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Viscosity Analysis of Water-based Copper Oxide Nanofluids

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ABSTRACT

In this paper, the effects of weight concentration of nanoparticles and temperature on the viscosity of water-based copper oxide nanofluids have been studied experimentally using analysis of variance (ANOVA)-based two-factor three-level (2^3) factorial design. The results show that a maximum increase of 23.12% in viscosity is observed at 30°C temperature as the weight concentration of nanoparticles increases from 0.03 to 0.3wt.%. Whereas the temperature increases from 30 to 60°C, the viscosity decreases up to 46.19% in the case of 0.3wt.% nanofluid. Temperature is found to be more dominant than the concentration of nanoparticles. The optimum value of viscosity (0.513 mPa.s) is found at concentrations of 0.1wt.% and 60°C temperature with an 18.72% enhancement in viscosity as compared to the base fluid. The experimental and model values of viscosity have been compared with the predictions of the proposed equation for viscosity. The experimentally measured results are found near the proposed results whereas the model underestimates the viscosity in the case of all nanofluids. The maximum underestimation of 25.92 % was observed in the case of 0.3wt.% nanofluid at 60°C temperature.

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NOMENCLATURE

DW	Distilled water	**Greek Symbols**	
CuO	Copper oxide	ρ	Density (kg/m^3)
XRD	X-ray Diffraction	μ	Viscosity (mPa.s)
FESEM	Field Emission Scanning Electron Microscopy	τ	Temperature (°C)
DRV	Deviation from the reference value	φ	Concentration of nanoparticles
d	Average particle diameter	λ	wavelength
w	Weight	β	full-width half-max. of diffraction peak
R^2	R Squared	κ	Debye Scherrer's constant
R^2 (adj.)	Adjusted R Squared	θ	Bragg's Diffraction angle
R^2 (pred.)	Predicted R Squared	**Subscripts**	
Adj.SS	Adjusted sum of squares	*np*	nanoparticle
Adj.MS	Adjusted mean sum of squares	*nf*	nanofluid
DF	Degree of freedom	*bf*	Base fluid

1. INTRODUCTION

These days nanofluids have been used to enhance the heat transfer rate in thermal industries. Nanofluids are the homogeneous suspensions of nanoparticles in conventional base fluids. But with an increase in the concentration of nanoparticles in the base fluid, the viscosity also increases, which further increases the pumping power required, which is not favorable [1-3]. This may be because of the increased chances of sedimentation and agglomeration.

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Gautam and Chudasama [4] found 22% thermal efficiency at a particle concentration of 0.2 wt.% for MWCNT nanofluids. Further increases in concentration lead to decreased thermal conductivity and increased pumping power. Adibi et al. [5] reported that the effective viscosity and thermal conductivity of nanofluid are more than those of base fluid. With the addition of nanoparticles, the friction factor was raised to 42% and the mean Nusselt number increased. Shiravi et al. [6] reported an enhancement of 40.7% in heat transfer at a mass concentration of 0.21% at a constant Reynold number for carbon-based nanofluids. The friction factor was increased by increasing particle concentration and decreasing the Reynolds number. The same trend was reported by Davarnejad and Mohammadi Ardehali [7].

Most of the models for viscosity are valid for small fractions of concentrations but Shahriari et al. [8] proposed a model for particle concentration up to 11 vol.%. Shahriari et al. [9] studied different models to estimate the thermal conductivity and viscosity of nanofluids. They reported that viscosity models showed more influence on the transfer the than thermal conductivity model. Equation (1) represents the Einstein model [3] that is mostly used by Davarnejad and Kheiri [10] and Ebrahimi et al. [11]. This model is used in the present study for the estimation of viscosity.

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

$$\varphi = [wnp \div (wnp + wbf)] \times 100 \tag{2}$$

A brief summary of other related research work is summarized in Table 1.

TABLE 1. Summary table of the related literature review

Nano-fluid	Main finding	Reference
CuO/ EG	Viscosity increased by 23% with the increase the in the concentration of nanoparticles (φ) from 1 to 4 vol.%. Viscosity was decreased by 80% when the temperature (τ) was increased from 293K to 353K.	[12]
Cu-SiO_2/ (Glycerin-water)	An enhancement of 50.3% in viscosity was observed when φ was increased by 1% at a constant τ of 80°C. Viscosity varied directly with φ and indirectly with τ.	[13]
Al_2O_3-CuO/ Water	With the addition of surfactant < 0.2 wt.%, no change in viscosity was observed but a significant increase was observed when surfactant was added beyond this limit. The optimum φ of 0.005 wt.% was obtained.	[14]
CuO-TiO_2/ Water	The maximum viscosity of 1.74 mPasec was obtained at φ = 1 vo1% and τ = 25°C. Significant enhancement was observed in viscosity with the increase in φ but an increase in temperature showed an adverse effect.	[15]
Al_2O_3-CuO/ (Water- EG)	Hybrid nanofluids were prepared at different particle ratios (Al_2O_3-CuO), i.e., 20:80,40:60,50:50 and 60:40. The particle ratio of 20:80 showed the lowest viscosity at a temperature of 70°C. A significant reduction in viscosity with an increase in τ was reported in all cases.	[16]
TiO_2-CuO/ EG	Enhancement of 80% and 17% was observed in viscosity and thermal conductivity respectively at φ = 2 vol.% and τ = 40.4°C. Viscosity decreased with an increase in temperature.	[17]
MWCNT/Water	Viscosity was decreased by 7.9% when the τ was increased from 30°C to 70°C. It was increased when φ was increased up to 0.9 vol.% with temperature ranging from 30-70°C.	[18]
Ag-MgO (50:50)/ Water	Viscosity was underestimated by the models used. Viscosity varied directly with the φ and values deviated from model values up to 10% with nanofluids having φ = 2 wt.%.	[19]
SiO_2/ Water	Viscosity was decreased by 44.89% when the τ was changed from 25 to 30°C at a lower φ = 0.075 vol.%. With the increase in τ from 35 to 40°C the viscosity decreased by 18.85%. However, with the further increase in τ beyond 40°C viscosity became independent of concentration (φ).	[20]

It is observed from the literature review that the concentration of the nanoparticles is the key parameter that affects the viscosity of the nanofluids. The addition of nanoparticles increases the thermal conductivity of nanofluid as well as the power that is required for pumping due to the enhanced viscosity [3]. The viscosity is directly proportional to particle concentration but varies inversely with the temperature. The nanofluids should achieve the highest thermal conductivity with the lowest possible concentrations of nanoparticles [10].

Most of the studies available in the literature are focused on the heat transfer characteristics of nanofluids using viscosity as one of the parameters. The number of research articles that evaluated heat transfer is significantly higher as compared to articles on viscosity and other properties of nanofluids [21]. There are few papers related to the investigation of the viscosity of CuO-based mono- nanofluids whereas studies based on the hybrid nanofluids containing CuO as one of the materials are more in number.

This motivates the authors to carry out the present work. Temperature and weight concentration of nanoparticles have been selected as factors to study their effects on the viscosity of prepared nanofluids by using ANOVA based on 2^3 factorial design. Viscosity was measured experimentally using a viscometer (Rheolab QC) and compared with the model values and values given by the correlation that is proposed for the viscosity. This analysis and correlation will help researchers and scientists to carry out further research in this area. Figure 1 depicts the layout of the present study.

2. MATERIALS AND METHODS

CuO nanoparticles (50 nm) were purchased from Nanoshel Company, Willmington United States and distilled water (DW) was obtained from the departmental lab of Dr. SSB UICET, PU, Chandigarh. Nanoparticles were nearly spherical and black with 99.9 % purity. The material was characterized and confirmed by using X-ray Diffraction (PAN analytical Xpert Pro-XRD) and Field Emission Scanning Electron Microscopy (HITACHI, H-7500-FESEM) methods. The results are presented in Figure 2(a and b). The peaks in the XRD report indicate the good crystallinity of CuO nanoparticles and agreed with that of monoclinic CuO as per the literature (JCPDS, File No. 01-080-1916). When compared with the published results, it has been observed that similar results have been reported by other researchers discussed in literature [22-25]. Khallili et al. [26] used Debay Scherrer Equation (3) to calculate the average size of the nanoparticles.

$$d = (k \times \lambda) \div (\beta \times \cos\theta) \tag{3}$$

The average particle size in the present study comes out to be 48.3 nm when k, λ, θ, and β are taken as 0.94, 1.54 Å, 17.6, and 0.172° respectively as per the XRD report. The calculated size is very close to the size (50nm) that was claimed by the supplier. FESEM result demonstrates the structure of CuO nanoparticles. Figure 2(b) shows that nanoparticles are nearly spherical and cylindrical in shape and are found in form of clusters. However, the supplier claimed the nanoparticles to be nearly spherical. The deformation in the shape may result from the agglomeration of nanoparticles.

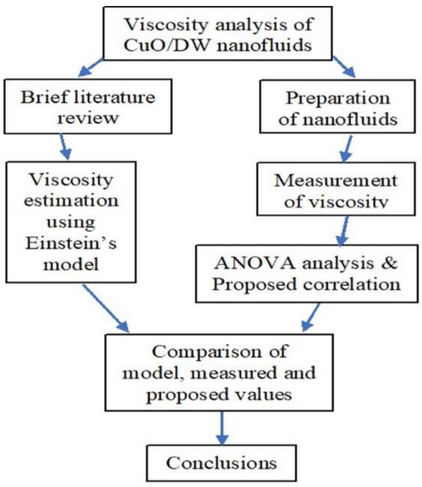

Figure 1. The layout of the present study

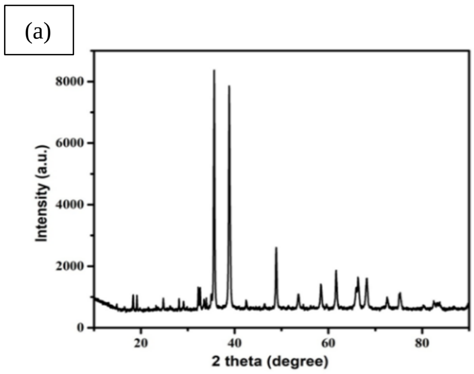

Figure 1(a). XRD pattern of CuO nanoparticles

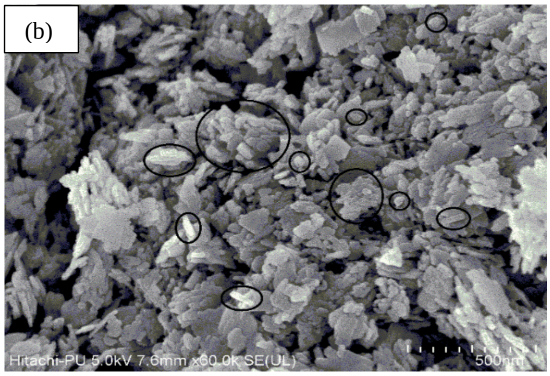

Figure 2(b). FESEM image of CuO nanoparticles

Nanofluids were prepared using a two-step method. Nanoparticles were measured by electronic balance (Sartorius BSA 224S-CW) and dispersed in DW to get different weight concentrations of 0.03, 0.1, and 0.3%. These mixtures were stirred for one hour using a magnetic stirrer (Heidolph's MR Hei-Tec.) to break down the clusters followed by ultrasonication using an ultrasonicator (Bandelin DT 255 H) for two hours to get stable and homogeneous nanofluids.

Table 2 contains the selected factors with their levels and Table 3 represents the different combinations of the factors as per the factorial design.

3. RESULTS AND DISCUSSION

The viscometer (Rheolab QC) was validated, by measuring the viscosity of DW at different temperatures

TABLE 2. Selected factors with their levels

Factors \ Levels	Low	Medium	High
φ (wt%)	0.03	0.1	0.3
τ (°C)	30	45	60

TABLE 3. Combination of factors as experimental sets

Experimental sets	Concentration φ (wt%)	Temperature τ (°C)
1	0.03	30
2	0.1	30
3	0.3	30
4	0.03	45
5	0.1	45
6	0.3	45
7	0.03	60
8	0.1	60
9	0.3	60

(30, 45, and 60°C) before the actual experiment. Each measurement was performed three times and mean values were considered. Table 4 compares the results for validation of the viscometer and their deviation from the reference values [27, 28]. It is observed that measured values are near the standard results with deviations varying from 2.5-8.3%. Thus, the viscometer was validated and used for nanofluids at different experimental sets as shown in Table 3. The results have been drawn graphically in Figure 3 (a and b).

The net increase in viscosity is observed in the case of prepared nanofluids when compared with base fluid. This increase is because of the addition of nanoparticles in the case of nanofluids which goes on increasing with an increase in particle concentration. The enhancement of viscosity varies from 15.49 to 38.68% for the given range of concentration (0.03-0.3%) and temperature (30°C-60°C) when compared with that of DW. The maximum enhancement is found at a high level of weight concentration (0.3%) and low level of temperature (30°C) whereas, minimum enhancement is found at a low level of weight concentration (0.03%) and high level of temperature (60°C). When the weight concentration was increased from 0.03 to 0.3%, the viscosity increased by 23.12, 19.09, and 16.41% at 30, 45, and 60°C, respectively. This increase in viscosity may be due to a direct influence on the fluid's internal shear stress, which is imposed by an increase in concentration [14, 15, 29]. Viscosity is reduced at a higher temperature. With an increase in temperature from 30 to 60°C the viscosity is decreased by 43.09, 43.61, and 46.19% at a weight concentration of 0.03, 0.1, and 0.3%, respectively. However, the maximum reduction of 44.5% is found in the case of base fluid with this increase in temperature. The reason behind the decreasing viscosity with increased temperature may be the weak adhesion forces between particles and molecules [12, 29, 30].

The intermolecular forces decrease with the increase in temperature; hence, the resistance to flow, i.e., viscosity, is decreased. Figure 3(a and b) shows the direct relationship of viscosity with the concentration of nanoparticles and the indirect relationship with temperature i.e., viscosity decreases with an increase in temperature.

TABLE 4. Measured viscosity of DW and deviation from reference values

Temperature (°C)	Measured (mPa.s)	A.Nagashima (mPa.s) [27]	Databook (mPa.s) [28]	DRV (%) [27]	DRV (%) [28]
30	0.7786	0.79844	0.8300	2.5	6.2
45	0.5623	0.60052	0.60825	6.4	7.6
60	0.4321	0.46601	0.4710	7.3	8.3

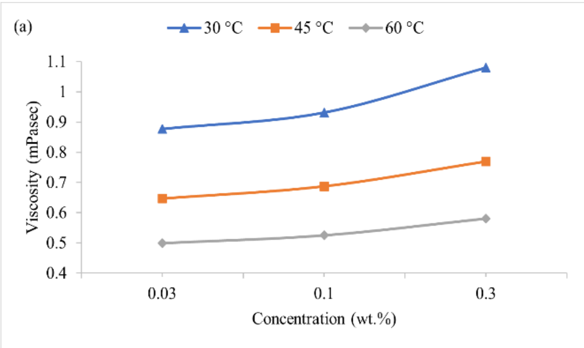

Figure 3(a). Variation of viscosity with concentration

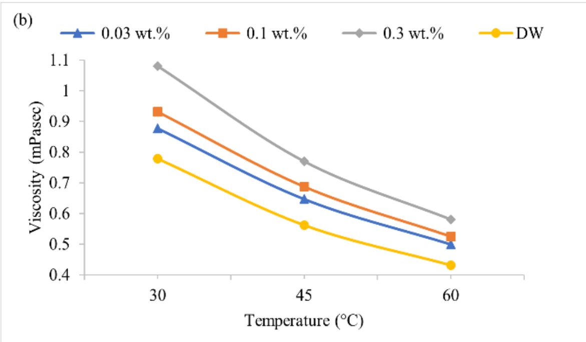

Figure 3(b). Variation of viscosity with temperature

3. 1. ANOVA Analysis

ANOVA was performed using MINITAB 17 to understand how the selected parameters i.e., the concentration of nanoparticles (x) and temperature (y), respond to the viscosity of CuO/DW nanofluids. To study the effects of parameters on the viscosity of CuO/DW nanofluid, an ANOVA-based 2^3 factorial design has been used. The following Table 5 presents the summary of the regression analysis and information regarding the significance of the model using constants and coefficients of the proposed equation.

TABLE 5. Results obtained from software for ANOVA and regression

Source	DF	Adj SSx10^{-3}	Adj MSx10^{-3}	F-Value	P-Value	Significance
Regression	3	307.5	102.5	107.5	0.000	Significant
φ (wt.%)	1	11.22	11.22	11.78	0.019	Significant
τ (°C)	1	76.90	76.90	80.69	0.000	Significant
2-Way (φ.τ)	1	4.0	4.0	4.20	0.096	Not significant
Error	5	4.765	0.953			
Total	8	312.3				

MODEL SUMMARY

S	R-sq (R^2)	R-sq (adj.)	R-sq (Pred.)
0.030872	98.47%	97.56%	91.36%

Regression Coefficients

Constant	φ	τ	φ.τ
1.2059	1.175	-0.01210	-0.01505

After analyzing the different values (P-value, F-value, R^2, R^2(adj.), and R^2(pred.), it may be concluded that the present model is a significant, fit, and valid model that contains only significant factors. The values of R^2, R^2(adj.), and R^2(pred.) are near 100% which proves the model to be a good fit model and ensures its validity. Small P-values and the least difference between R^2 and R^2(adj.) indicates the absence of any insignificant factor [31, 32].

Figure 4 shows that the main effects of parameters are significant but interactive effects are insignificant. The trends of the main effects in Figure 4 are the same as shown in Figure 3(a and b). Moreover, the slope of the temperature line in Figure 4 indicates that temperature is more significant or dominant than the concentration of nanoparticles.

3. 2. Response Optimization and Proposed Equation

The response is optimized using the experimentally obtained data to minimize the viscosity of the nanofluid to improve its rheological characteristics. The fit optimum value as predicted by the software for the present model is 0.513 mPa.s with a confidence interval of 95%. The predicted value is close to the actual experimental value of 0.525 mPa.s. So, optimum viscosity (0.513 mPa.s) with 18.72% enhancement is observed at a medium level of A and a high level of B (i.e., 0.1% and 60°C). Based on ANOVA analysis of the experimental data, Equation (4) is proposed for estimating the viscosity of nanofluid under the given conditions of the present work. The proposed equation is valid for the ranges of 0.03 ≤ φ ≤ 0.3 wt.% and 30 ≤ τ ≤ 60 °C.

$$\mu_{nf} = 1.259 + 1.5\times(\varphi) - 0.0121\times(\tau) - 0.01505\times(\varphi)\times(\tau) \quad (4)$$

The high value of R^2 (98.47%) indicates the high precision of the equation and proves the equation to be acceptable for the given range of factors in the present work.

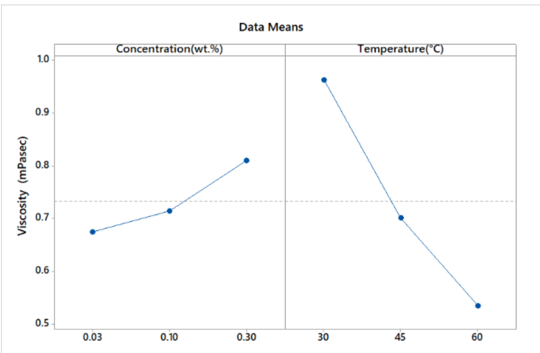

Figure 2. Main effects of the parameters on viscosity

3. 3. Contour and Surface Plots

The selected factors' effects on nanofluids' viscosity are shown in Figure 5(a and b). In a contour plot, viscosity is represented as contours having different colors. As the temperature increases, the contour's color changes from dark green to dark blue. This shows the decreasing trend of viscosity with rising temperature. The surface plot shows the relationship between viscosity, concentration, and temperature. The surface plot shows that viscosity has an increasing and decreasing trend with concentration and temperature respectively. Viscosity is maximum at the lowest temperature and highest concentration. The lowest value of viscosity is found at the highest temperature and lowest concentration. The peaks and valleys in the surface correspond to the combination of concentration and temperature that produce the local maximum and minimum thermal conductivity. The trends of the plots in Figure 5(a and b) comply with the graphs in Figures 3 and 4. Plots show that viscosity increases with an increase in concentration at a constant temperature but decreases with an increase in temperature at a constant concentration.

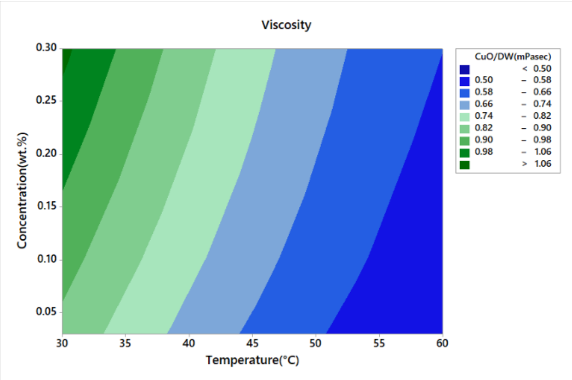

Figure 5 (a). Contour plot showing the effects of factors on viscosity

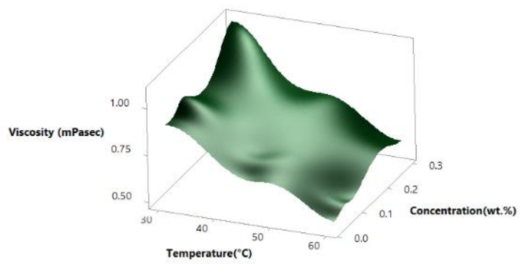

Figure 5 (b). Surface plot showing the relation between the factors and viscosity

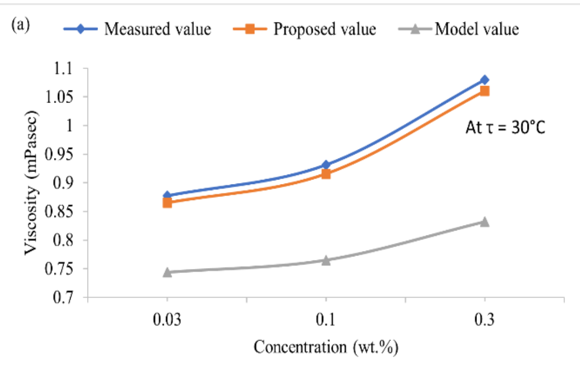

Figure 6 (a). Viscosity versus concentration at 30°C

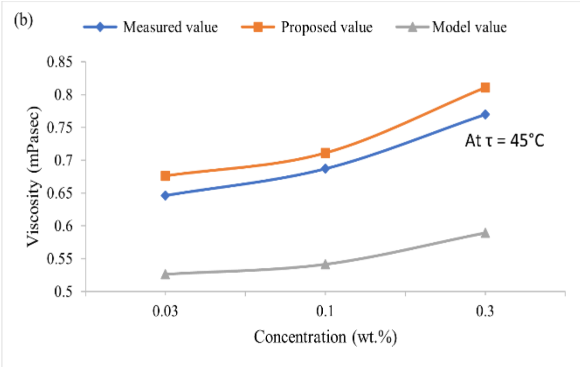

Figure 6 (b). Viscosity versus concentration at 45°C

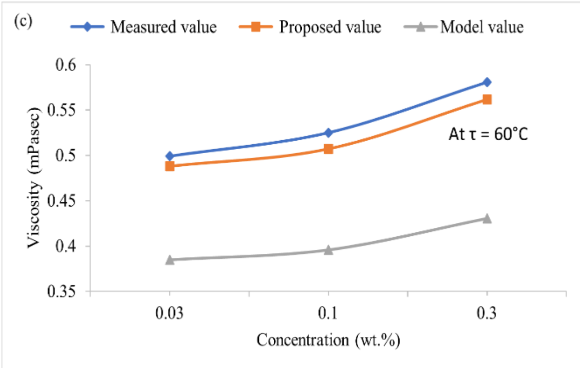

Figure 6(c). Viscosity versus concentration at 60°C

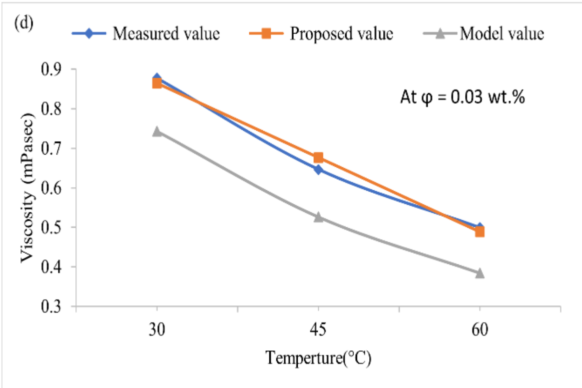

Figure 6(d). Viscosity versus temperature at 0.03 wt.%

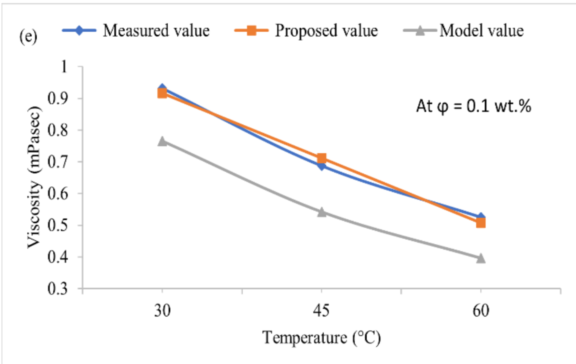

Figure 6(e). Viscosity versus temperature at 0.1 wt.%

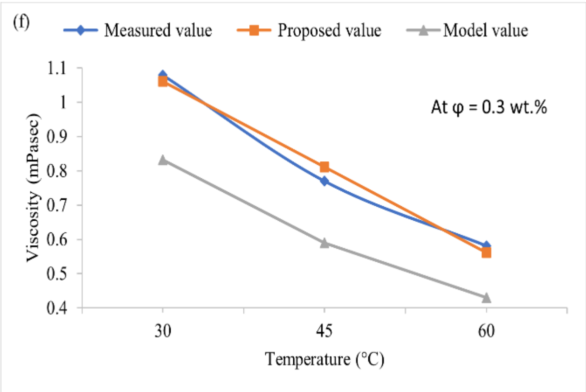

Figure 6(f). Viscosity versus temperature at 0.3 wt.%

3. 4. Comparison of Results

The proposed Equation (4) and Einstein model Equation (1) have been used to calculate the viscosity under the same conditions which are used to determine viscosity experimentally. A comparison among measured proposed, and model values have been made and presented graphically in Figure 6(a-f). It is observed that the modal underestimates the viscosity as the model values are on the lower side in all the cases. The overall underestimation by the model varies from 15.24 to 25.92%. The amount of underestimation is increased with an increase in the weight concentration of nanoparticles and temperature. The maximum underestimation is observed at 0.3 wt.% and 60°C. Whereas minimum underestimation is observed at 0.03 wt.% and 30°C.

The model used is empirical and does not include the effects of factors like the shape and size of nanoparticles etc. and various mechanisms that influence the viscosity. This underestimation by the model may be attributed to such reasons. However, the values found from the proposed Equation (4) are close to the experimentally measured values. This proves the accuracy and validity of the proposed equation for the given set of conditions.

4. CONCLUSION

Effects of weight concentration of nanoparticles and temperature on the viscosity of prepared nanofluids were studied using ANOVA-based 2^3 factorial design. The following conclusions are drawn from the present study:

1. The viscosity of nanofluids is more than base fluid i.e., DW in all the cases. It shows a direct relationship with the concentration of nanoparticles but varies indirectly with temperature.
2. The net enhancement in viscosity varied from 15.49 to 38.68% in nanofluids when compared with that of DW. The maximum value is observed at a high level of concentration of nanoparticles (0.3 wt.%) and a low level of temperature (30°C) whereas, whereas minimum enhancement is observed at a low level of concentration of nanoparticles (0.03 wt.%) and high level of temperature (60°C).
3. With the increase in the concentration of nanoparticles from 0.03 to 0.3 wt.%, the viscosity is increased by 23.12, 19.09, and 16.41 % at 30, 45, and 60°C respectively.
4. With the increase in temperature from 30 to 60°C the viscosity is decreased by 43.09, 43.61, and 46.19% at concentrations of 0.03, 0.1, and 0.3 wt.% respectively. However, the maximum reduction of 44.5% is found in the case of DW.
5. The 18.72% enhancement in viscosity has been noticed at the optimum conditions i.e., a medium level of concentration and a high level of temperature (i.e., 0.1% and 60°C).
6. The model underestimates the viscosity. The maximum 25.92% underestimation is observed at a concentration of 0.3 wt.% and 60°C whereas the minimum 15.24% underestimation is found at a concentration of 0.03 wt.% and 30°C.
7. The results of the proposed correlation are very close to the experimental findings. The high value of R^2 (98.47 %) indicates the high precision of the equation and proves the equation to be acceptable for the given range of factors in the present work.

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Persian Abstract

چکیده

در این مقاله، اثرات غلظت وزنی نانوذرات و دما بر ویسکوزیته نانوسیالات اکسید مس مبتنی بر آب با استفاده از طرح فاکتوریل دو عاملی سه سطحی (23) مبتنی بر تحلیل واریانس (ANOVA)به صورت تجربی مورد بررسی قرار گرفته است. نتایج نشان می دهد که با افزایش غلظت وزنی نانوذرات از ۰.۰۳ به ۰.۳ وزنی، حداکثر افزایش ۲۳.۱۲ درصد در ویسکوزیته در دمای ۳۰ درجه سانتی گراد مشاهده می شود. در حالی که دما از ۳۰ تا ٦۰ درجه سانتی گراد افزایش می یابد، ویسکوزیته در مورد نانوسیال ۰.۳ درصد وزنی تا ٤٦.۱۹ درصد کاهش می یابد. دما غالبتر از غلظت نانوذرات است. مقدار بهینه ویسکوزیته ۰.۵۱۳ mPa.s در غلظت‌های ۰.۱ درصد وزنی و دمای ٦۰ درجه سانتی‌گراد با افزایش ۱۸.۷۲ درصدی ویسکوزیته در مقایسه با سیال پایه یافت می‌شود. مقادیر تجربی و مدل ویسکوزیته با پیش‌بینی‌های معادله پیشنهادی برای ویسکوزیته مقایسه شده است. نتایج اندازه‌گیری‌شده تجربی در نزدیکی نتایج پیشنهادی یافت می‌شوند در حالی که مدل ویسکوزیته را در مورد همه نانوسیال‌ها دست‌کم می‌گیرد. حداکثر کمترین برآورد ۲۵.۹۲ درصد در مورد نانوسیال ۰.۳ درصد وزنی در دمای ٦۰ درجه سانتی گراد مشاهده شد.