	Acceptable (reliable)/%	Rejected (unreliable)/%
Statistically status	53.6	46.4
Physical examination	73.2	26.8
Total status	35.7	64.3

Table 3 Status of evaluation of viscosity equations based on water-based nanofluid

Viscosity correlations of water-based nanofluid	Acceptable (reliable)/%	Rejected (unreliable)/%
Statistically status	38.9	61.1
Physical examination	83.3	16.7
Total status	27.7	72.3

According to the issues mentioned above and based on the sensitivity analysis results performed on viscosity models, the temperature factor plays a decisive role in viscosity models. Therefore, the results show the inherent dependence of nanofluid viscosity on temperature.

Table 4 Status of evaluation of viscosity equations based on ethylene glycol-based nanofluid

Viscosity correlations of EG-based nanofluid	Acceptable (reliable)/%	Rejected (unreliable)/%
Statistically status	54.5	45.5
Physical examination	54.5	45.5
Total status	27.2	72.8

Overall analysis of empirical correlations

Table 1 is statistically and physically examined the prediction correlations of nanofluid viscosity. In the statistical study, variance analysis for temperature and volume (mass) fraction of nanofluid has been performed, and the results have been presented in the column related to the statistical study. In addition, in physical examination, three factors of Data, Term, and Trend have been considered. The Data column in Table 1 examines the experimental correlations' ability to respond at zero concentration to reach the value of the base fluid viscosity. In the Term column of Table 1, the results have been mentioned regarding the existence of numerous and irrational terms for estimating the viscosity of the mentioned experimental correlations. The compliance and the role of the variables introduced in the empirical correlations presented in Table 1 relative to the physics governing the viscosity of the nanofluid are evaluated in the Trend column of Table 1.

In evaluating viscosity relationships, it was observed that there are relationships that have good conditions in the physical examination but are not statistically similar. Also, reverse conditions for equations are possible. Therefore, it was decided to report the relationships with good status in two physical and statistical states in the total section.

By examining all the correlations in Table 1 and their statistical analysis and examining the physical performance of the correlations and the validity of each equation, it can be concluded that 53.6% of the equations are statistically valid. Also, 73.2% of the equations have accuracy and simplicity in terms of performance; in total, 35.7% of the equations in both physical and statistical states have an acceptable condition (Table 2).

The results of the evaluation of the experimental correlations presented in Table 1 for nanofluids based on water and ethylene glycol, which are widely used in the field of research, have been developed. Accordingly, in a comprehensive study on the correlations of Table 1 for water-based nanofluids, it is statistically and physically determined that statistically, 38.9% of the correlations are acceptable, 83.3% are physically reliable correlations, and a total of 27.7% of the correlations are acceptable. The results of this study are presented in Table 3.

Suppose the examination for water-based nanofluid is performed again for ethylene glycol-based nanofluids, as shown in Table 4. In that case, 54.5% of the correlations are statistically acceptable, 54.5% are physically reliable, and a total of 27.2% of the ethylene glycol-based nanofluid equations in both physical and statistical states had an acceptable condition.

Thus, the statistically and physically acceptable correlations for the water- and ethylene glycol-based nanofluid are presented in Tables 5 and 6.

Proposing a viscosity model and its validation

Preliminary analysis

By studying the correlations proposed by the researchers, the relationship of variables with the viscosity of nanofluid was determined. Therefore, it was confirmed by the analysis of variance that temperature and concentration variables play a decisive role in the relationship between the viscosity of nanofluids. In addition, the results of the statistical tools of sensitivity analysis showed that the viscosity of nanofluid is directly dependent on the temperature factor.

Table 5 Acceptable correlations for the viscosity of water-based nanofluid

No	Author	Correlation	Material Nanoparticle (Base fluid)
1	Duangthongsuk and Wongwises [21]	$\mu_{nf} = \left[\left(a_1 + a_2\varphi + a_3\varphi^2\right)\right]\mu_{bf}$	TiO_2 (water)
2	Moldoveanu et al. [53]	$Al_2O_3 : \mu_{nf} = \left[4135\varphi^2 - 91.72\varphi + 2.06\right]\mu_{bf}$ $SiO_2 : \mu_{nf} = \left[-769\varphi^2 + 42\varphi + 1.1\right]\mu_{bf}$	Al_2O_3, SiO_2 Hybrid Separately (Water)
3	Moldoveanu et al. [54]	$Al_2O_3 : \mu_{nf} = \left[0.6152\varphi^2 - 1.5449\varphi + 2.3792\right]\mu_{bf}$ $TiO_2 : \mu_{nf} = \left[0.2302\varphi^2 - 0.3202\varphi + 1.5056\right]\mu_{bf}$	Al_2O_3, TiO_2 Hybrid Separately (Water)
4	Toghraie et al. [68]	$\mu_{nf} = \left[1.01 + \left(0.007165T^{1.171}\varphi^{1.509}\right) \times \exp(-0.00719T\varphi)\right]\mu_{bf}$	Fe_3O_4 (water)
5	Dalkilic et al. 2016	$\mu_{nf} = 1.1686\mu_{bf} + 1.3764 \times 10^{-4}\varphi - 1.8027 \times 10^{-4}$	Graphite (Water)

Table 6 Acceptable correlations for the viscosity of ethylene glycol-based nanofluid

No	author	Correlation	Material Nanoparticle (Base Fluid)
1	Saeedi et al. [55]	$\mu_{nf} = \left[781.4 \times T^{-2.117} \times \varphi^{0.2722} + \frac{0.05776}{T^{-0.7819} \times \varphi^{-0.04009}} + 0.511 \times \varphi^2 - 0.1779 \times \varphi^3\right]\mu_{bf}$	CeO_2 (EG)
2	Adio et al. [73]	$\mu_{nf} = \left[1 + a_o\varphi + a_1\left(\frac{T}{T_o}\right)\varphi + a_2\left(\frac{d_p}{h}\right)\varphi + a_3\left(\frac{T}{T_o}\right)\varphi + a_4\left(\left(\frac{d_p}{h}\right)\varphi\right)^2 + a_5\left(\left(\frac{T}{T_o}\right)\varphi\right)^2\right]\mu_{bf}$	MgO (EG)
3	Li et al. [79]	$\mu_{nf} = \left[1.07879 + 0.45546\varphi + 0.4051\varphi^2 - 0.2871\varphi^3\right]\mu_{bf}$	SiC (EG)

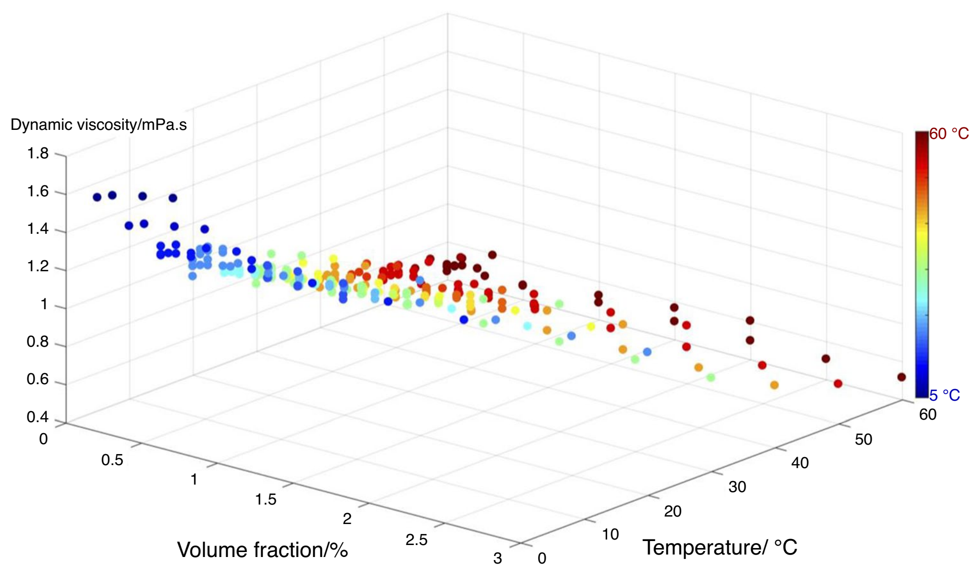

Fig. 12 Three-dimensional representation of the viscosity dispersion of nanofluids with water-based nanofluid. [21, 43, 64, 78, 81–84]

Given that the volume fraction variable of nanoparticles affects nanofluid's viscosity, and the rate of viscosity changes relative to the volume fraction of nanoparticles depends on the type of the base fluid.

On the other hands, it is crucial for the viscosity of the nanofluid with water-based nanofluid and ethylene glycol, which does not have limited use in terms of temperature, volume fraction, and especially particle material. Therefore, in the present study, two models with very high accuracy for nanofluids with water-based nanofluid in a wide range of volume fractions and temperature have been presented, and this important has been done for ethylene glycol-based nanofluid.

Evaluating the experimental studies on the viscosity of nanofluids in proportion to temperature and concentration, approximately the physical conditions of more than 1200

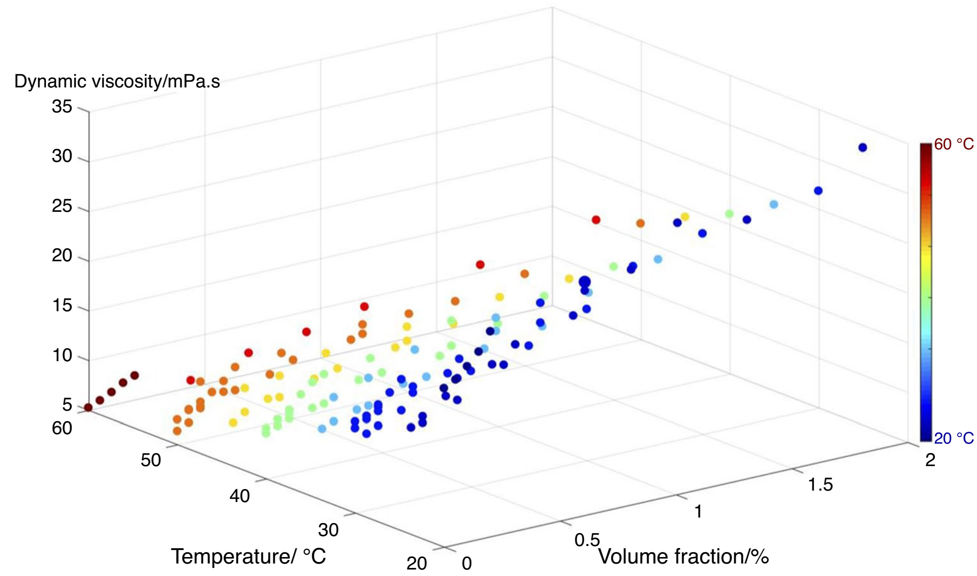

Fig. 13 Three-dimensional representation of the viscosity dispersion of nanofluids with ethylene glycol-based nanofluid. [55, 85–88]

experimental data were examined, and dispersed viscosity values were observed for the experimental data under the same physical conditions. Therefore, to increase the accuracy of the proposed correlation, a group of articles has been removed, and articles with appropriate and centralized experimental data have been selected to provide the correlation.

Figure 12 is plotted in terms of temperature and volume fraction of the water-based nanofluid to know the physical condition of the experimental data used. [21, 43, 64, 78, 81–84]

Figure 12 shows that the congestion of experimental data for the viscosity of water-based nanofluid at concentrations less than 1%, and the temperature range of 30 to 40 °C is higher.

Also, the dispersion of experimental data to present the viscosity model is shown in Fig. 13 in terms of temperature and volume fraction of ethylene glycol-based nanofluid. [55, 85–88]

Also, according to Fig. 13, at low concentrations and the temperature range of 30 to 50 °C, the viscosity of ethylene glycol-based nanofluid has higher congestion.

Proposed correlation

Experimental viscosity correlations proposed by previous researchers cover a limited temperature range and volume fraction. Most experimental correlations proposed for nanofluid viscosity are unable to estimate the base fluid viscosity. On the other hands, in the analysis of variance, it was found that most of the mentioned correlations do not depend on the independent variables of those correlations. The sensitivity analysis results also showed that the factor of temperature directly affects the viscosity of nanofluid, and the variable of temperature has a more significant contribution in estimating the viscosity of nanofluid than other variables. In such conditions, to eliminate these shortcomings, a model has been presented for estimating the viscosity of water- and ethylene glycol-based nanofluid entitled BAG, Barkhordar-Armaghani-Ghasemiasl. The summary of the statistical and physical study of the BAG model is given in Table 7. According to the variance analysis, the temperature variable and the volume fraction have the appropriate P Values for the BAG model.

The results of estimating the viscosity of water- and ethylene glycol-based nanofluid based on the BAG model in Table 7 compared to the experimental data in Figs. 12 and 13 based on R^2 of water-based nanofluid are 97.01% and for ethylene glycol-based nanofluid are 96.08%.

Evaluation of BAG viscosity model

For assessing the validity of the accuracy of the presented correlations, it is necessary to compare the obtained results with the conventional and selected correlations. For this purpose, some conventional correlations in articles are introduced as follows. Einstein [1] was the first to introduce a microfluidic viscosity model for suspensions containing metal particles in 1906. This correlation applies to the viscosity of microfluid with spherical particles at a volume fraction of less than 5%. This model is given in Eq. (17).

$$\mu_{\mathrm{nf}} = (1 + 2.5\varphi)\mu_{\mathrm{bf}} \tag{17}$$

Brinkman [19] proposed a new model in 1952 according to Einstein's model. This correlation is suitable for

Table 7 BAG models for nanofluids viscosity

No.	Symbol	Base fluid	Correlation	Range of temperature concentration	Analysis			Atatus	
					ANOVA [Variances]		Data	Statistical	Physical
					P Value For T	*P* Value For φ	Term Trend		
1	BAG I	Water	$\mu_{nf} = \left(1.89841 + \left(\frac{\varphi}{0.03}\right)^{3.3616}\right) \times \left(-0.27265 \cdot \left(\frac{T}{60}\right)^{0.701322}\right) + \left(\frac{T}{60}\right)^{-0.213772} + 0.248161 \cdot \left(\frac{\varphi}{0.03}\right)^{1.65192}$		0.000	0.000	✓ ✓ ✓	Acceptable	Reliable
2	BAG II	Ethylene glycol	$\mu_{nf} = \left(0.85614 + \left(\frac{\varphi}{0.02}\right)^{0.81593}\right) \times \left(6.30106 \cdot \left(\frac{T}{60}\right)^{-1.10622}\right) + \left(\frac{T}{60}\right)^{-0.23249} + \left(\frac{\varphi}{0.02}\right)^{0.24584}$		0.000	0.000	✓ ✓ ✓	Acceptable	Reliable

suspensions with a volume fraction of less than 4%. This correlation is given in Eq. (18), used in most studies by researchers.

$$\mu_{nf} = \left(\frac{1}{(1-\varphi)^{2.5}}\right)\mu_{bf} \tag{18}$$

In 1977, Batchelor [20] proposed a viscosity model for single-phase suspensions based on the Brownian motion of particles. Moreover, Eq. (19) is derived according to the Einstein equation and the existence of spherical particles.

$$\mu_{nf} = \left(1 + 2.5\varphi + 6.2\varphi^2\right)\mu_{bf} \tag{19}$$

In recent studies, Wang et al. [89] performed experiments on Al_2O_3 nanofluids separately for water and ethylene glycol-based nanofluid. Equations (20) and (21) are obtained for water-based Al_2O_3 nanofluid and ethylene glycol-based Al_2O_3 nanofluid.

$$\mu_{nf} = \left(1 + 7.3\varphi + 123\varphi^2\right)\mu_{bf} \tag{20}$$

$$\mu_{nf} = \left(1 + 4.6\varphi + 6.7\varphi^2\right)\mu_{bf} \tag{21}$$

In another study, Chen et al. [90] presented Eq. (22) for nanofluid viscosity. This correlation has been used in numerous previous articles.

$$\mu_{nf} = \left(1 + 10.6\varphi + (10.6\varphi)^2\right)\mu_{bf} \tag{22}$$

Ho et al. [91] then performed an experimental experiment based on convection heat transfer and examined the variation trend of viscosity with increasing nanofluid concentration and presented Eq. (23).

$$\mu_{nf} = \left(1 + 4.93\varphi + 222.4\varphi^2\right)\mu_{bf} \tag{23}$$

Then, the results of estimating the viscosity of water-based nanofluid based on the BAG I model in row 1 of Table 7 have been evaluated with the conventional and selected correlations in Eqs. (17) to (23) according to the experimental data in Fig. 12.

In Fig. 14, parts a and b, the results for the nanofluid viscosity have been plotted at the temperature of 20 and 50 °C and a variable volume fractions of 0 to 3%, respectively. In the results, where scattered data are available, the values estimated by the BAG I model are more accurate than the points where the data are most concentrated.

Given that the present study uses a variety of experimental data, the experimental data used in this study have been extracted from several sources; also, the existence of data scatter in constant physical conditions seems reasonable. Therefore, in such cases, it is expected that BAG models can predict the values in which the data are more focused.

According to Fig. 14, parts c and d, the results for the nanofluid viscosity have been plotted at volume fractions of 0.1 and 1% and a variable temperature of 20–60 °C, respectively. The results indicated the BAG I model accurately predicts nanofluid viscosity according to the trend of temperature changes.

In another analysis, the BAG I model with the acceptable correlations in Table 1 for water-based nanofluid has been examined based on the experimental data in Fig. 12.

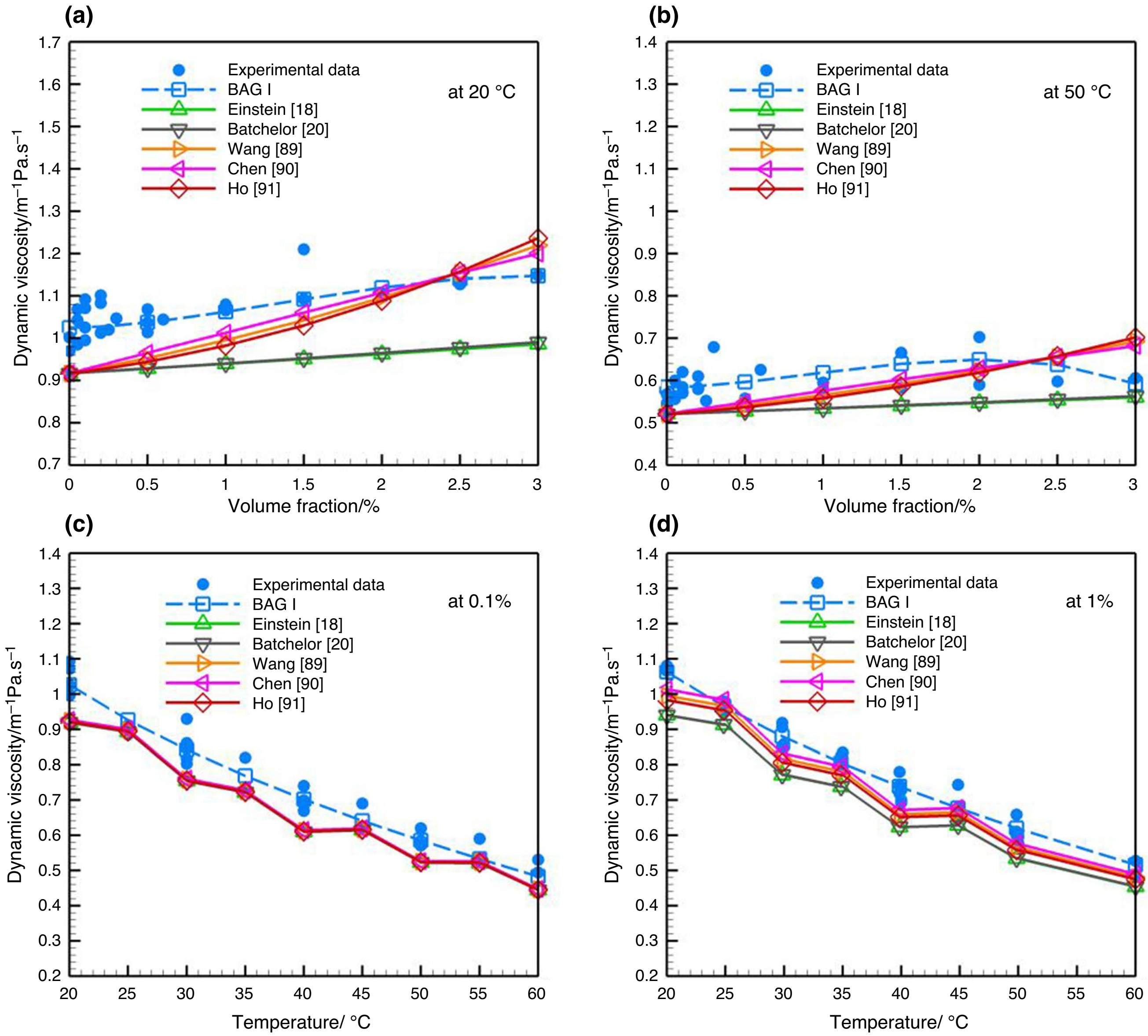

Fig. 14 Comparison of BAG I model with conventional correlations in Eqs. (17) to (23)

However, the accuracy range of the acceptable correlations in Table 1 is not the same as the range of experimental data in Fig. 12, but to quantitatively express the estimation of the considered correlations relative to the BAG I model, which can estimate over a wide range of temperature 5–60 °C and volume fraction 0–3%. The results in the same physical conditions in Fig. 14 is also shown in Fig. 15; as can be seen, the results obtained from the BAG I model relative to the acceptable correlations in Table 1 are in good agreement with the experimental data.

RMSE measures the error rate of two datasets. This parameter compares the predicted values and the experiment's values with each other, and the lower value leads to the lower error of the model. Thus, RMSE is an appropriate tool to compare correlations.

Based on Eqs. 24 and 25, to determine the error of the equations in predicting the experimental viscosity values, the "root mean square error," or RMSE index, has been used. Also, the accuracy of the equations in estimating the experimental viscosity values is expressed by the R-squared index.

Table 8 shows the RMSE values obtained for the conventional correlations and acceptable correlations in Table 1 and the BAG I model on the experimental points for estimating the viscosity of the water-based nanofluid.

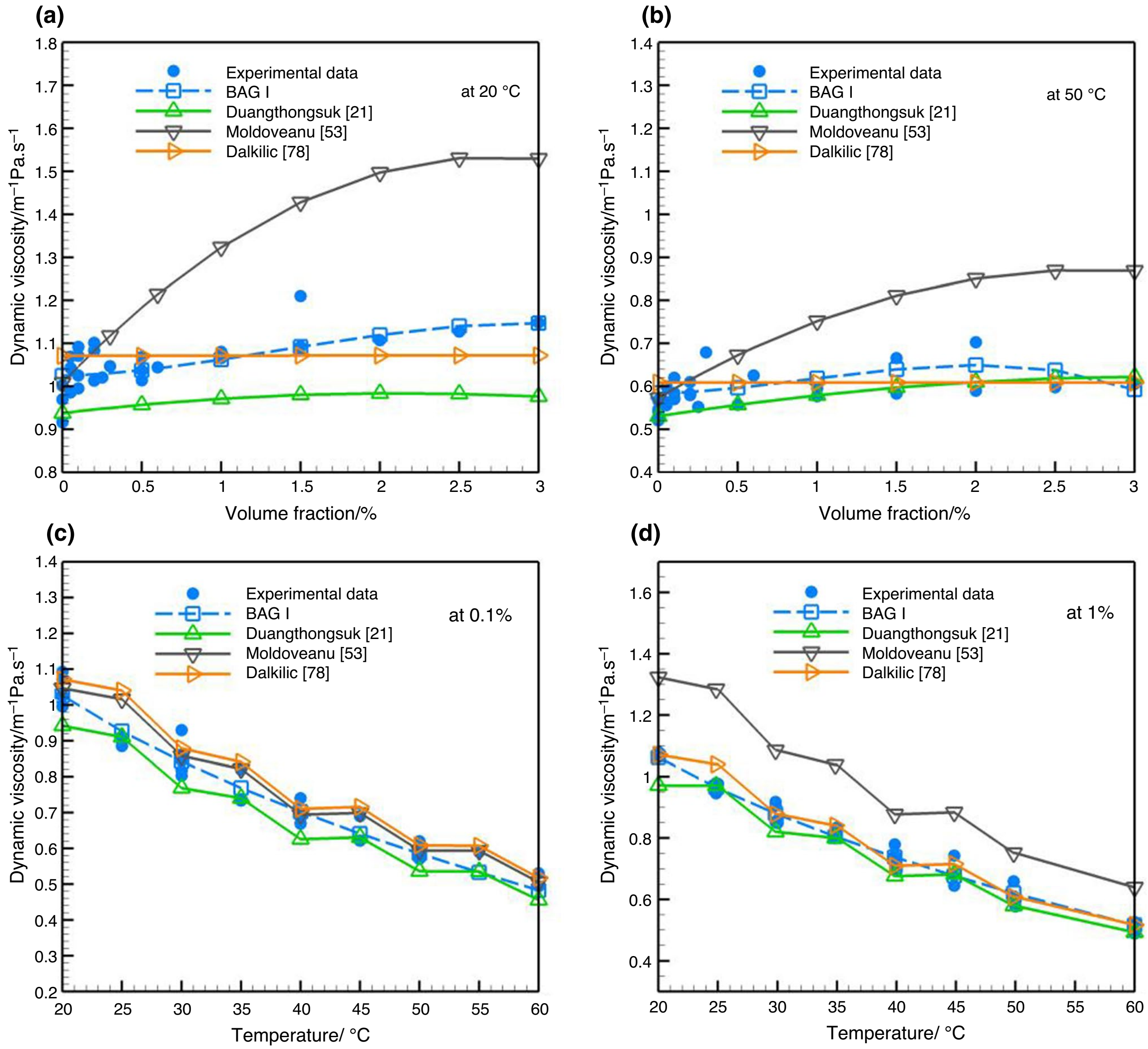

Fig. 15 A comparison of the BAG I model with acceptable correlations appeared in Table 1

Table 8 The RMSE value of the BAG I model compared to other correlations for water-based nanofluids

Equations	RMSE
Einstien [18]	0.083422758
Batchelor [20]	0.083058883
Wang [89]	0.066209608
Chen [90]	0.062280061
Ho [91]	0.069636179
Duangthongsuk [21]	0.060700168
Moldoveanu [53]	0.173518889
Dalkilic [78]	0. 081515186
BAG I	0.038959537

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} \left(\mu_{\mathrm{pre}} - \mu_{\mathrm{exp}}\right)^2}{N}} \tag{24}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N} \left(\mu_{\mathrm{pre}} - \mu_{\mathrm{exp}}\right)}{\sum_{i=1}^{N} \left(\mu_{\mathrm{pre}} - \overline{\mu_{exp}}\right)} \tag{25}$$

Findings based on the RMSE value indicate that the BAG I model has a 35.82% lower performance error than the best correlation presented by the researchers to estimate the viscosity of water-based nanofluids.

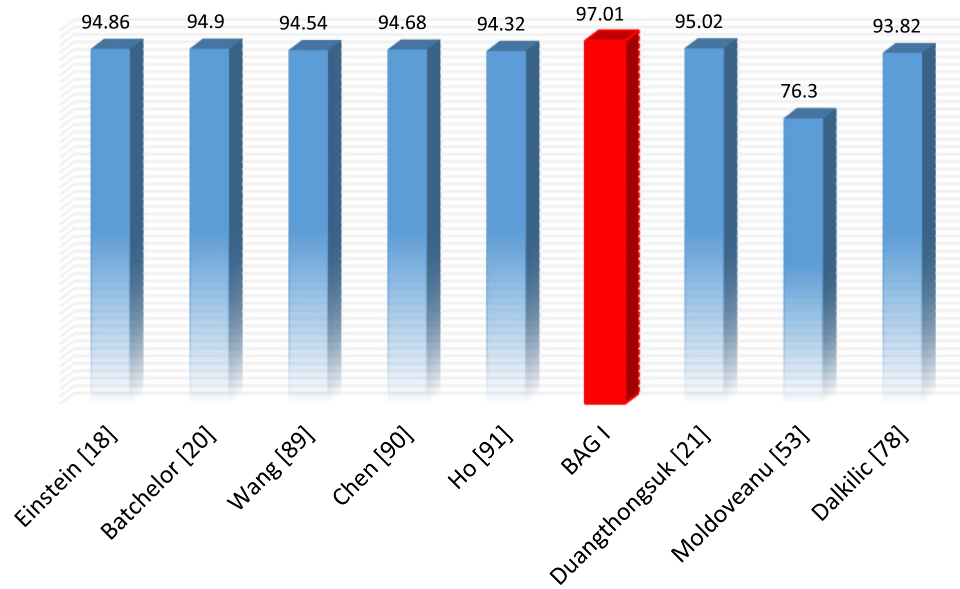

Fig. 16 The value of R^2 in the BAG I model compared to other correlations for water-based nanofluids

In addition, the diagram of the results of the R^2 coefficient for the conventional and acceptable correlations of Table 1 and the BAG I model is presented in Fig. 16. Besides the reasonable accuracy of other correlations in estimating nanofluid viscosity, the BAG I model has higher accuracy than other correlations in estimating nanofluid viscosity according to the trend of nanofluid viscosity changes.

In most studies on the viscosity of nanofluids, especially the conventional correlations, the correlations cannot predict the viscosity of nanofluids with the ethylene glycol-based nanofluid. One of the reasons for the weakness of these correlations is the high concentration of ethylene glycol-based nanofluid viscosity relative to water. On the other hands, usual correlations have been optimized for the viscosity of low concentration nanofluids. Therefore, conventional correlations do not respond proportionally to the nanofluid's viscosity with the ethylene glycol-based nanofluid. With these interpretations, the BAG II model for the viscosity for the nanofluids with ethylene glycol-based nanofluid has high accuracy for estimating viscosity.

Then, the results of estimating the viscosity of ethylene glycol-based nanofluid based on the BAG II model in row 1 of Table 7 have been evaluated with the conventional and selected correlations in Eqs. (17) to (23) according to the experimental data in Fig. 13.

In Fig. 17, parts a and b, the viscosity of the nanofluid is, respectively, at 30 and 50 °C and the variable concentration. In sections c and d, the results for the nanofluid viscosity have been plotted at volume fractions of 0.2 and 0.8% and variable temperature, respectively.

As expected, because the conventional correlations for the viscosity of nanofluids with the water-based nanofluid have been optimized, they cannot estimate the viscosity of nanofluids with ethylene glycol-based nanofluid. Considering the experimental data, the viscosity values predicted by the BAG II relation are much more accurate than the conventional relations.

In another analysis, the BAG II model with the acceptable correlations in Table 1 for ethylene glycol-based nanofluids has been investigated based on the experimental data in Fig. 13.

However, the accuracy range of the acceptable correlations in Table 1 is not the same as the range of experimental data in Fig. 13, but to quantitatively present the estimation of the considered correlations relative to the BAG II model, which can estimate in a wide range of temperature 20 to 60 °C and volume fraction 0 to 2%. Also, the results are presented in Fig. 18.

According to parts a and b of Fig. 18, at the volume fraction range of 1–2% and temperatures of 30 and 50 °C, the BAG II model is significantly more accurately predicted than the other correlations.

Also, in Fig. 18, parts c and d, at volume fractions of 0.2 and 0.8% and in the temperature range of 20–60 °C, the BAG II model has mainly provided better results than other correlations.

Table 9 shows the RMSE values obtained for the conventional correlations and acceptable correlations in Table 1 and the BAG II model on the experimental points for estimating the viscosity of the ethylene glycol-based nanofluid.

Findings based on the RMSE value indicate that the BAG II model has a 49.84% lower performance error than the best correlation presented by the researchers to estimate the viscosity of ethylene glycol-based nanofluids.

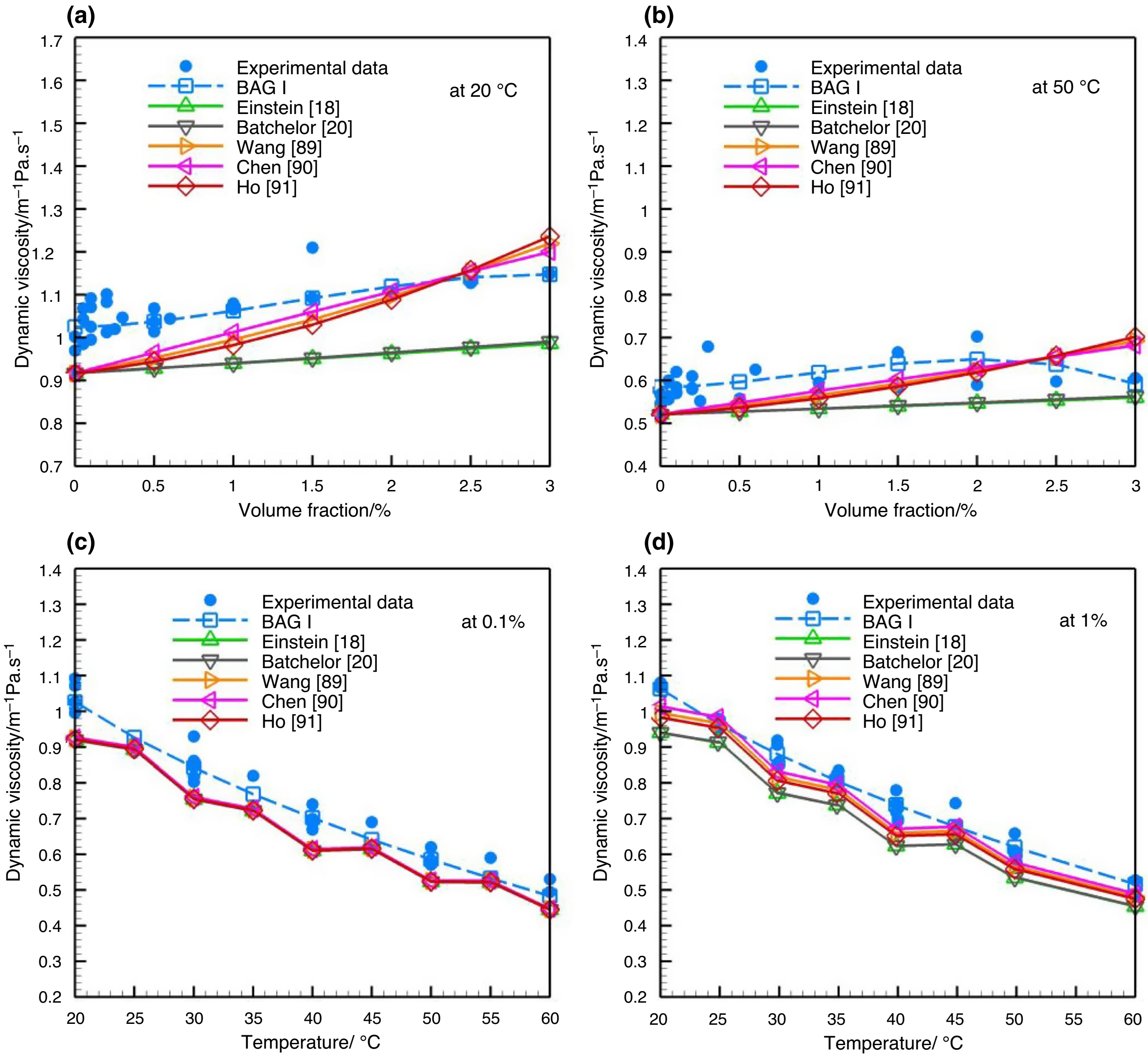

Fig. 17 Comparison of BAG I model with conventional correlations in Eqs. (17) to (23)

To know the accuracy of the BAG II model for ethylene glycol in terms of R^2 coefficient, Fig. 19 is plotted. The results show that the accuracy of the BAG II model is significantly higher than other correlations.

The base fluid viscosity parameter μ_{bf} is available in most of the correlations presented in Table 1 and the conventional correlations for calculating nanofluid viscosity. In this case, the viscosity of the base fluid plays the role of the variable temperature of the base fluid in addition to its role in the calculations so that the viscosity of the base fluid changes with the change of temperature. Therefore, the viscosity of the base fluid must also show the effect of temperature. Thus, by assuming the nanofluid type to be constant with temperature change, the base fluid viscosity in the nanofluid viscosity estimation correlation changes. On the other hands, in the nanofluid viscosity estimation correlations, the nanofluid temperature factor is not directly present in the above correlations. Therefore, these correlations alone are not able to estimate the nanofluid viscosity. Thus, when the nanofluid temperature is variable, the mentioned correlations increase the error probability in the calculations.

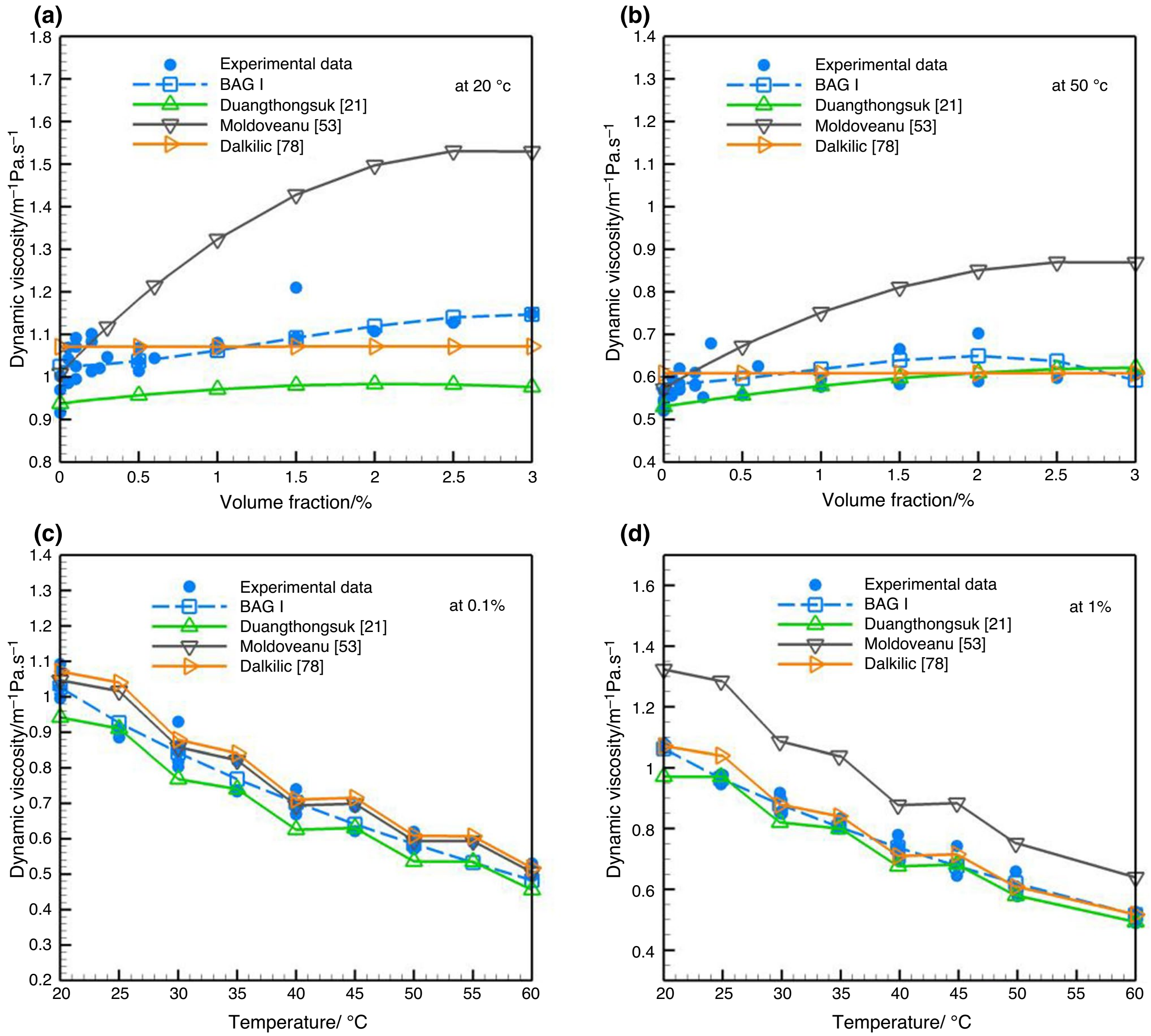

Fig. 18 A comparison of the BAG II model with acceptable correlations appeared in Table 1

Table 9 The RMSE value of the BAG II model compared to other correlations for ethylene glycol-based nanofluid

Equations	RMSE
Einstein [18]	5.26808813
Batchelor [20]	5.261787151
Wang [89]	5.101411188
Chen [90]	4.665411049
Ho [91]	4.860567618
Saeedi [55]	2.08799302
Adio [73]	4.863051208
Li [79]	2.63545833
BAG II	1.047228701

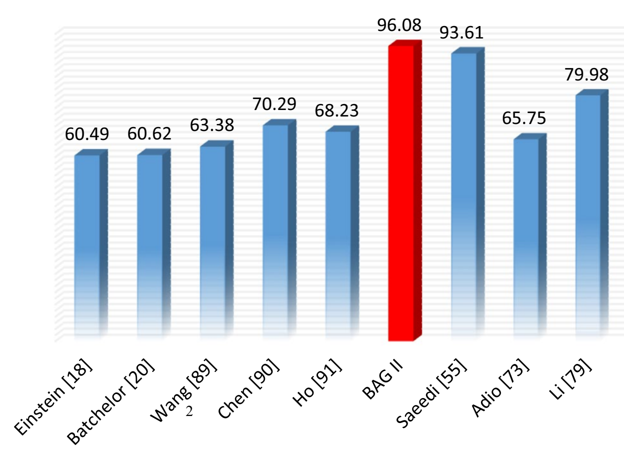

Fig. 19 The value of R^2 in the BAG II model compared to other correlations for ethylene glycol-based nanofluid

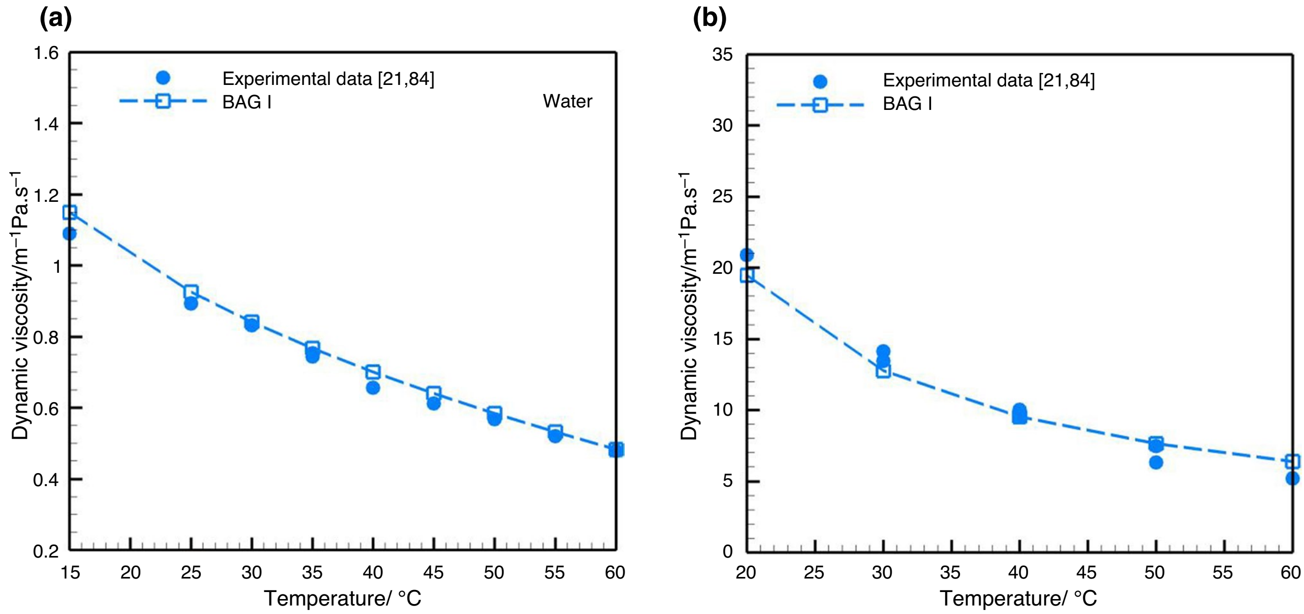

Fig. 20 Estimation of water- and ethylene glycol-based nanofluid viscosity using the BAG model

Also, while solving numerical problems of heat transfer due to temperature changes in the problem, it is sometimes impossible to change the base fluid's viscosity in the problem, which deviates the answer from the correct path. Therefore, the presence of a temperature variable in viscosity models is also felt here. Under such circumstances, the BAG model in Table 7 could be a turning point for other viscosity models in the future.

According to the above, another strength of BAG models is the ability to estimate the viscosity of the base fluid in the conventional temperature range used in heat transfer, which is less likely to provide a suitable response at zero concentration. To demonstrating the relationship ability of BAG, the values predicted by the BAG relation are examined with the experimental values of the viscosity of water-based nanofluid and ethylene glycol in Fig. 20, parts a and b, respectively.

Conclusions

The viscosity component plays a crucial role in heat transfer, especially convection heat transfer. The addition of nanoparticles to the base fluid is commonly considered to increase the viscosity rate. With the increase in the number of nanofluid viscosity models proposed, it has become necessary to review these models in the present study. We also evaluated the correlations in terms of physical compatibility with the viscosity of nanofluids and performed statistical tests of variance and sensitivity analysis on the viscosity models.

Finally, based on the weakness identified in previous models, through our statistical and correlation evaluations, two general equations for water- and ethylene glycol-based nanofluids were presented to predict the behavior of nanofluids. A summary of the results presented in this study is as follow;

- The results of variance analysis on the viscosity correlations showed the non-dependence of 42.2% of the correlations on the temperature component and another 27.3% on the volume (mass) fraction component.
- The volume (mass) fraction variables in nanofluid viscosity models are valid only in a certain range, and most correlations are not able to provide a solution at a zero volume (mass) fraction. Therefore, most nanofluid viscosity models do not cover the range of volume (mass) fractions used in heat transfer.
- In some of the viscosity models introduced by researchers, correlations sometimes have complex and long terms unrelated to viscosity physics. The presence of such terms in viscosity models only increases the likelihood of errors in calculations. However, many of these correlations can be corrected and modified with simple and short models.
- According to the study conducted physically and statistically on the viscosity models of nanofluids, only 53.6% of the correlations are statistically acceptable, and 73.2% of the correlations are physically reliable, and a total of 35.7% of the correlations have acceptable conditions.
- Sensitivity analysis revealed the significant contribution of temperature component in estimating nanofluid vis-

cosity. It is while the effect of temperature in the form of nanofluid viscosity models is not directly considered. Instead, the effect of temperature is determined by the independent variable of base fluid viscosity μ_{bf} in the desired viscosity models. Therefore, the viscosity models cannot estimate the nanofluid's viscosity in proportion to the temperature variation trend, and this factor can cause problems.
- For modeling, the viscosity of nanofluids separated to water or ethylene glycol-based nanofluids, which is valid in a wide temperature and volume fraction range and function independent of the type of nanoparticles, BAG models were introduced.
- The BAG models presented for nanofluid viscosity for water- and ethylene glycol-based nanofluid have 97.01% and 96.08% accuracy, respectively. Also, the RMSE value improved by 35.82% and 49.84% compared to the best correlation presented by the researchers for estimating the viscosity of water-based and ethylene glycol-based nanofluids, respectively.
- Most of the viscosity models have been optimized for nanofluids with water-based nanofluids. However, the BAG model has the ability to estimate the viscosity of nanofluid with ethylene glycol-based nanofluid with much higher accuracy than other correlations.
- Unlike other correlations, the results of BAG models showed that by changing the temperature of the nanofluid, BAG models maintain the ability to estimate the viscosity of the nanofluid accurately. Also, when the nanoparticle concentration is zero, the viscosity of the base fluid is well predicted.

Given that nanofluid with the oil base such as the applied fluids in industry and few correlations have been provided for oil-based nanofluids. Therefore, developing correlations for oil-based nanofluids is a challenge and an open field of research.

References

1. Mondal S, et al. A theoretical nanofluid analysis exhibiting hydromagnetics characteristics employing CVFEM. J Braz Soc Mech Sci Eng. 2020;42(1):1–12.
2. Seyyedi SM, Dogonchi A, Hashemi-Tilehnoee M, Ganji D, Chamkha AJ. Second law analysis of magneto-natural convection in a nanofluid filled wavy-hexagonal porous enclosure. Int J Numer Methods Heat Fluid Flow. 2020;30:4811.
3. Dogonchi A, Waqas M, Seyyedi SM, Hashemi-Tilehnoee M, Ganji D. A modified Fourier approach for analysis of nanofluid heat generation within a semi-circular enclosure subjected to MFD viscosity. Int Commun Heat Mass Trans. 2020;111:104430.
4. Tlili I, Seyyedi SM, Dogonchi A, Hashemi-Tilehnoee M, Ganji D. Analysis of a single-phase natural circulation loop with hybrid-nanofluid. Int Commun Heat Mass Trans. 2020;112:104498.
5. Dogonchi A, Waqas M, Gulzar MM, Hashemi-Tilehnoee M, Seyyedi SM, Ganji D. Simulation of Fe3O4-H2O nanoliquid in a triangular enclosure subjected to Cattaneo-Christov theory of heat conduction. Int J Numer Methods Heat Fluid Flow. 2019;29:4430.
6. Seyyedi SM, Dogonchi A, Hashemi-Tilehnoee M, Waqas M, Ganji D. Investigation of entropy generation in a square inclined cavity using control volume finite element method with aided quadratic Lagrange interpolation functions. Int Commun Heat Mass Transf. 2020;110:104398.
7. Abdelmalek Z, Tayebi T, Dogonchi A, Chamkha A, Ganji D, Tlili I. Role of various configurations of a wavy circular heater on convective heat transfer within an enclosure filled with nanofluid. Int Commun Heat Mass Trans. 2020;113:104525.
8. Sadeghi M, Tayebi T, Dogonchi A, Nayak M, Waqas M. Analysis of thermal behavior of magnetic buoyancy-driven flow in ferrofluid–filled wavy enclosure furnished with two circular cylinders. Int Commun Heat Mass Trans. 2021;120:104951.
9. Hashemi-Tilehnoee M, Dogonchi A, Seyyedi SM, Sharifpur M. Magneto-fluid dynamic and second law analysis in a hot porous cavity filled by nanofluid and nano-encapsulated phase change material suspension with different layout of cooling channels. J Energy Storage. 2020;31:101720.
10. Dogonchi A, Asghar Z, Waqas M. CVFEM simulation for Fe3O4-H2O nanofluid in an annulus between two triangular enclosures subjected to magnetic field and thermal radiation. Int Commun Heat Mass Trans. 2020;112:104449.
11. Dogonchi A, Selimefendigil F, Ganji D. Magneto-hydrodynamic natural convection of CuO-water nanofluid in complex shaped enclosure considering various nanoparticle shapes. Int J Numer Methods Heat Fluid Flow. 2019;5:1663.
12. Selimefendigil F. Natural convection in a trapezoidal cavity with an inner conductive object of different shapes and filled with nanofluids of different nanoparticle shapes. Iran J Sci Technol Transact Mech Eng. 2018;42(2):169–84.
13. Selimefendigil F, Öztop HF (2020) Effects of a rotating tube bundle on the hydrothermal performance for forced convection in a vented cavity with Ag–MgO/water hybrid and CNT–water nanofluids. J Therm Anal Calorim, pp. 1–18, 2020
14. Chamkha AJ, Molana M, Rahnama A, Ghadami F. On the nanofluids applications in microchannels: a comprehensive review. Powder Technol. 2018;332:287–322.
15. Izadi S, Armaghani T, Ghasemiasl R, Chamkha AJ, Molana M. A comprehensive review on mixed convection of nanofluids in various shapes of enclosures. Powder Technol. 2019;343:880–907.
16. Molana M. A comprehensive review on the nanofluids application in the tubular heat exchangers. Am J Heat Mass Transf. 2016;3(5):352–81.
17. Pandya NS, Shah H, Molana M, Tiwari AK. Heat transfer enhancement with nanofluids in plate heat exchangers: a comprehensive review. Eur J Mech B/Fluids. 2020;81:173–90.
18. Einstein A (1905) Eine neue bestimmung der moleküldimensionen, ETH Zurich
19. Brinkman H. The viscosity of concentrated suspensions and solutions. J Chem Phys. 1952;20(4):571–571.
20. Batchelor G. The effect of Brownian motion on the bulk stress in a suspension of spherical particles. J Fluid Mech. 1977;83(1):97–117.
21. Duangthongsuk W, Wongwises S. Measurement of temperature-dependent thermal conductivity and viscosity of TiO2-water nanofluids. Exp Thermal Fluid Sci. 2009;33(4):706–14.
22. Esfe MH, Saedodin S. An experimental investigation and new correlation of viscosity of ZnO–EG nanofluid at various temperatures and different solid volume fractions. Exp Therm Fluid Sci. 2014;55:1–5.
23. Sharifpur M, Adio SA, Meyer JP. Experimental investigation and model development for effective viscosity of Al2O3–glycerol

nanofluids by using dimensional analysis and GMDH-NN methods. Int Commun Heat Mass Transfer. 2015;68:208–19.
24. Aberoumand S, Jafarimoghaddam A, Moravej M, Aberoumand H, Javaherdeh K. Experimental study on the rheological behavior of silver-heat transfer oil nanofluid and suggesting two empirical based correlations for thermal conductivity and viscosity of oil based nanofluids. Appl Therm Eng. 2016;101:362–72.
25. Akbari M, Afrand M, Arshi A, Karimipour A. An experimental study on rheological behavior of ethylene glycol based nanofluid: proposing a new correlation as a function of silica concentration and temperature. J Mol Liq. 2017;233:352–7.
26. Li W, Zou C. Experimental investigation of stability and thermophysical properties of functionalized β-CD-TiO2-Ag nanofluids for antifreeze. Powder Technol. 2018;340:290–8.
27. Yu L, Bian Y, Liu Y, Xu X. Experimental investigation on rheological properties of water based nanofluids with low MWCNT concentrations. Int J Heat Mass Transf. 2019;135:175–85.
28. Yan SR, Kalbasi R, Nguyen Q, Karimipour A (2020) Rheological behavior of hybrid MWCNTs-TiO2/EG nanofluid: a comprehensive modeling and experimental study. J Mol Liq. p. 113058
29. Molana M, Ghasemiasl R, Armaghani T (2021) A different look at the effect of temperature on the nanofluids thermal conductivity: focus on the experimental-based models. J Therm Anal Calorim, pp. 1–25
30. Fisher RA (1992) Statistical methods for research workers. In: Breakthroughs in statistics: Springer, 1992, pp. 66–70
31. Scheffe H. The analysis of variance. New Jersey: John Wiley & Sons; 1999.
32. Dalkılıç AS, et al. Experimental investigation on the viscosity characteristics of water based SiO2-graphite hybrid nanofluids. Int Commun Heat Mass Transfer. 2018;97:30–8.
33. Li L, Zhai Y, Jin Y, Wang J, Wang H, Ma M. Stability, thermal performance and artificial neural network modeling of viscosity and thermal conductivity of Al2O3-ethylene glycol nanofluids. Powder Technol. 2020;363:360–8.
34. Alarifi IM, Alkouh AB, Ali V, Nguyen HM, Asadi A. On the rheological properties of MWCNT-TiO2/oil hybrid nanofluid: An experimental investigation on the effects of shear rate, temperature, and solid concentration of nanoparticles. Powder Technol. 2019;355:157–62.
35. Ruhani B, Barnoon P, Toghraie D. Statistical investigation for developing a new model for rheological behavior of Silica–ethylene glycol/Water hybrid Newtonian nanofluid using experimental data. Physica A. 2019;525:616–27.
36. Huminic A, Huminic G, Fleacă C, Dumitrache F, Morjan I. Thermo-physical properties of water based lanthanum oxide nanofluid. An experimental study. J Mol Liq. 2019;287:111013.
37. Esfe MH, Esfandeh S, Niazi S. An experimental investigation, sensitivity analysis and RSM analysis of MWCNT (10)-ZnO (90)/10W40 nanofluid viscosity. J Mol Liq. 2019;288:111020.
38. Esfe MH, Abad ATK, Fouladi M. Effect of suspending optimized ratio of nano-additives MWCNT-Al2O3 on viscosity behavior of 5W50. J Mol Liq. 2019;285:572–85.
39. Esfe MH, Esfandeh S. The statistical investigation of multi-grade oil based nanofluids: Enriched by MWCNT and ZnO nanoparticles. Phys A Stat Mech Appl. 2019;554:122159.
40. Li Z, Asadi S, Karimipour A, Abdollahi A, Tlili I. Experimental study of temperature and mass fraction effects on thermal conductivity and dynamic viscosity of SiO2-oleic acid/liquid paraffin nanofluid. Int Commun Heat Mass Trans. 2020;110:104436.
41. Sahoo RR, Kumar V. Development of a new correlation to determine the viscosity of ternary hybrid nanofluid. Int Commun Heat and Mass Trans. 2020;111:104451.
42. Tian Z, et al. Prediction of rheological behavior of a new hybrid nanofluid consists of copper oxide and multi wall carbon nanotubes suspended in a mixture of water and ethylene glycol using curve-fitting on experimental data. Phys A Stat Mech Appl. 2020;554:124101.
43. Li Z, et al. Nanofluids as secondary fluid in the refrigeration system: Experimental data, regression, ANFIS, and NN modeling. Int J Heat Mass Trans. 2019;144:118635.
44. Kumar PG, Sakthivadivel D, Meikandan M, Vigneswaran V, Velraj R. Experimental study on thermal properties and electrical conductivity of stabilized H2O-solar glycol mixture based multi-walled carbon nanotube nanofluids: developing a new correlation. Heliyon. 2019;5(8):e02385.
45. Asadi A, Pourfattah F. Heat transfer performance of two oil-based nanofluids containing ZnO and MgO nanoparticles; a comparative experimental investigation. Powder Technol. 2019;343:296–308.
46. Shahsavar A, Khanmohammadi S, Karimipour A, Goodarzi M. A novel comprehensive experimental study concerned synthesizes and prepare liquid paraffin-Fe3O4 mixture to develop models for both thermal conductivity & viscosity: a new approach of GMDH type of neural network. Int J Heat Mass Transf. 2019;131:432–41.
47. Li F, Li L, Zhong G, Zhai Y, Li Z. Effects of ultrasonic time, size of aggregates and temperature on the stability and viscosity of Cu-ethylene glycol (EG) nanofluids. Int J Heat Mass Transf. 2019;129:278–86.
48. Esfe MH, Raki HR, Emami MRS, Afrand M. Viscosity and rheological properties of antifreeze based nanofluid containing hybrid nano-powders of MWCNTs and TiO2 under different temperature conditions. Powder Technol. 2019;342:808–16.
49. Soman DP, Karthika S, Kalaichelvi P, Radhakrishnan T. Impact of viscosity of nanofluid and ionic liquid on heat transfer. J Mol Liq. 2019;291:111349.
50. Ruhani B, Toghraie D, Hekmatifar M, Hadian M. Statistical investigation for developing a new model for rheological behavior of ZnO–Ag (50%–50%)/Water hybrid Newtonian nanofluid using experimental data. Physica A. 2019;525:741–51.
51. Elcioglu EB, Yazicioglu AG, Turgut A, Anagun AS. Experimental study and Taguchi analysis on alumina-water nanofluid viscosity. Appl Therm Eng. 2018;128:973–81.
52. Ghasemi S, Karimipour A. Experimental investigation of the effects of temperature and mass fraction on the dynamic viscosity of CuO-paraffin nanofluid. Appl Therm Eng. 2018;128:189–97.
53. Moldoveanu GM, Ibanescu C, Danu M, Minea AA. Viscosity estimation of Al2O3, SiO2 nanofluids and their hybrid: an experimental study. J Mol Liq. 2018;253:188–96.
54. Moldoveanu GM, Minea AA, Iacob M, Ibanescu C, Danu M. Experimental study on viscosity of stabilized Al2O3, TiO2 nanofluids and their hybrid. Thermochim Acta. 2018;659:203–12.
55. Saeedi AH, Akbari M, Toghraie D. An experimental study on rheological behavior of a nanofluid containing oxide nanoparticle and proposing a new correlation. Phys E. 2018;99:285–93.
56. Karimipour A, Ghasemi S, Darvanjooghi MHK, Abdollahi A. A new correlation for estimating the thermal conductivity and dynamic viscosity of CuO/liquid paraffin nanofluid using neural network method. Int Commun Heat Mass Transfer. 2018;92:90–9.
57. Alrashed AA, Gharibdousti MS, Goodarzi M, de Oliveira LR, Safaei MR, Bandarra Filho EP. Effects on thermophysical properties of carbon based nanofluids: experimental data, modelling using regression, ANFIS and ANN. Int J Heat Mass Trans. 2018;125:920–32.
58. Khodadadi H, Toghraie D, Karimipour A. Effects of nanoparticles to present a statistical model for the viscosity of MgO-Water nanofluid. Powder Technol. 2019;342:166–80.
59. Esfe MH, Arani AAA. An experimental determination and accurate prediction of dynamic viscosity of MWCNT (% 40)-SiO2 (% 60)/5W50 nano-lubricant. J Mol Liq. 2018;259:227–37.
60. Esfe MH, Reiszadeh M, Esfandeh S, Afrand M. Optimization of MWCNTs (10%)–Al2O3 (90%)/5W50 nanofluid viscosity

using experimental data and artificial neural network. Phys A. 2018;512:731–44.
61. Hamid KA, Azmi W, Nabil M, Mamat R, Sharma K. Experimental investigation of thermal conductivity and dynamic viscosity on nanoparticle mixture ratios of TiO2-SiO2 nanofluids. Int J Heat Mass Transf. 2018;116:1143–52.
62. Nabil M, Azmi W, Hamid KA, Mamat R, Hagos FY. An experimental study on the thermal conductivity and dynamic viscosity of TiO2-SiO2 nanofluids in water: ethylene glycol mixture. Int Commun Heat Mass Transfer. 2017;86:181–9.
63. Żyła G, Fal J. Viscosity, thermal and electrical conductivity of silicon dioxide–ethylene glycol transparent nanofluids: an experimental studies. Thermochim Acta. 2017;650:106–13.
64. Amani M, Amani P, Kasaeian A, Mahian O, Kasaeian F, Wongwises S. Experimental study on viscosity of spinel-type manganese ferrite nanofluid in attendance of magnetic field. J Magn Magn Mater. 2017;428:457–63.
65. Soltani O, Akbari M. Effects of temperature and particles concentration on the dynamic viscosity of MgO-MWCNT/ethylene glycol hybrid nanofluid: experimental study. Physica E. 2016;84:564–70.
66. Ilhan B, Kurt M, Ertürk H. Experimental investigation of heat transfer enhancement and viscosity change of hBN nanofluids. Exp Thermal Fluid Sci. 2016;77:272–83.
67. Esfe MH, Ahangar MRH, Rejvani M, Toghraie D, Hajmohammad MH. Designing an artificial neural network to predict dynamic viscosity of aqueous nanofluid of TiO2 using experimental data. Int Commun Heat Mass Transfer. 2016;75:192–6.
68. Toghraie D, Alempour SM, Afrand M. Experimental determination of viscosity of water based magnetite nanofluid for application in heating and cooling systems. J Magn Magn Mater. 2016;417:243–8.
69. Abdolbaqi MK, et al. Experimental investigation and development of new correlation for thermal conductivity and viscosity of BioGlycol/water based SiO2 nanofluids. Int Commun Heat Mass Transfer. 2016;77:54–63.
70. Sundar LS, Hortiguela MJ, Singh MK, Sousa AC. Thermal conductivity and viscosity of water based nanodiamond (ND) nanofluids: An experimental study. Int Commun Heat Mass Transfer. 2016;76:245–55.
71. Mostafizur R, Aziz AA, Saidur R, Bhuiyan M. Investigation on stability and viscosity of SiO2–CH3OH (methanol) nanofluids. Int Commun Heat Mass Transfer. 2016;72:16–22.
72. Asadi M, Asadi A. Dynamic viscosity of MWCNT/ZnO–engine oil hybrid nanofluid: an experimental investigation and new correlation in different temperatures and solid concentrations. Int Commun Heat Mass Transfer. 2016;76:41–5.
73. Adio SA, Mehrabi M, Sharifpur M, Meyer JP. Experimental investigation and model development for effective viscosity of MgO–ethylene glycol nanofluids by using dimensional analysis, FCM-ANFIS and GA-PNN techniques. Int Commun Heat Mass Transfer. 2016;72:71–83.
74. Esfe MH, Afrand M, Gharehkhani S, Rostamian H, Toghraie D, Dahari M. An experimental study on viscosity of alumina-engine oil: effects of temperature and nanoparticles concentration. Int Commun Heat Mass Transfer. 2016;76:202–8.
75. Baratpour M, Karimipour A, Afrand M, Wongwises S. Effects of temperature and concentration on the viscosity of nanofluids made of single-wall carbon nanotubes in ethylene glycol. Int Commun Heat Mass Transfer. 2016;74:108–13.
76. Afrand M, Najafabadi KN, Akbari M. Effects of temperature and solid volume fraction on viscosity of SiO2-MWCNTs/SAE40 hybrid nanofluid as a coolant and lubricant in heat engines. Appl Therm Eng. 2016;102:45–54.
77. Abdolbaqi MK, et al. An experimental determination of thermal conductivity and viscosity of BioGlycol/water based TiO2 nanofluids. Int Commun Heat Mass Transfer. 2016;77:22–32.
78. Dalkilic A, et al. Prediction of graphite nanofluids' dynamic viscosity by means of artificial neural networks. Int Commun Heat Mass Transfer. 2016;73:33–42.
79. Li X, Zou C, Lei X, Li W. Stability and enhanced thermal conductivity of ethylene glycol-based SiC nanofluids. Int J Heat Mass Transf. 2015;89:613–9.
80. Saltelli A, et al. Global sensitivity analysis: the primer. New Jersey: John Wiley & Sons; 2008.
81. Gangadevi R, Vinayagam B. Experimental determination of thermal conductivity and viscosity of different nanofluids and its effect on a hybrid solar collector. J Therm Anal Calorim. 2019;136(1):199–209.
82. Topuz A, Engin T, Özalp AA, Erdoğan B, Mert S, Yeter A. Experimental investigation of optimum thermal performance and pressure drop of water-based Al 2 O 3, TiO 2 and ZnO nanofluids flowing inside a circular microchannel. J Therm Anal Calorim. 2018;131(3):2843–63.
83. Ghodsinezhad H, Sharifpur M, Meyer JP. Experimental investigation on cavity flow natural convection of Al2O3–water nanofluids. Int Commun Heat Mass Transfer. 2016;76:316–24.
84. Sundar LS, Singh MK, Sousa AC. Turbulent heat transfer and friction factor of nanodiamond-nickel hybrid nanofluids flow in a tube: an experimental study. Int J Heat Mass Transf. 2018;117:223–34.
85. Zadeh AD, Toghraie D. Experimental investigation for developing a new model for the dynamic viscosity of silver/ethylene glycol nanofluid at different temperatures and solid volume fractions. J Therm Anal Calorim. 2018;131(2):1449–61.
86. Sundar LS, Singh MK, Ferro M, Sousa AC. Experimental investigation of the thermal transport properties of graphene oxide/Co3O4 hybrid nanofluids. Int Commun Heat Mass Transfer. 2017;84:1–10.
87. Selvam C, Lal DM, Harish S. Heat transport and pressure drop characteristics of ethylene Glycol-based Nano fluid containing silver nanoparticles. IOP Conf Ser Mater Sci Eng. 2018;402(1):012005.
88. Nadooshan AA, Eshgarf H, Afrand M. Measuring the viscosity of Fe3O4-MWCNTs/EG hybrid nanofluid for evaluation of thermal efficiency: Newtonian and non-Newtonian behavior. J Mol Liq. 2018;253:169–77.
89. Wang X, Xu X, Choi SU. Thermal conductivity of nanoparticle-fluid mixture. J Thermophys Heat Transfer. 1999;13(4):474–80.
90. Chen H, Ding Y, Tan C. Rheological behaviour of nanofluids. New J Phys. 2007;9(10):367.
91. Ho C, Liu W, Chang Y, Lin C. Natural convection heat transfer of alumina-water nanofluid in vertical square enclosures: an experimental study. Int J Therm Sci. 2010;49(8):1345–53.