Effect of the non-electrically conductive spindle on the viscosity measurements of nanofluids subjected to the magnetic field

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Highlights

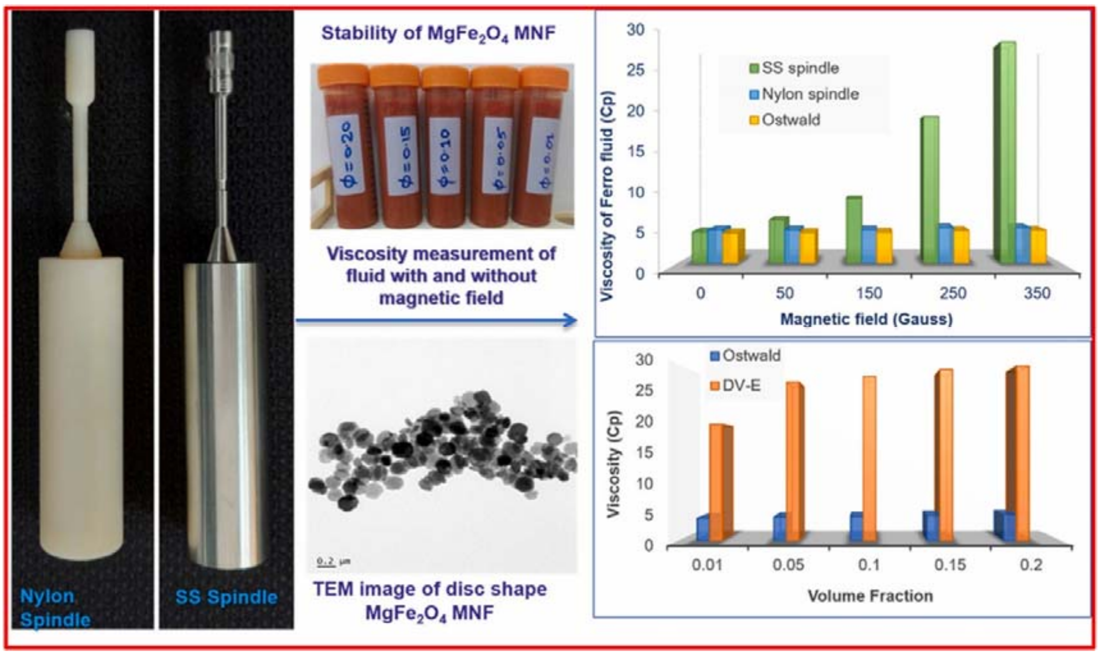
- Critically analyzed the impact of the magnetic field on the viscosity measurement devices.
- Ferrofluid viscosity enhanced unrealistically 725% for 0.20% volume fraction of $MgFe_2O_4$ at 350 G using DV-E viscometer.
- Viscosity of ferrofluid enhanced 27.68% for 0.20% volume fraction of $MgFe_2O_4$ at 350G using glass capillary viscometer.
- Causes for the deviation in viscosity is identified and rectified.
- A new spindle for viscosity measurement is fabricated and tested.

Abstract

The viscosity measurements of magnetic nanofluid subjected to the magnetic field are indispensable in various heat transfer studies. Intention of the present discussion is to critically analyze the magnetic field's influence on the working of two viscometers; a Glass capillary viscometer and a DV-E Brookfield viscometer. The novelty of the present study is in the identification of the underlying reason for the massive escalation in viscosity when the magnetic nanofluid is subjected to magnetic field and rectification of the error caused. The stainless-steel spindle in the viscometer is replaced with a non-electrically and non-magnetically conductive nylon spindle to rectify the error. The dynamic viscosity of magnesium ferrite nanofluid of different volume fractions at a temperature of 25°C in the

occurrence of magnetic field was measured. The viscosity of magnetic nanofluid measured using DV-E Brookfield viscometer escalated to a maximum of 725% over the same measured using glass capillary viscometer with the magnetic field application. The application of the nylon spindle in the viscometer eliminates the error caused due to the eddy current formation in the spindle. Therefore, this study recommends using viscometers with non-electrically and non-magnetically conductive spindles for accuracy while measuring the viscosity of magnetic fluids.

Graphical abstract



Keywords: *Erroneous Viscosity; Magnetic nanofluid; Magnetic field; Glass capillary viscometer*

1. Introduction

Thermophysical properties of coolants are critical for efficient heat transfer in thermal management of compact electronics, PV panels, transformers, etc. The conventional coolant properties are limited, and therefore the application of coolants in modern thermal management is increasingly challenging. Choi et al.[1] developed a novel coolant named nanofluid by suspending nanosized metals (copper nanoparticles) in water and understood that the thermal conductivity of copper nanofluid augmented three times compared to the conventional coolant water. After this breakthrough, metals, metal oxide nanoparticles, and a mixture of both metals and metal oxides (hybrids) were added to enhance the thermophysical properties of conventional coolants [2–5]. Besides, various nano coolants have been developed and tested in various systems such as solar thermal and heat exchanging [6–8]. The nanofluids are also utilized in other areas such as bio-natural convection, rotating machinery, and fuel storage applications [9–12].

Magnetic nanofluid (MNF) is a fluid prepared by suspending ferromagnetic nanoparticles such as Fe_3O_4 nanoparticles, $CoFe_3O_4$ nanoparticles, $MnFe_3O4$ nanoparticles, $NiFe_2O_4$ nanoparticles, etc. in the cooling fluid whose thermal and physical properties can be tuned by the influence of magnetic field (MF)[13]. The dispersion of magnetic nanoparticles into the cooling fluid to enhance its thermophysical properties for the augmentation of heat transmission with or without the MF application was investigated by numerous researchers [14]. As per the observations, MNFs thermal conductivity and viscosity showed tremendous enhancement with the MF application [15]. Therefore, the rheological property of MNF is a significant feature to be considered before exploring heat transfer applications. The increase in viscosity adversely affects MNF's heat transfer mechanism, rendering it unsuitable for heat transfer applications. Furthermore, increased viscosity and density of the working fluid limit the fluid's buoyancy effects, resulting in reduced fluid motion and diminished convection heat exchange [16–21]. The previous studies emphasize that the viscosity of MNFs subjected to MF was estimated with the aid of Glass capillary viscometers, Ubbelohde viscometer, DV-E Brookfield viscometers, Vibro-viscometers, and Physica MCR 300 viscometers.

Several research studies have shown that the viscosity of the MNF is enhanced enormously due to MF application. Contrary to this, a few investigations show a minor enhancement in viscosity with the MF. Li et al.[22] measured the viscosity of Fe_3O_4-H_2O MNF using a glass capillary viscometer under the influence of MF (210 Gs) and observed a maximum viscosity ratio of 24 at a volume concentration of 2.83%. Using MCR301 Rheometer, Shima et al.[23] reported 70% increase in viscosity at 0.0171 volume fraction of Fe_3O_4-Kerosene MNF subjected to 450 Gs MF. Wang et al.[24] used a Vibro- viscometer for measuring the viscosity of Fe_3O_4-H_2O MNF in the presence of the MF and marked 80% rise in the viscosity at 5% volume concentration. The experiment's outcome explains that the viscosity was enhanced by 60% at MF strength of around 160 Gs compared to the viscosity of water. Amani et al.[25] noticed 75% enhancement in viscosity for $MnFe_2O_4$-H_2O MNF at a volume concentration of 3% and the MF of 400 Gs by using DV-E Brookfield viscometer. Paul et al.[26] investigated the rheological property of Fe_3O_4-H_2O MNF under the MF with the aid of the MCR 301 Rheometer. The findings conclude that the viscosity of prepared MNF was raised enormously from 0.01 to 0.09 Pa.s at 5000 Gs at 0.045 volume fraction. Pouyan et al.[27] experimentally studied the MF influence on the viscosity of CNT: Fe_3O_4-H_2O hybrid MNF by MCR 300 Rheometer. The results indicated that the MF application richly increased the viscosity of hybrid nanofluid by 23398.76% at volume fraction 1.5% and a shear rate of 1 S^{-1} compared to the viscosity of the same MNF without the application of the MF. Malekzadeh et al.[28] utilized LVDV-II Pro DV-E Brookfield viscometer for viscosity measurement of Fe_3O_4/H_2O MNF in the presence of MF. It was disclosed that the viscosity of MNF raised by 175% at 1 vol% and 550 Gs. The impact of the MF on the viscosity of hybrid MNF Fe_3O_4: CNT/H_2O was explored by Shahsavar et al.[29] with the aid of the MCR 300 Rheometer. The dynamic viscosity of this hybrid MNF (0.9% Fe_3O_4+ 1.35%CNT) increased from 0.009 to 0.034 Pa. s at MF 480 Gs at a shear rate of 100 S^{-1}. Gu et al.[30] assessed the viscosity of ferrite MNF in the presence of MF at a volume fraction of 1% with SDBS surfactant (mass fraction 6%) by using Ubbelohde viscometer. It was learned that the viscosity of ferrite MNF was enhanced by 60% at MF of 160 Gs compared to that of water. Yang et al.[31] used the torsional oscillation cup viscometer to determine the viscosity of Fe_3O_4-H_2O MNF in the presence of MF and observed a rise of 65 Cp related to the viscosity of water at volume concentration of 8vol% and MF of 950 Gs. Nurdin et al.[32] examined the viscosity of maghemite-water nanofluid with a glass capillary viscometer, and the results showed 31.91% enhancement in viscosity of MNF in the presence of 300 Gs MF. Yaghoub et al.[33] used glass capillary viscometer to measure the viscosity of magnetite-hydraulic oil MNF and observed 14% enhancement in the viscosity with the application of 300 Gs MF. Andhariya et al.[34] analyzed the MF influence on viscosity of Fe_3O_4-H_2O MNF at various volume fractions by using capillary viscometer and found that a maximum of 32% enhancement in viscosity at 0.06 Tesla and 0.64% volume fraction. From the above literature, it is clear that there is a stark contradiction in the viscosity data.

Table 1 summarizes the viscosity of Fe_3O_4/water-based MNF at various volume fractions and different MF strengths. It was understood that the viscosity of MNF may depend on the kind of base fluid, particle size, particle shape, particle concentration, the intensity of MF, the direction of MF, and many other parameters. However, the data extracted from the studies summarized in Table 1 shows that the MF is responsible for the significant increase in viscosity compared to other parameters. Moreover, the literature review presents inconsistent measurements on the viscosity of MNF subjected to MF. Among these, the Rheometer, DV-E Brookfield viscometer, and Vibro viscometer showed a high percentage of increase in MNF viscosity under the influence of MF compared to the observations using glass capillary viscometer. It is interesting to note that the above viscometers have non-magnetic probes or spindles which are not susceptible to MF and variations in viscosity measurements are still observed. These contrary results indicate an inevitability to substantiate the viscosity measurements of MNFs subjected to MF. Rosensweig et al.[35] modified the Wells-Brookfield viscometer using a non-magnetic cone-and-plate for viscosity measurement of magnetite MNF in the presence of MF. The name of the cone and plate material is not declared in the above study. Also, this paper does not mention whether the material is electrically conductive or electrically non-conductive. In electrically conductive materials, eddy current may be generated in the presence of MF and generates an error in the measurement system even if the spindle is non-magnetic. Though the non-magnetic cone and plate is employed for viscosity measurement, they still observed that the MF has a substantial effect on viscosity. A torque measurement of applying polycarbonate material immersed in MNF subjected to rotating MF and tangential stresses estimation of a glass cylinder immersed in MNF subjected to a rotational MF is reported in the literature [36,37]. However, these studies do not relate their results to the viscosity measurement enhancements. Therefore, the current investigation is significant in the field of magneto rheological property.

Table 1 Viscosity of Fe_3O_4/Water MNF at different measuring conditions

Author	Nano fluid	Size and shape nanoparticle	Volume fraction/Volume concentration	Magnetic field		Type of viscometer	Viscosity enhancement
				Strength	Direction		
Wang et al.[24]	Fe_3O_4-water	Spherical and 7.5 nm	0.5 to 5% volume fraction	0 to 300 Gauss	Perpendicular to the vibration direction of SV-10 viscometer	Sine-wave vibro viscometer	Enhanced by 80% at 5% volume fraction and 300 Gauss
Malekzadeh et al.[28]	Fe_3O_4-water	Spherical and less than 100 nm	0 to 1 vol%	0 to 550 Gauss	Not mentioned	LVDV-II+Pro, Brookfield	Enhanced by 175% at 1vol% and 550 Gauss
Gu et al.[30]	Fe_3O_4-water	Spherical and 12 nm	0.5 to 2.5% volume fraction	0 to 400 Gauss	Not mentioned	Ubbelohde viscometer	Enhanced by 60% at magnetic field strength of around 160 Gauss
Yang et al.[31]	Fe_3O_4-water	Cubic spinel and 10-20 nm	2 to 8 % volume concentration	0 to 950 Gauss	Not mentioned	Torsional oscillation cup viscometer	Rise of 65 Cp compared to the viscosity of water at volume fraction 8% and 950 Gauss
Andhariya et al.[34]	Fe_3O_4-water	Not mentioned	0.64%	0 to 600 Gauss	Parallel to the direction of fluid flow	Capillary viscometer	Enhanced by 32% of at 600 Gauss and 0.64% volume fraction

Hence, the present study investigates the viscosity of $MgFe_2O_4$ MNF in the presence of MF using DV-E Brookfield viscometer and glass capillary viscometer for clarifying the effect of MF on the working of Brookfield viscometer. This study also investigates the effect of MF direction and strength on the viscosity of MNF using a capillary viscometer. Moreover, this study investigates the importance of using non-electrically conducting and non-magnetically conducting spindle in the DV-E Brookfield viscometer while measuring the viscosity of MNF under the MF influence. In addition, this paper investigates the origins of anomalous enhancement and the method to rectify the deviation in viscosity measurement.

2. Materials and Method

2.1 Preparation of MNF

In this experiment, $MgFe_2O_4$ magnetic nanoparticles with a base fluid comprising EG: H_2O in a 60:40 volume ratio are used to prepare MNF. The selection of nanoparticles is related to the application of interest in which a low-density NF is necessary to improve buoyancy and enhance the natural convection process. $MgFe_2O_4$ nanoparticles are synthesized by hydrothermal method [38,39] and the morphology is analyzed using TEM. The TEM analysis presented in Fig. 1 shows that the synthesized $MgFe_2O_4$ nanoparticles exhibited a disk shape with a diameter of 92.285 nm. The prepared $MgFe_2O_4$ nanoparticles at various weights were dispersed in the 100 ml base fluid and sonicated with an ultrasonicate probe for 40 minutes for obtaining various volume fractions of stable MNF (0.01% to 0.20%) and the prepared MNF continued in its stable state for more than 4 weeks without any addition of surfactant. The stability of the MNF was also verified using viscosity measurements. Fig. 2 shows the variation of viscosity of $MgFe_2O_4$ MNF over a time of 4 weeks measured by glass capillary viscometer, and it is clear that there is no significant change in the viscosity of MNF over this period. This result proves that the prepared fluid is stable for more than four weeks.

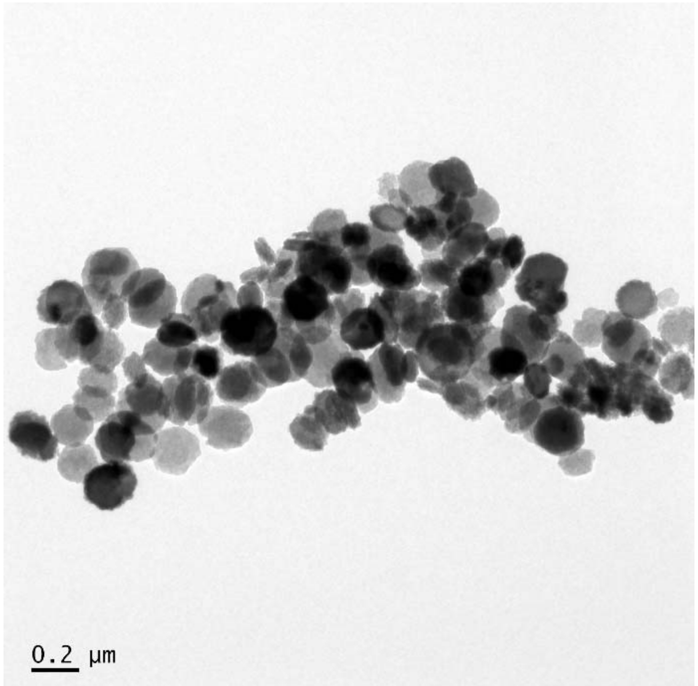


Fig. 1 TEM Image of $MgFe_2O_4$ nanoparticles synthesized by hydrothermal method

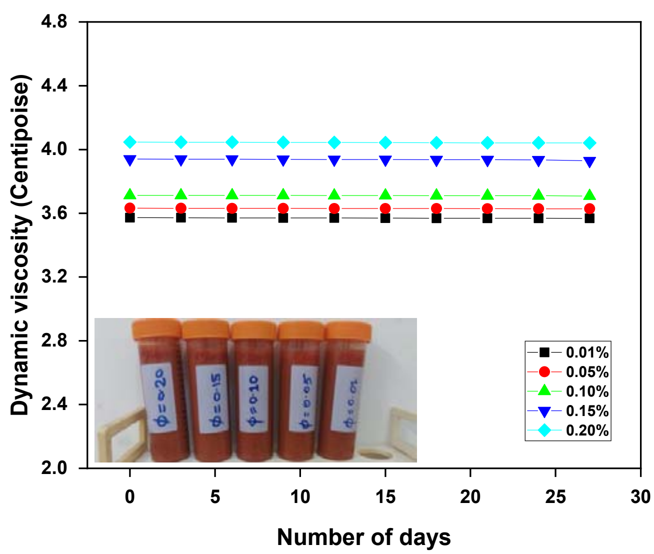


Fig. 2 Stability of the prepared MNF

2.2 Experimental setup for viscosity measurement

Fig.3 shows the experimental setup to measure the viscosity of $MgFe_2O_4$ MNF using DV-E Brookfield viscometer and glass capillary viscometer (Borosil 3500). The viscosity measurement system consists of a DC supply, a Viscometer, and an electromagnet pair, as shown in Fig. 3. The DV-E Brookfield viscometer is primarily employed for measuring the viscosity of $MgFe_2O_4$ MNF of various volume fractions (0.01% to 0.20%). Viscosity is measured with and without the MF generated by the electromagnets. The desired MF intensity is provided by connecting electromagnets to a DC power supply. Uniform MF is provided in the measurement location and was gauged by Gaussmeter. The spindle number used for the measurement was S61, and the angular velocity for the measurement was 20 RPM. Secondly, a glass capillary viscometer was used to find the viscosity of $MgFe_2O_4$ MNF with and without MF application at a temperature of 25°C. By measuring the flow time of MNF through the capillary tube, the viscosity of the fluid can be calculated as

$$\mu_{nf} = \left[\frac{\rho_{nf} * t_2}{\rho_w * t_1}\right] * \mu_w \tag{1}$$

where the dynamic viscosity of MNF is denoted by μ_{nf}, the density of the MNF is denoted by ρ_{nf}, t_2 is the time taken for MNF to flow from the upper to lower points of bulb 2, and t_1 denotes the time for water to flow from bulb 2's upper to lower level. The glass capillary viscometer was kept in the centre of two electromagnets when MF was applied. In all the above experiments, the distance between the two electromagnets is kept constant.

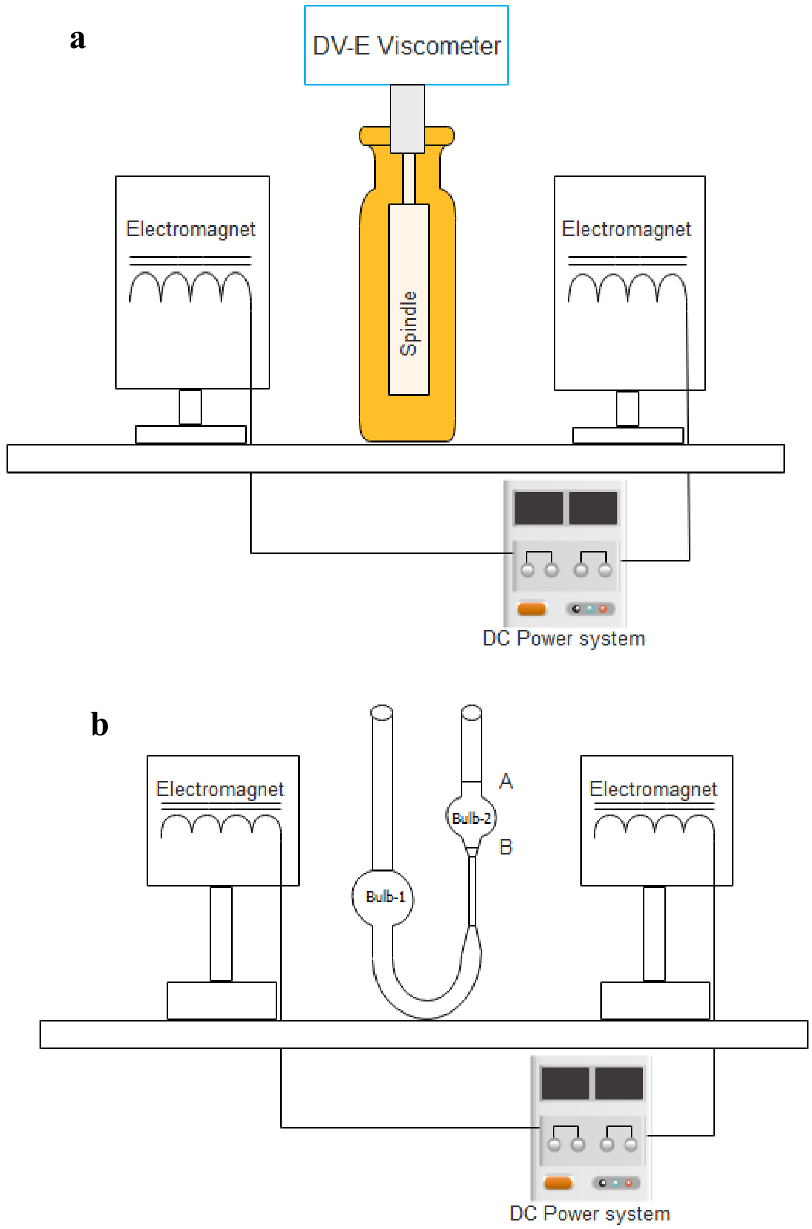


Fig. 3 Schematic experimental layout of viscosity measurement using a) DV-E Brookfield ; and b) glass capillary viscometer for MNF

2.3 Uncertainty in viscosity measurement

The uncertainty in the measurement of viscosity was determined by using equation (2)

$$\text{Uncertainty} = \sqrt{\sum_{1}^{n} \frac{(xi - X)^2}{n(n-1)}} \tag{2}$$

where the sample viscosity value is denoted by x_i , average viscosity value is denoted by X, and the sample count is denoted by n, respectively. Table 2 presents the uncertainty measured during the viscosity measurement of $MgFe_2O_4$ MNF at different measurement conditions.

Table 2 Uncertainty in measurement of viscosity at various measuring conditions

Viscometer	**Condition**	**Average Uncertainty**
DV-E Brookfield Viscometer- Stainless steel spindle	Without MF	0.454%
DV-E Brookfield Viscometer- Stainless steel spindle	With MF	1.149%
DV-E Brookfield Viscometer- Nylon spindle	Without MF	0.59%
DV-E Brookfield Viscometer- Nylon spindle	With MF	0.98%
Glass capillary viscometer	Without MF	0.0028%
Glass capillary viscometer	With MF	0.010%

3. Results and Discussion

3.1 Validation of the results

Fig. 4 (a) represents the validation of viscosity measurements using DV-E Brookfield viscometer and capillary tube viscometer with the results of the Sundar Model [40] uninfluenced by MF. The comparison reveals that the present results are overpredicting the Sundar model with an average deviation of 3.5% for both DV-E Brookfield viscometer and glass capillary viscometer. However, the trend of present measurements and the Sunder model are similar. Also, the present viscosity measurements using DV-E Brookfield viscometer and glass capillary viscometer are comparable. Fig. 4(b) represents the validation of MF-dependent viscosity of MNF at volume fraction 0.20% with the model proposed by Amani et al.[25] and Kumar et al.[14]. The present measurements with a glass capillary viscometer are comparable with the Kumar model and underpredict by 76% with the Amani model. The present viscosity measurement using DV-E Brookfield viscometer shows an exponentially increasing trend and is comparable with the Amani model at a higher MF.

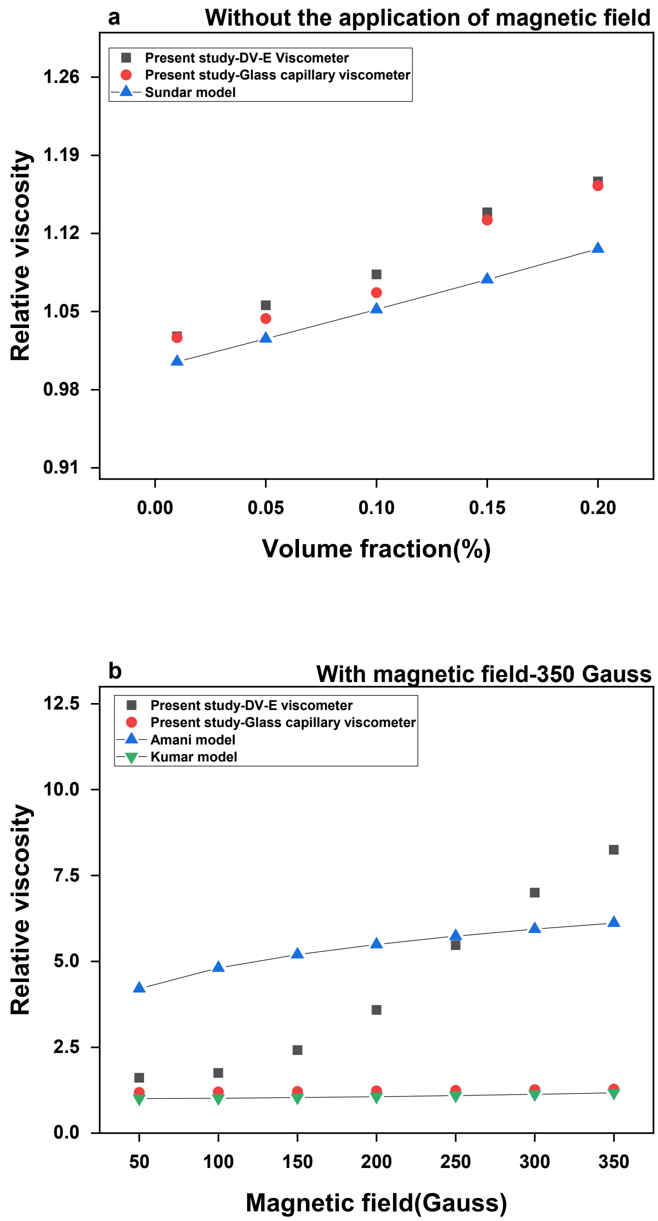


Fig. 4 Comparison of measured viscosity of MNF with theoretical models a) Without; and (b) With MF at 0.20% volume fraction

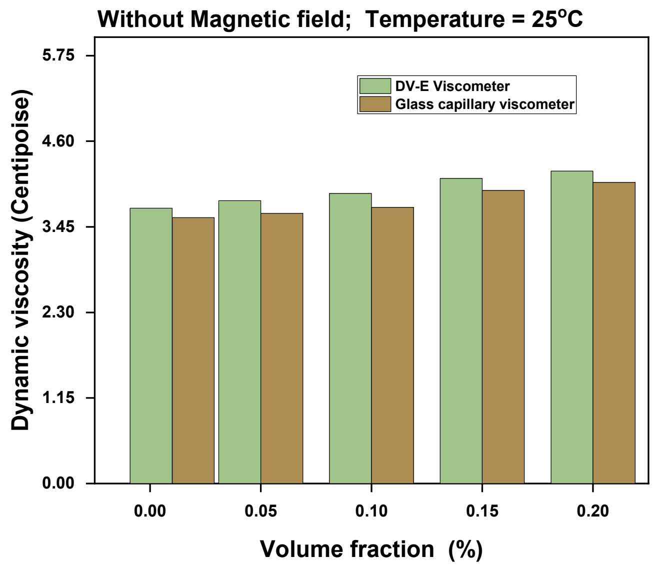


Fig. 5 Comparison of the viscosity of MNF measured by DV-E Brookfield and glass capillary viscometer without the MF application

3.2 Rheological behavior of $MgFe_2O_4$ MNF without MF

Fig.5 shows the viscosity of $MgFe_2O_4$/EG: H_2O MNF at different volume fraction ranges from 0.01% to 0.20% at 25°C measured by DV-E Brookfield viscometer and glass capillary viscometer without the application of MF. The results show that the viscosity of MNF increased linearly with the rise in volume fraction. In case of Brookfield viscometer, the viscosity of MNF at volume fraction 0.01%, 0.05%, 0.10%, 0.15%, and 0.20% are boosted by 2.78%, 5.56%, 8.33%, 13.89%, and 16.67% respectively compared to the viscosity of EG:H_2O mixture. The viscosity data measured from glass capillary viscometer shows that percentage of increase in viscosity with respect to base fluid is 2.66% for 0.01% volume fraction, 4.37% for 0.05% volume fraction, 6.68% for 0.10% volume fraction, 13.19% for 0.15% volume fraction and 16.27% for 0.20% volume fraction. These observations made from Brookfield viscometer and glass capillary viscometer are comparable with the average deviation of 0.8045. From this data, it can be understood that the viscosity of MNF at 0.20% volume fraction is enhanced by a maximum of 16% for both glass capillary viscometer and DV-E Brookfield viscometer compared to that of the base fluid. The addition of nanoparticles in the base fluid leads to formation of the nanoparticle cluster resulting in viscosity enhancement. Nevertheless, the viscosity measurements made using DV-E Brookfield viscometer and glass capillary viscometer showed a similar trend with minimum variation. These results indicate that the viscosity measurements using both DV-E Brookfield viscometer and glass tube viscometer are comparable as expected, and both devices are suitable for measuring the viscosity of MNF without applying the MF.

3.3 Rheological behavior of $MgFe_2O_4$ MNF with the MF

In this section, the effect of MF direction and strength on the viscosity of MNF using a glass capillary viscometer is reported. The viscosity of MNF while applying MF in parallel and perpendicular to the fluid flow direction using the capillary tube viscometer is studied. It is observed that there is no significant deviation in the viscosity of MNF measured in both directions of MF (Fig. 6). Also, the effect of MF strength on the viscosity of MNF using glass capillary viscometer and DV-E Brookfield viscometer is studied and compared in Figs. 7 (a), (b) &(c). By the application of 50 Gs MF, the viscosity of MNF is enhanced by 2.9%, 5.9%,7.7%,14.6%, and 18.20%, respectively for the volume fractions of 0.01%,0.05%,0.10%,0.15%, and 0.20% using glass capillary viscometer. On the contrary, there is a huge enhancement in viscosity of the same MNF measured by DV-E Brookfield viscometer with MF application. The viscosity enhancement of MNF is 8.3%, 25%, 41.6%, 47.2% and 61.1%, respectively, for the volume fractions of 0.01%, 0.05%, 0.10%, 0.15%, and 0.20%, as shown in Fig. 7(a). Further increase in MF resulted in a huge enhancement in viscosity; however, the trend is similar to the 50Gs MF (Fig 7b). The viscosity of MNF measured by glass capillary viscometer showed a maximum rise of 27.68% over the same of base fluid at 350Gs and 0.20% volume fraction, as presented in Fig 7(c). Moreover, a disproportionate increase in viscosity over the base fluid of 725% is observed for 0.20% volume fraction of MNF at 350 Gs MF while using DV-E Brookfield viscometer. Therefore, it is clear that the measurements of DV-E Brookfield viscometer increase exponentially with the increase in MF strength, while the viscosity measured by the glass capillary viscometer shows a moderate linear increase. Table 3 shows the percentage of enhancement in viscosity at all volume fractions of MNF with and without the MF measured using DV-E Brookfield viscometer and capillary tube viscometer. The remarkable enhancement observed from the DV-E Brookfield viscometer data over the glass capillary viscometer signifies that the former's working is affected due to the MF.

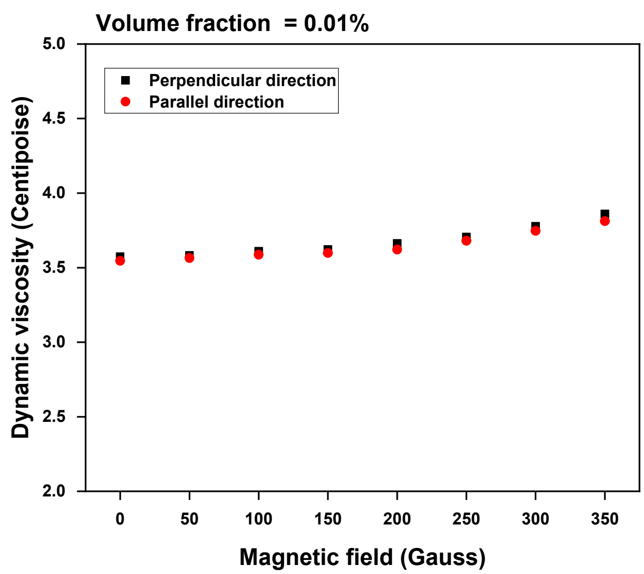
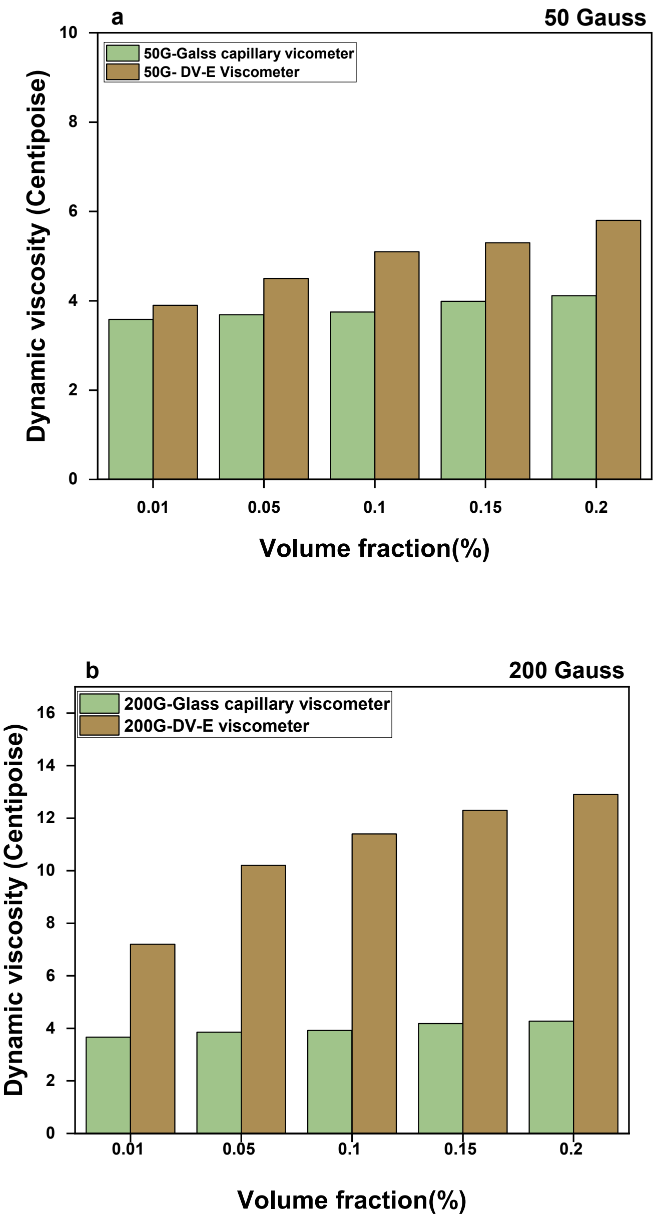


Fig. 6 Variation of viscosity measured by glass capillary viscometer with respect to the direction of MF

Table 3 Comparison of MNF viscosity measured by DV-E Brookfield and Glass capillary viscometer with and without the **application of MF**

Volume fraction	without magnetic field		With Magnetic Field (350 Gauss)	
	DV-E Brookfield Viscometer	Glass capillary viscometer	DV-E Brookfield Viscometer	Glass capillary viscometer
0.01%	2.78%	2.66%	450%	10.92%
0.05%	5.56%	4.37%	650%	15.50%
0.10%	8.33%	6.68%	675%	19.03%
0.15%	13.89%	13.19%	708%	24.30%
0.20%	16.67%	16.27%	725%	27.68%


a
50 Gauss
50G-Galss capillary vicometer
50G- DV-E Viscometer
Dynamic viscosity (Centipoise)
0
2
4
6
8
10
0.01
0.05
0.1
0.15
0.2
Volume fraction(%)
b
200 Gauss
200G-Glass capillary viscometer
200G-DV-E viscometer
Dynamic viscosity (Centipoise)
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Volume fraction(%)

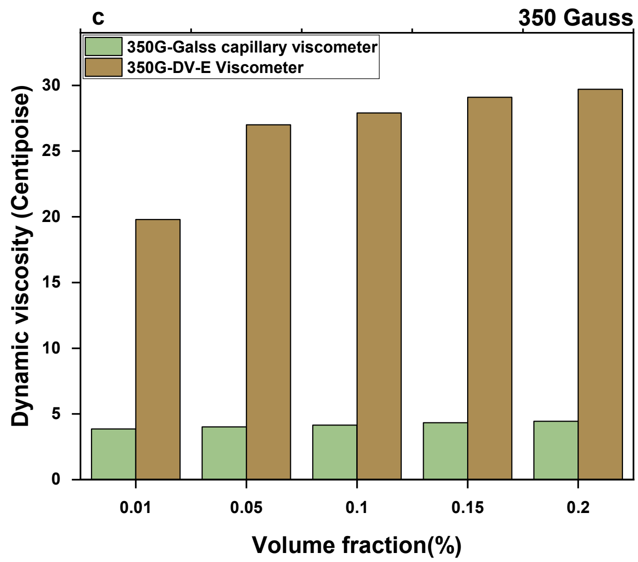

Fig. 7 Comparisons of the viscosity measured using DV-E Brookfield and glass capillary viscometer a) at 50 Gs; b) at 200 Gs; and at 350 Gs for MNF

3.4 Effect of MF on the working of DV-E Brookfield viscometer

The DV-E Brookfield viscometer consists of several mechanical components such as a stepper motor, non-magnetic beryllium-copper spring, pivot drive shaft, and the non-magnetic spindle made up of stainless steel (Grade 316). The synchronous motor is placed inside the housing to avoid the effect of external disturbances. The viscometer display shows the spindle number, RPM of the spindle, the torque generated, and the viscosity of the sample fluid. The viscosity shown in the display is a function of torque generated in the calibrated spring, spindle rotation, and spindle factor [41]. In this experiment, the spindle used to measure viscosity is S61, and its spindle factor can be calculated as in Equation 3 [41].

$$\text{Spindle factor} = \frac{60}{N_s} \tag{3}$$

where N_s is the spindle rotation. The specimen fluid's viscosity can be calculated using the spindle factor and the torque generated in the spindle[41], as represented in Equation 4.

$$\text{Dynamic viscosity} = \text{Spindle factor} \times \text{Torque} \tag{4}$$

From equation 4, it is clear that the MNF viscosity depends on the torque variation generated in the calibrated spring. Experiments were carried out to understand the MF effect on the torque generation of the calibrated spring with non-magnetic fluid deionized water. Interestingly, it was noticed that the viscosity of DIW in the presence of the MF at 30 RPM is sharply increasing, as shown in Fig.8. The DV-E Brookfield viscometer's reading signifies that the MF affects the measurement device, although a non-magnetic fluid is used. In general, the viscosity of the fluid is calculated using Newton's law of viscosity. According to the law, the relation between the shear stress and the viscosity can be represented as

$$\tau = \mu \frac{du}{dy} \tag{5}$$

where μ is the dynamic viscosity of the fluid, τ is the shear stress, and du/dy is the rate of shear strain. Therefore, the viscosity can be represented as

$$\mu = \frac{\tau}{\left(\frac{du}{dy}\right)} \tag{6}$$

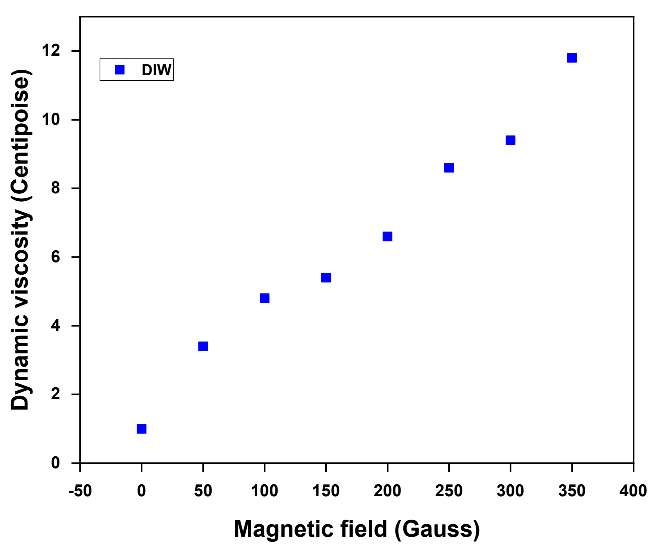

Fig. 8 Viscosity of DIW subjected to MF using DV-E Brookfield viscometer

The above equation clearly states that the viscosity is directly proportional to the shear stress. In the DV-E Brookfield viscometer, the fluid's viscosity depends on the shear stress and the torque[41], as represented in Equation 7.

$$\text{Shear stress} = \frac{T}{2\pi \times {R_s}^2 \times L_s} \qquad (7)$$

where T is the torque generated in the calibrated spring, R_s is the radius of the spindle, and L_s is the spindle's length. The DV-E Brookfield viscometer measured torque of 0.5 at 30 RPM of the stainless-steel spindle displayed in Fig. 9(a) without the MF application, and hence, it displays the viscosity of water as 1 Cp as per equation 4. Under the same experimental conditions, the influence of MF 350 Gs elevated the torque to 5.9, and therefore, DV-E Brookfield viscometer displayed a torque of 11.8 Cp. This torque rise indicates that it is a primary cause of the error. Therefore, an effort has been made to find the source of excess torque and reduce the torque. In the DV-E Brookfield viscometer, the stainless-steel spindle rotates inside a fluid. As per Faraday's law of induction, circular electric current loops (eddy current) could be formed in a conducting material when this material cuts the MF produced by the electromagnet. Thus, eddy current loops generate torque on the spindle and result in erroneous measurement by the DV-E Brookfield viscometer in the MF presence. However, the possibility of erroneous measurement in the case of glass capillary viscometer is nil due to the absence of electrically conductive material in the device. Fluid viscosity is assessed in a glass capillary viscometer by measuring the time taken for a known volume of fluid to move through the capillary tube due to gravity. Hence, it can be concluded that the viscosity measured by the glass capillary viscometer is more accurate than the observation made using the DV-E Brookfield viscometer.

Fig. 9 Photographs of spindle used in the viscosity measurement of MNF a) Stainless steel ; and b) Nylon spindle.

3.5 Solution to the problem

It is well known that eddy current loops are formed in electrically conductive material irrespective of magnetic property. The eddy current also forms in magnetically non-susceptible material if it is an electrically conductive material. Therefore, a new spindle was made using a nylon material with the exact dimension of the S61 spindle as shown in Fig.9(b) to avoid eddy current formation. The viscosity of DIW and MNF were measured using this new spindle. There is no variation in the viscosity of water measured by the DV-E Brookfield viscometer with the aid of a nylon spindle in the MF presence. Simultaneously, the viscosity of water measured using stainless steel spindle shows significant variations as shown in Table 4. Fig. 10 shows the MNF viscosity at 0.20% volume fraction measured by glass capillary viscometer and DV-E Brookfield viscometer using stainless steel spindle and non-conducting spindle. It is noted that the viscosity assessed by DV-E Brookfield viscometer with nylon spindle is comparable with the same measured by glass capillary viscometer. In contrast, viscosity measured using DV-E Brookfield viscometer stainless spindle shows an enormous surge in viscosity. From the above results, it is clear that the MF affects the readings of the DV-E Brookfield viscometer due to the eddy current, and it can be eliminated by using a non-electrically conducting spindle.

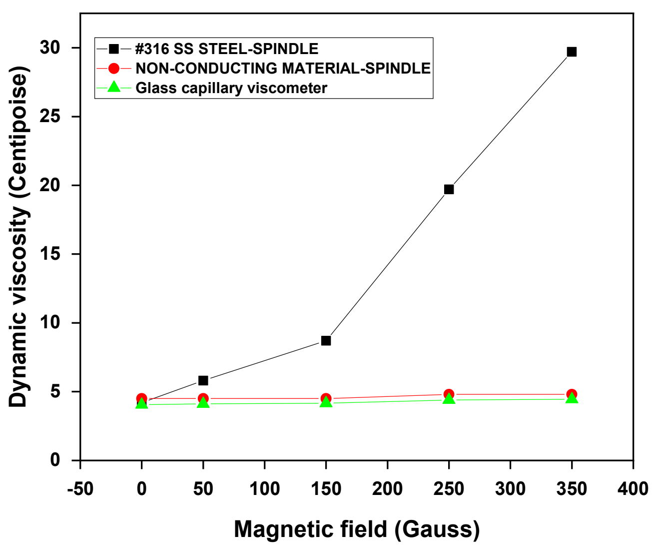

Fig. 10 Comparison of MNF viscosity measured using glass capillary and DV-E Brookfield viscometer with the aid of stainless-steel and Nylon spindle at volume fraction 0.20% in the attendance of the magnetic field.

Table 4 Viscosity of DIW measured with DV-E Brookfield viscometer by using stainless steel and Nylon spindle with and without the application of MF

Spindle-Stainless steel		Spindle-Nylon
With Magnetic field (350 Gauss)	**Without Magnetic field**	**With Magnetic field (350 Gauss)**
11.8 Cp at torque 5.9%	**1 Cp at torque 0.5%**	**1 Cp at torque 0.5%**

Conclusion

The effect of the non-electrically conductive spindle on the viscosity measurements of MNF subjected to MF is studied, and the reason for anomalous enhancement in viscosity while using DV-E Brookfield viscometer was identified. Finally, a solution to rectify the error during viscosity measurement under the magnetic field is proposed. This experimental investigation shows the contradictory results of viscosity obtained from two viscometers (DV-E Brookfield viscometer, Glass capillary viscometer) under the attendance of MF. The results obtained from these investigations lead to the conclusions presented below:

- The observation of two viscometers shows that the viscosity of $MgFe_2O_4$ MNF augmented by rise in volume fraction of MNF uninfluenced by MF and are comparable.
- The viscosity of MNF measured using DV-E Brookfield viscometer escalated to a maximum of 725% over the same measured using glass capillary viscometer with the MF application.
- The viscosity obtained by DV-E Brookfield viscometer with nylon spindle and glass capillary viscometer is comparable with the enhancement of 28% for the MNF of 0.20% volume fraction at 350Gs MF.
- The viscosity measurement under the MF application results in an eddy current in the stainless-steel spindle of the DV-E Brookfield viscometer leading to enormous enhancement in the measurement. The nylon spindle application in the DV-E Brookfield viscometer rectifies the enormous enhancement in the measurement, and it is comparable with the glass capillary viscometer measurements in the presence of the MF.

Therefore, this study recommends using viscometers with non-electrically and non-magnetically conducting spindles or probes for the viscosity measurement while measuring under the influence of MF.

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Nomenclature

$MgFe_2O_4$	Magnesium Ferrite
MNF	Magnetic Nanofluid
MF	Magnetic Field
Gs	Gauss
EG	Ethylene Glycol
H_2O	Water
SDBS	Sodium Dodecylbenzene Sulfonate Surfactant
Cp	Centi poise
SDS	Sodium Dodecyl Sulfate
TEM	Transmission Electron Microscopy
RPM	Revolution Per Minute
DIW	Deionized Water
Greek Symbols	
μ	Dynamic viscosity (Cp)
ρ	Density (kg/m^3)
Φ	Volume fraction (%)
τ	Shear stress (N/m^2)
Subscripts	
nf	nanofluid
bf	base fluid
np	nanoparticle
s	spindle