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Effects of temperature and concentration on the viscosity of nanofluids made of single-wall carbon nanotubes in ethylene glycol☆

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ABSTRACT

This paper includes an examination of the dynamic viscosity of single-wall carbon nanotubes (SWCNTs) in ethylene glycol (EG) at temperatures ranging from 30 °C to 60 °C for various suspensions at solid volume fractions of 0.0125%, 0.025%, 0.05%, 0.075%, and 0.1%. Experimental findings revealed that SWCNTs/EG nanofluid behaves as a Newtonian fluid at solid volume fractions of 0.1% and at all considered temperatures. The measurements also indicated that dynamic viscosity increases with increasing solid volume fraction and decreases with increasing temperature. Moreover, relative viscosity results showed that that the viscosity of the nanofluid increases to 3.18 times that of the base fluid at a temperature of 30 °C and a solid volume fraction of 0.1%. Finally, using experimental data to estimate the dynamic viscosity of SWCNTs/EG nanofluid, a new correlation with acceptable accuracy was suggested.

1. Introduction

Ethylene glycol (EG) is an organic complex that is mostly used as a raw material in the manufacture of polyester fibers for the fabric industry. It is also used as an ingredient in engineering applications, such as for antifreeze and other industrial products. The most important use of EG is as a material for convective heat transfer in automobiles, chilled-water air conditioning systems, geothermal heat pumps, heat exchangers, liquid-cooled computers, and systems that must be cooled to below water's freezing temperature. However, EG has low thermal conductivity, which many researchers have tried to increase it. In this way, the researchers found that adding nanoparticles into traditional liquids (such as water, oil, and EG) can lead to an increase in thermal conductivity [1–6]. When nanoparticles are added into EG to increase its thermal conductivity, other thermo-physical properties are also affected, including viscosity [7–11]. Hence, viscosity changes due to the addition of nanoparticles to EG should be considered.

Many researchers have experimentally studied the effects of temperature and the concentration of metal or metal oxide nanoparticles on the viscosity of nanofluids containing EG. A brief review of the previous research on the viscosity of nanofluids is provided in Table 1. In these works, the authors showed the behavior of nanofluids for various temperatures, nanoparticle concentrations, and nanoparticle sizes. Moreover, they showed that these fluids behaved in a non-Newtonian fashion in some experiments.

In the many studies, the measured viscosities of nanofluids were compared with existing well-known models. One of these models was introduced by Batchelor [22], who presented a correlation to predict the viscosity of nanofluids with spherical nanoparticles:

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

Moreover, Wang et al. [23] proposed a model for predicting the viscosity of nanofluids:

$$\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{bf}}} = \left(1 + 7.23\varphi + 123\varphi^2\right) \tag{2}$$

In the above-mentioned studies, researchers focused on evaluating and comparing the effects of different nanoparticles on the thermo-physical properties of various base fluids. Carbon nanotubes (CNTs) have been among the most-studied nanoparticles because of their unique properties. Despite CNTs' potential, their rheological behaviors have received comparatively little attention in the literature. Previous works carried out by Vakili-Nezhaad and Dorany [24,25], Chen et al. [26], Vasheghani et al. [27], Bobbo et al. [28], Ettefaghi et al. [29,30], and Hemmat Esfe et al. [31,32] deal with this issue. Although some information is currently available on the rheological behaviors of CNT,

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Table 1
A summary of experimental works for the viscosity of nanofluids containing EG.

Authors	Base fluid	Nanoparticles	Size (nm)	Temperature range (°C)	Volume fraction (%)
Namburu et al. [12]	EG:water	CuO	29	(−35)–50	0–6.12
Sahoo et al. [13]	EG:water	Al_2O_3	53	(−35)–50	1–10
Sundar et al. [14]	EG:water	Fe_3O_4	5–70	0–50	0–1
Vajiha and Das [15]	EG:water	Al_2O_3	45	20–90	10
		CuO	29		6
		SiO_2	20, 50, 100		10
Yiamsawas et al. [16]	EG:water	Al_2O_3	120	15–40	0–4
		TiO_2	21		
Said et al. [17]	EG	Al_2O_3	13	25–80	0.05–0.1
Hemmat Esfe et al. [18]	EG	ZnO	18	25–50	0.25–5
Elias et al. [19]	EG:water	Al_2O_3	13	10–50	0–1
Sundar et al. [20]	EG:water	Al_2O_3	36	20–60	0–1.5
Hemmat Esfe et al. [21]	EG:water	MgO	NA	20–50	0–3

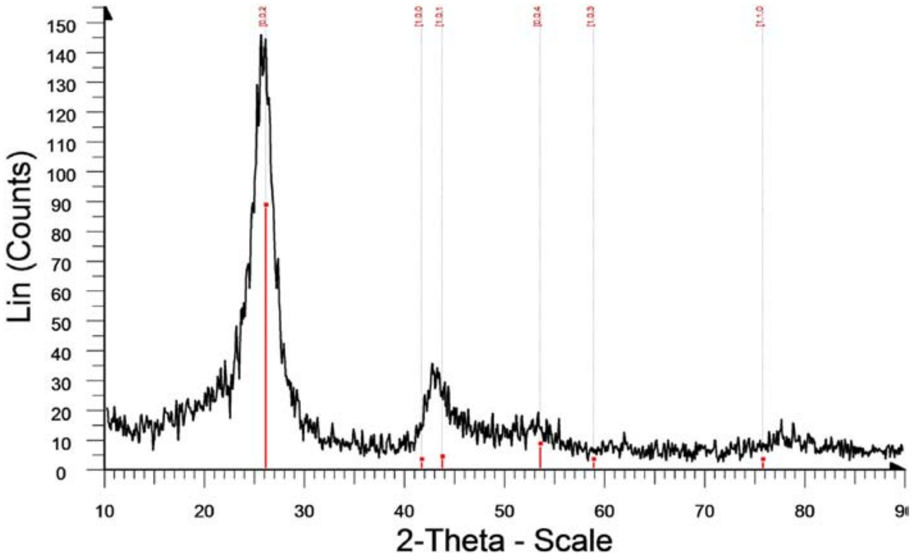

Fig. 1. XRD pattern for single-wall carbon nanotubes.

room for further research remains, especially regarding the effects that relevant parameters have on the viscosity of nanofluids made of single-wall carbon nanotubes (SWCNTs) in EG.

In this work, SWCNTs/EG nanofluid was prepared at various solid volume fractions. The effects of nanoparticle concentration and temperature on the dynamic viscosity of the nanofluids were examined by a viscometer. Moreover, the measured viscosities of the nanofluids were compared with those obtained from the existing models [22,23]. Finally, using experimental data, a new correlation was suggested to predict the dynamic viscosity of SWCNTs/EG nanofluid in engineering applications.

2. Experiments

2.1. Samples preparation

In the present work, SWCNTs were dispersed into an EG base fluid. SWCNTs/EG nanofluids with solid volume fractions of 0.0125%, 0.025%, 0.05%, 0.075%, and 0.1% were prepared using a two-step method. In order to create stable SWCNTs/EG nanofluids, after magnetic stirring for 2 h, the suspensions were exposed to an ultrasonic processor (Hielscher Company, Germany) for 6 h. In order to obtain a characterization of the sample, the structural properties of the dry SWCNTs were measured by X-ray diffraction, as presented in Fig. 1.

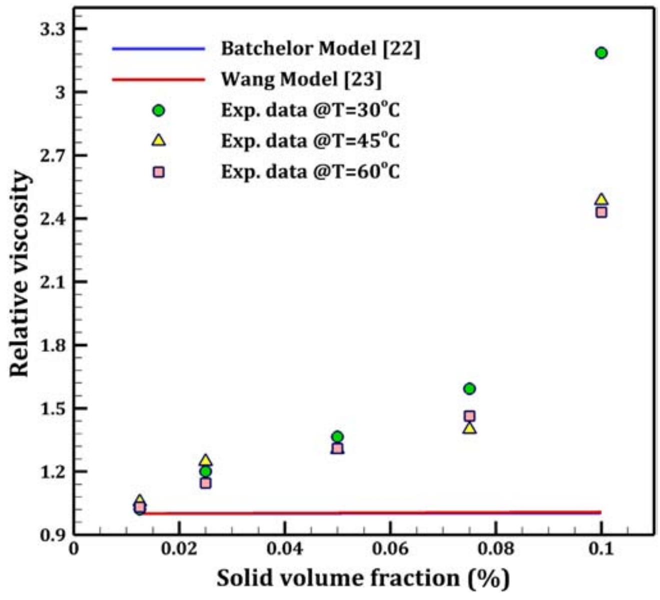

Fig. 2. Comparison between theoretical models and experimental findings.

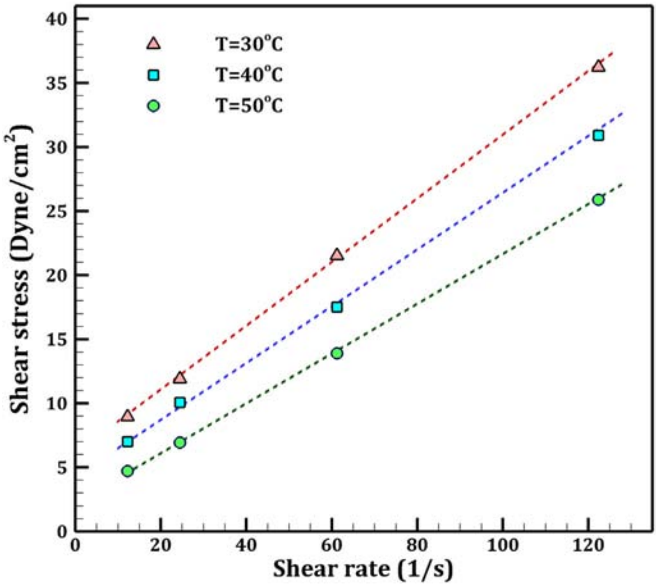

Fig. 3. Shear stress versus shear rate for SWCNTs/EG nanofluid at solid volume fraction of 0.1% for various temperatures.

2.2. Measurement of dynamic viscosity

The viscosity of SWCNTs/EG nanofluids with solid volume fractions ranging from 0.0125% to 0.1% were measured in a temperature range from 30 °C to 60 °C. A Brookfield viscometer with a temperature bath (supplied by Brookfield Engineering Laboratories) was used to measure the viscosities of SWCNTs/EG nanofluids in the shear rate range of 12.24 s^{-1} to 122.4 s^{-1}. The ranges of repeatability and accuracy of the viscometer are, respectively, ±0.2% and ±1.0%. Before measuring the dynamic viscosity of the nanofluids, the viscometer was tested with EG and glycerin at room temperature. In order to ensure Newtonian flow behavior, all experiments were repeated at different shear rates for each solid volume fraction. Then the average of the measured data was recorded.

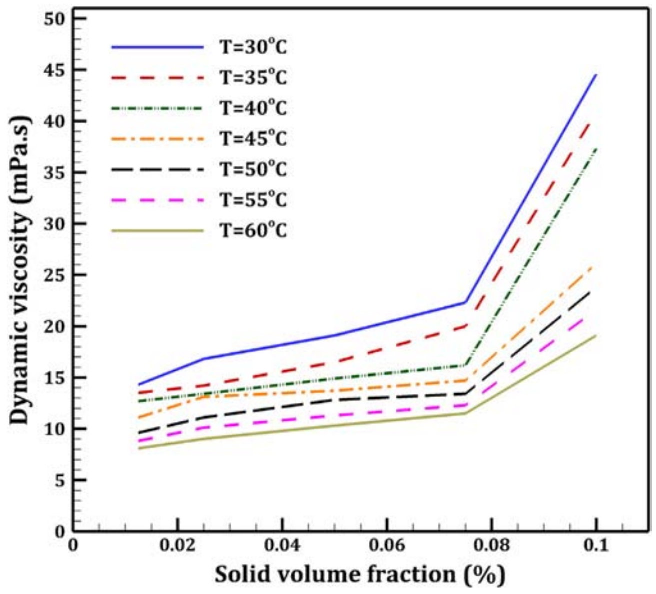

Fig. 4. Variations of dynamic viscosity with solid volume fraction at different temperatures.

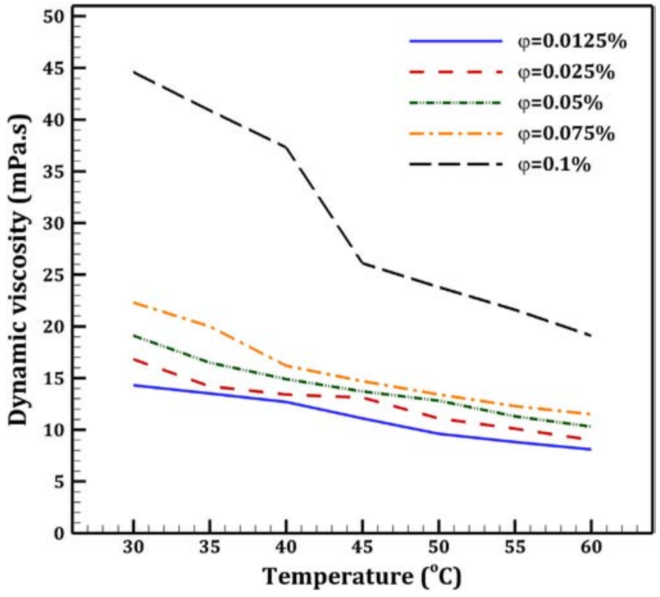

Fig. 5. Variations of dynamic viscosity with temperature at different solid volume fractions.

Based on the results, relative viscosity is defined as the ratio of the dynamic viscosity of SWCNTs/EG nanofluids to dynamic viscosity of base fluid: $\frac{\mu_{nf}}{\mu_{bf}}$.

3. Results and discussion

The measurements of the dynamic viscosity of the SWCNTs/EG nanofluids were performed at temperature ranges from 30 °C to 60 °C for several suspensions with volume fractions of 0.0125%, 0.025%, 0.05%, 0.075%, and 0.1%.

A comparison of relative viscosity with respect to solid volume fraction for both the measured values and the predicted values from the Batchelor [22] and Wang [23] models is illustrated in Fig. 2. Neither theoretical models are able to calculate the relative viscosity of SWCNTs/EG nanofluids correctly in all concentrations.

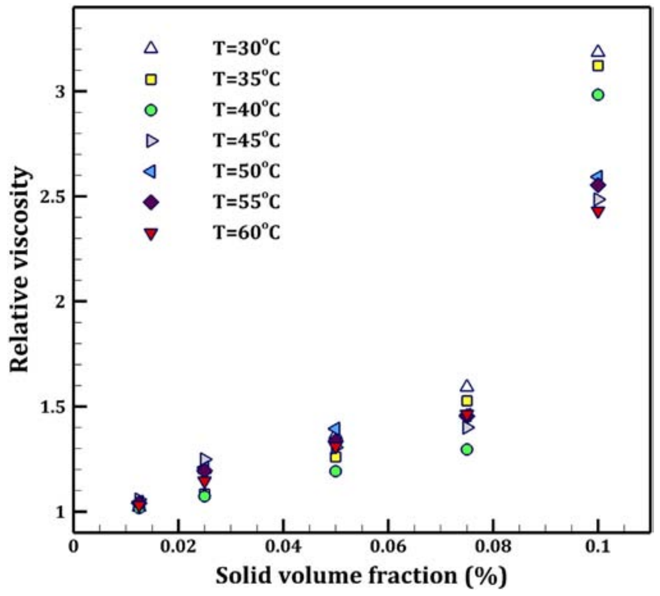

Fig. 6. Relative viscosity versus solid volume fraction for different temperatures.

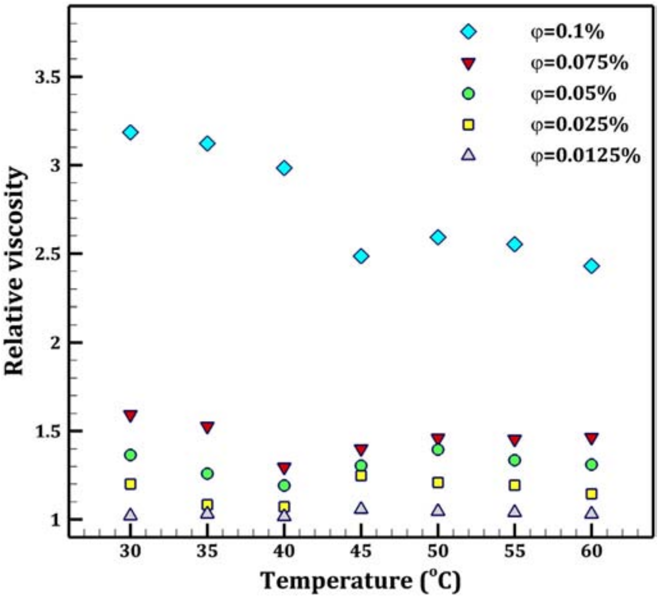

Fig. 7. Relative viscosity versus temperatures for different solid volume fractions.

In order to understand the rheological behavior (Newtonian or non-Newtonian) of SWCNTs/EG nanofluids at various solid volume fractions, the shear stress (as a function of shear rate) for the solid volume fraction of 0.1% is shown in Fig. 3. There is a linear relation between shear stress and shear rate. This linear relation indicates that SMWCNTs/EG nanofluids behave as Newtonian fluids at the maximum solid volume fraction considered in this paper (0.1%).

Fig. 4 shows the variations in the dynamic viscosity of SWCNTs/EG nanofluids with solid volume fractions at different temperatures. The viscosity of the nanofluids increases as the solid volume fraction increases. Moreover, at lower temperatures, the variation of the dynamic viscosity (with respect to the solid volume fraction) is greater than it is at higher temperatures.

To understand the effect of temperature on the dynamic viscosity of SWCNTs/EG nanofluids, the dynamic viscosity is graphed against the temperature at various solid volume fractions in Fig. 5. The experimental data show that for a solid volume fraction of 0.1%, the effect of temperature on the dynamic viscosity of nanofluids is more noticeable than it is at lower solid volume fractions.

The relative viscosity is also illustrated in Figs. 6 and 7 as a function of solid volume fraction and temperature, respectively. The viscosity of the nanofluids increased to a maximum of 3.18 times that of the base fluid at a temperature of 30 °C and a solid volume fraction of 0.1%. At greater

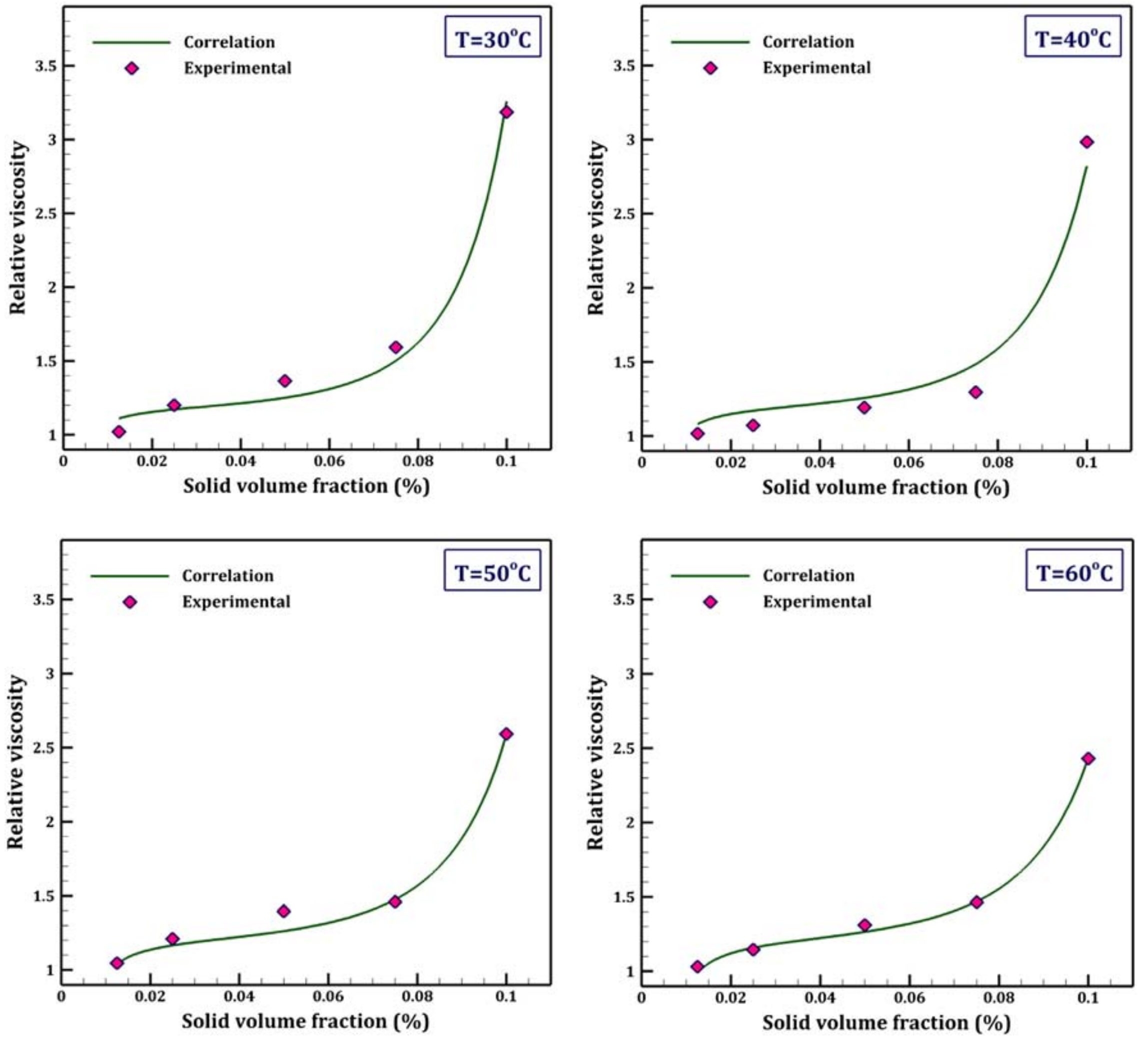

Fig. 8. Adapting the correlation outputs with experimental data at different temperatures.

solid volume fractions, relative viscosity is greater than it is at lower volume fractions.

4. Proposing a new correlation

As mentioned above, theoretical models are unable to predict the viscosity of SWCNTs/EG nanofluids. Hence, based on experimental findings, a new correlation is proposed to predict the relative viscosity of SWCNTs/EG nanofluids. This correlation would be more accurate than previously proposed correlations, and it could be employed to easily estimate the dynamic viscosity of SWCNTs/EG nanofluids in several applications. The correlation is as follows:

$$\frac{\mu_{\mathrm{nf}}}{\mu_{\mathrm{bf}}} = 1.089 + \left[-7.722 \times 10^{-9}\left(\frac{T}{\varphi}\right)^2 + 1.1917\,T^{0.298}\varphi^{0.4777}\right]\exp\left(19457\,T^{-0.453}\varphi^{3.219}\right) \tag{3}$$

In the correlation, μ is the dynamic viscosity, T is the temperature of the nanofluid (in °C), and φ is the solid volume fraction (in %). Moreover, the subscripts of nf and bf indicate, respectively, nanofluid and base fluid. In order to evaluate the accuracy of this correlation, Fig. 8 presents an adaptation of the correlation outputs with experimental data at different temperatures. In most measured data, the curve of correlation and the points corresponding to the experimental results overlap each other or appear to have only a small deviation, which indicates that the suggested correlation has a suitable accuracy.

5. Conclusion

This paper examined the dynamic viscosity of SWCNTs/EG nanofluids at temperatures ranging from 30 °C to 60 °C for various suspensions and at solid volume fractions of 0.0125%, 0.025%, 0.05%, 0.075%, and 0.1%. Experimental results showed that SWCNTs/EG nanofluids behave as Newtonian fluids at the solid volume fraction of 0.1%. The measurements also indicated that the dynamic viscosity increases with increasing solid volume fractions and decreases with increasing temperatures. Moreover, the results showed that the viscosity of nanofluids increased to 3.18 times that of the base fluid at temperature of 30 °C and solid volume fraction of 0.1%. In addition, a comparison between experimental findings and the outputs of theoretical models revealed that previous theoretical models are unable to predict the viscosity of SWCNTs/EG nanofluids accurately. Thus, using experimental data to estimate the dynamic viscosity of SWCNTs/EG nanofluids, a new correlation was suggested. Comparisons between the experimental data and the correlation outputs showed that the suggested model can be used to predict the relative viscosity of SWCNTs/EG nanofluids at solid volume fractions ranging from 0.0125% to 0.1% and a temperature range of 30 °C to 60 °C.

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