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INFLUENCE OF ELECTROMAGNETIC WAVES ON VISCOSITY AND ELECTRORHEOLOGY OF DIELECTRIC NANOFLUIDS-SCALE-BASED APPROACH

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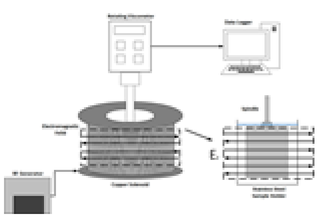
Graphical abstract



Abstract

The appearance of electric field and shear dependent viscosity change in dielectric nanofluids provide potential for prospective applications especially in enhanced oil recovery. When nanofluids are activated by an applied electric field, it behaves as a non-Newtonian fluid under electrorheological effect, where the augment of electric field intensity increases the interaction among nanoparticles. Hence the mobility of the fluid can be efficiently controlled by regulating the applied field. Electrorheological characteristics of ZnO and Al_2O_3 nanofluids with various nanoparticles concentration (0.1, 0.05, 0.01 wt%) were measured. Results show that all the nanofluids exhibit pseudoplastic (shear thinning) behavior, while the electric field causes a visible increase in viscosity at a high shear rate. From the experimental results, it is also explained how the polarization of induced dipoles affects the electrorheology of nanofluids, by creating chains that align with the applied electric field. This paper also describes the designing and experimental aspects of the electromagnetic system, to investigate the change in viscosity of nanofluids.

Keywords: Dielectric, nanofluid, electromagnetic, viscosity, pseudoplastic, electrorheological effect, polarization, enhanced oil recovery

1.0 INTRODUCTION

A nanofluid is a novel class of engineered fluid in a new interdisciplinary area of great significance, which includes nanoscience, nanotechnology, and nanoengineering [1]. Nanofluids have attracted attention in a vast range of fields in recent years. However, we focus on employing nanofluids in upstream oil industries, particularly for enhanced oil recovery (EOR) purposes. Most of the researchers observed that nanoparticles are very attractive for EOR purposes. However, most of those studies used silica-based nanoparticles. Therefore the use of other types of nanoparticles should be investigated further for the alternatives and potentially innovative solutions. Currently, metal oxides play a very vital role in numerous areas of chemistry, physics and material science [2]. These metal oxide nanoparticles (Al_2O_3, ZnO, TiO_2, ZrO_2, Fe_2O_3, etc.) show vital enhancement in their characteristics (i.e. structural, chemical, thermal, electrical and magnetic properties) compared to that of bulk material.

In oil and gas industries, the uses of metal oxides have been investigated recently. The metal oxide nanoparticles have presented great potential for enhanced oil recovery for both light and heavy oil [3 - 6]. For instance, these nanoparticles have been developed to promote wettability alteration, viscosity reduction of oil, stabilization of foam or emulsion and interfacial tension reduction – in some cases involving application of an external electric or magnetic field. Ogolo *et al.* [7] have also introduced them into EOR purposes. They investigated the effect of aluminum oxide for EOR purposes. They observed that aluminum oxide nanoparticles were most efficient in increasing oil recovery (oil with viscosity approx. 53.3 cP) when it was dispersed in brine and distilled water. It will reduce the oil viscosity. In overall, other metal oxide nanoparticles such as nickel and iron oxide also showed good potential for EOR. In heavy oil, Ehtesabi *et al.* [8] used titanium dioxide (63±8 nm) to enhance the oil (> 40 cP) recovery in sandstone core samples. Hendraningrat and Torseater [6] has furthermore described a method to enhance oil recovery by wettability alteration using Aluminium, Silicon and Titanium oxide nanoparticles. He concluded that oil recovery (and the contact angle alteration decreased towards more water-wet quartz) increased as nanoparticles size decreased.

Haroun *et al.* [9] had shown that certain metal oxide nanoparticles, such as Copper oxide and Nickel oxide (50 nm) can be used to enhance oil recovery using an applied electrical field. Flooding with nanoparticles increased the oil recovery by 9-22% over the recovery after waterflooding. They termed it as electrical EOR (EEOR). Currently the oil displacement mechanism using metal oxide nanoparticles under an applied electric field is not clearly understood. However, electrorheological effect may be one of oil displacement mechanism involved in EEOR process. According to Sheng and Wan [10], electric susceptibility arising from the induced dielectric polarization and the orientational polarization of molecular dipoles, leads to the electrorheological (ER) effect. This effect causes the viscosity of the suspension to increase due to the formation of fibrillated network when polarized molecules are reoriented along the direction of the applied electric field [11, 12].

In enhanced oil recovery, if the viscosity ratio between the displacing fluid and oil to be recovered were reduced, the mobility of oil to the production well will increase. Therefore, ZnO and Al_2O_3 are chosen as a dielectric nanoparticles to exploit their enhanced dielectric behavior in order to achieve an electrorheological effect for EOR purpose. This work aims at understanding the rheological behaviour of dielectric nanofluids through designing and experimental testing of an electromagnetic (EM) system, implies to investigate the change in viscosity of nanofluids.

2.0 EXPERIMENTAL

2.1 Materials

The as-synthesized ZnO (43 and 47 nm), γ-Al_2O_3 (94 nm), θ-Al_2O_3 (69.4 nm), κ-Al_2O_3 (55.1 nm) and α-Al_2O_3 (25 nm) nanoparticles were employed for this investigation. These nanoparticles were synthesized earlier using sol-gel auto-combustion method [13]. Sodium dodecylbenzenesulfonate (SDBS), anionic surfactant, from Sigma Aldrich was used as a stabilizer. The surfactant was chosen based on our previous stability test, and employed without any purification. Deionized water (with σ = 18 MΩ) was used as a solvent. NaCl obtained from Fisher Scientific, was employed as a salt to prepare brine of a concentration of 30000 ppm (equivalent to sea water concentration). The pH value of the system was adjusted with HCl and NaOH solution by precise pH meter (Mettler Toledo, FE20-Basic).

2.2 Nanofluids Preparation

The nanofluids (NFs) were prepared using two steps method. In first step, the nanoparticles were dispersed in brine as the base fluid and magnetically stirred for 1 hour to produce nanoparticles suspension. In second step, SDBS as stabilizing agent was added in the suspension which enables long-term stability of nanofluid. The surfactant concentrations were selected using critical micelle concentration (CMC) determination methods. In this step, the pH was adjusted below isoelectric point to a certain value. Then the suspension was agitated in an ultrasonic bath at ambient temperature for optimum time to get a homogenous suspension in the basefluid.

2.3 Experimental Design of EM Setup

The computational designing was carried out by Computer Simulation Technology (CST) package, which involves the design and simulation of solenoid at a designed frequency of 167 MHz (as shown in Figure 1). This was done to evaluate the field strength with respect to the lab-scaled frequency and propagation medium, in order to optimize the voltage (≈ applied field strength) needed to be supplied for activating the nanoparticles to achieve ER effect. Subsequently, the simulations results were comparatively evaluated by experimental observations, done in a lab scaled tank with 4360 scale factor under the similar environment.

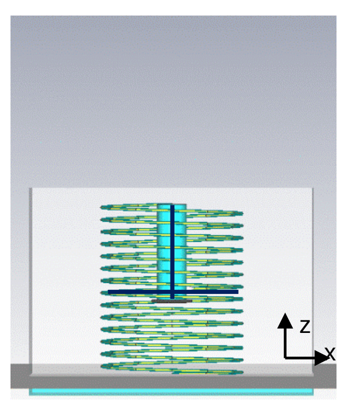


Figure 1 Heat Simulation model of copper solenoid at 167 MHz

2.4 Viscosity of Nanofluids

In this section, nano-ZnO samples with varying solid contents (0.1 and 0.05 wt %) were prepared, along with optimal stability parameters. Whereas, the concentration of Al_2O_3 nanoparticles were fixed at 0.01 wt % for all cases. A rotating viscometer (Brookflied DV-I+) attached to a custom-built solenoid coil was used to measure the viscosity of nanofluid. The schematic diagram of measuring setup is depicted in Figure 2. The electric field perpendicular to the stainless steel (SS) sample chamber was generated by the solenoid surrounding the spindle. The UL adapter spindle was chosen to be used with viscometer, which required 16 mL of nanofluid for every measurement. The torque during the experimental measurement was kept within 10-90% of the maximum torque.

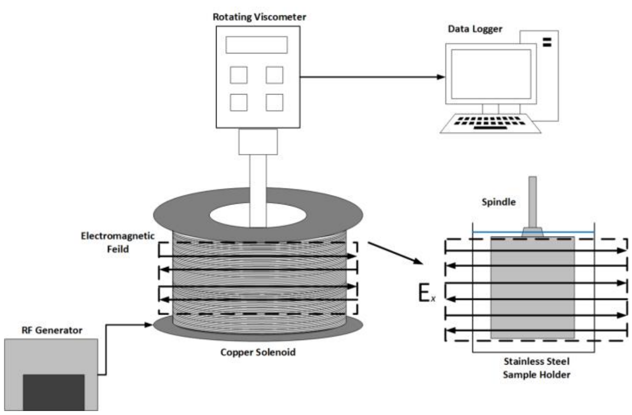


Figure 2 Schematic diagram of experimental setup for measuring nanofluid viscosity under applied electromagnetic field

3.0 RESULTS AND DISCUSSION

3.1 Simulation Modeling and Experimental Validation of EM Setup

Serge Haroche [14] and his group measured the electric field of a photon trapped in a cavity. By equating the energy of photon to the classical energy of a magnetic and electric field in a box of volume V, given as

$$h\omega = \frac{\varepsilon_0}{2}\left|\vec{E}\right|^2 V + \frac{1}{2\mu_0}\left|\vec{B}\right|^2 V \quad (1)$$

where, ħω is the energy of a photon corresponding to band gap energy; ε_0 is the free space permittivity, Epeak is the electric field at peak, and V is the volume of a box.

In our case, the magnetic contribution is consider as zero for dielectric material due to the negligible permeability. However the uncertainty principle makes measuring a single photon problematic. Therefore, the equation derived by the as-mentioned group is likewise valid only for the group of photons.

Based on above equation, the approximate electric field strength (in volts) was calculated corresponding to band gap energy of nanoparticles (i.e. energy of group of photons). For ZnO, it is found in the range of 0.3837 to 0.39 mV, corresponding to band gap energy of 3.017 to 3.11 eV. On the other hand, the electric field strength between 0.52 to 0.525 mV is required to activate Al_2O_3 nanoparticles having a band gap in range of 5.546 to 5.647 eV. Therefore, the simulation and experimental work has been done further to determine the optimum applied voltage required to achieve the activation of nanoparticle under EM setup.

3.1.1 Comparative Analysis of E-field Strength

The spectral response of E-field for simulated and experimental EM system is shown in Figure 3 at a frequency of 167 MHz. According to simulation results, the peak value for E-field is found to be 177, 266 and 355 mV at a supplied voltage of 1, 1.5 and 2 V. However these values show a huge reduction to 1.56, 2.11 and 2.025 mV when compared with the experimental measurements in air at the same distance of ~9 cm. This big deviation along with inconsistent readings could be the reason of confined boundary condition for simulated model. Whereas, the highest increment in E-field strength between 8 to 10 cm (i.e. center of solenoid) is due to the fact that E-field strength is concentrated at the center in a solenoid. On the other hand, experimental results presents a big loss in field strength due to infinite boundary.

Similar behavior is observed in the presence of stainless steel chamber, for both simulated and experimental results where the E-field strength reduced due to the shielding effect. In this case, the maximum electric field strength is found to be 0.5, 0.75 and 1.01 mV inside the stainless steel (SS) chamber, compare to experimental values of 0.28, 1.09 and 0.70 mV. It is noted that the magnitude of electric field decreases slightly by the increase in applied voltage from 1.5 to 2 V. This is due to the unmatched impedance of RF generator to the solenoid, where the signal loss increases as the applied voltage increase. Hence, 1.5 V is taken as the optimum voltage to provide the required E-field strength in order to polarize the nanoparticles for the ER effect.

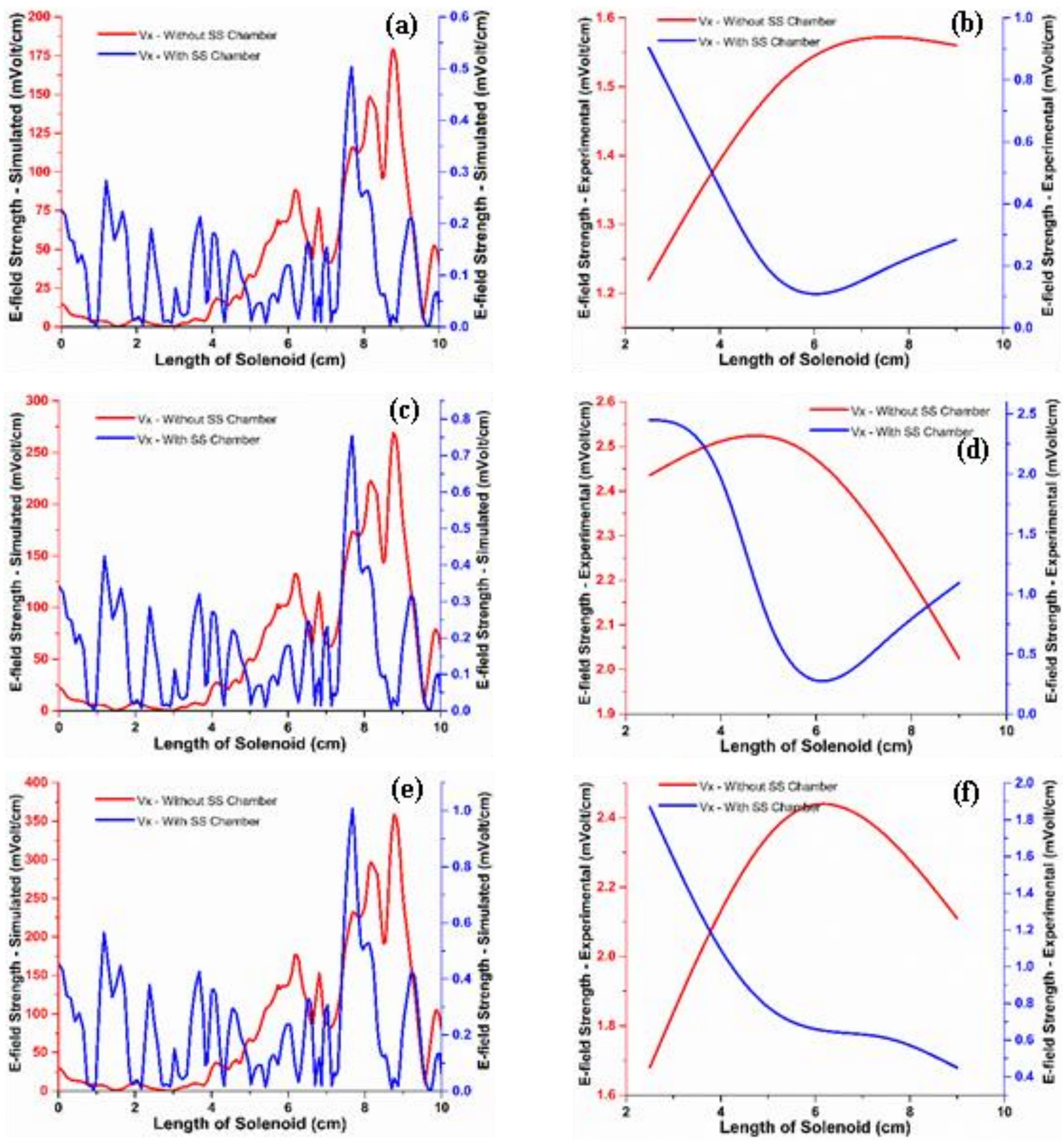


Figure 3 Comparative results of E-field strength via simulation and experiment at an applied voltage of 1V (a, b), 1.5V (c,d) and 2V (e, f)

3.2 Electrorheological Properties of Nanofluids

In this section, nano-ZnO samples with varying solid contents (0.1 and 0.05 wt %) were prepared, along with optimal stability parameters. Whereas, the concentration of Al_2O_3 nanoparticles were fixed at 0.01 wt % for all cases. Nanofluid is sheared from 10 s^{-1} to 122.4 s^{-1} considering the instrument restrictions.

3.2.1 Shear-thinning Behaviour

When the shear rate increases, there are three types of variation for the viscosity of any soft matter: Newtonian, pseudoplastic (shear-thinning) and dilatant (shear thickening). Figure 4 shows that the each NF exhibits the shear-thinning behaviour without the applied electric field. It can be seen that the shear rate depends non-linearly up on the viscosity (especially from 0 to 25 s^{-1}), indicating the non-Newtonian behaviour of dielectric NFs under the condition of this work. With an increase in shear rate particle-particle interactions become weaker and are even broken down and nanofluids show Newtonian behaviour.

Figure 5 demonstrates similar trend as that of Fig. 4. The shear-thinning behvior is also observed when there is an applied electric field via a solenoid at a voltage of 1.5 V.

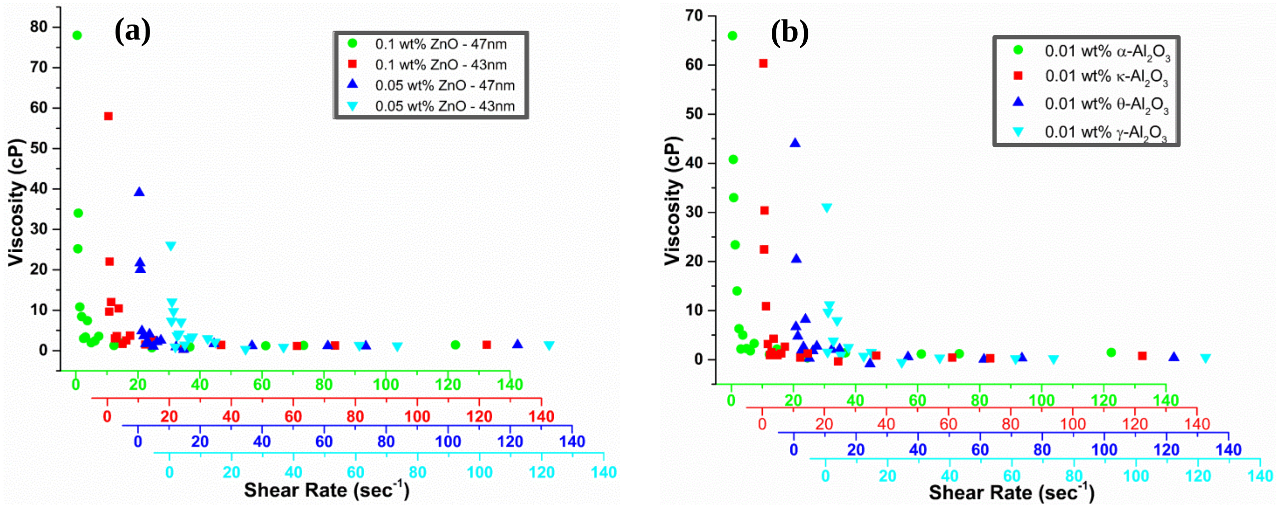


Figure 4 Viscosity versus shear rate of (a) ZnO and (b) Al_2O_3 nanofluids at different particle concentrations

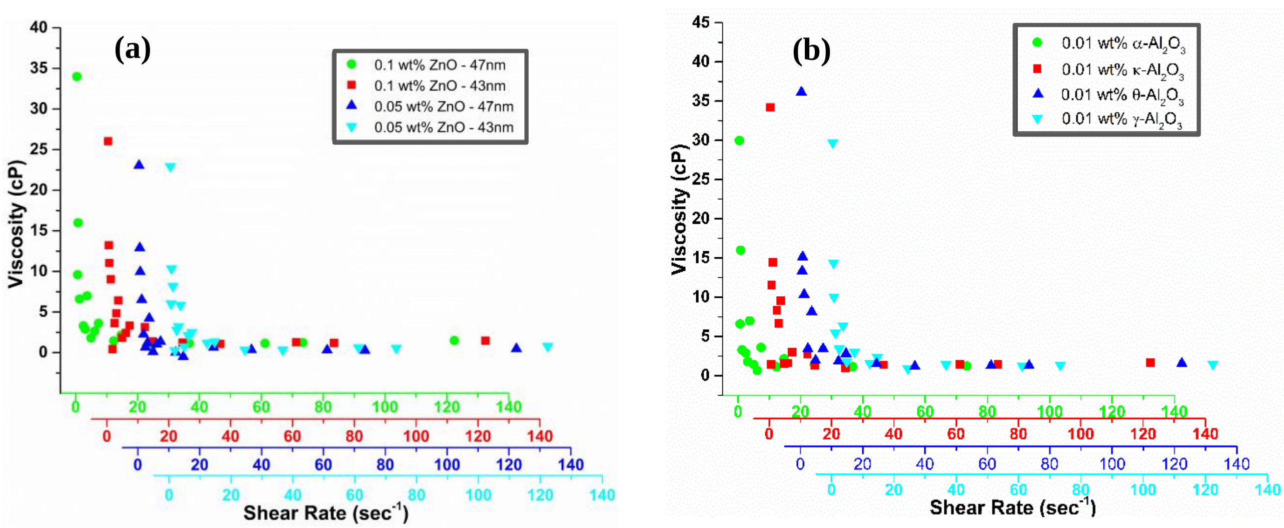


Figure 5 Viscosity versus shear rate of (a) ZnO and (b) Al_2O_3 nanofluids under applied electromagnetic waves at a applied volatege of 1.5V

3.2.2 Viscosity versus Electric Field

By comparing the curves (Figure 4 and Figure 5), it is found that the applied electric field had an apparent effect on the viscosity of NFs due to electrorheological effect. Since the viscosity of basefluid was not affected by an applied electric field, the viscosity of NFs is determined by the properties of dielectric nanoparticles. Under electric field, dielectric nanoparticles are polarized and the dipole moments rotate, leading to the occurring of rotational/orientational polarization at the interfaces of nanoparticles. This creates chains that align with the applied electric field. However, at a frequency of 167 MHz, bigger dipolar groups find it hard to orient at the equal pace as the alternating field. Therefore it is suggested that the influence of these dipolar groups provide an increase in the relaxation time which weakens the chain structure of NFs, leading to a reduction in viscosity at low shear rate. Whereas, with the increased of share rate, the oriented microstructure of NF provide a greater resistance to the flow. Thus the viscosity of NFs under electric field shows a low decrement than without electric field, as the share rate increasing. The comparative analysis between Fig. 4 and Fig. 5 are in accordance with it, showing the decrement in viscosity at low share rate; whereas an increment at 122.4 s^{-1} for all NFs, except γ-Al_2O_3. It is noted that γ-Al_2O_3 NFs doesn't show any change in viscosity with and without E-field, due to the poor dielectric properties of γ-Al_2O_3.

3.2.2 Effect of Particle Size

The viscosity of the NFs with the same nanoparticles varies with the particle size. For ZnO nanoparticles, it is noticed that the viscosity increases with the increased in particle size from 43 to 47 nm. This increament is in accordance with the investigation performed by Sinha *et al* [15]. However, the Al_2O_3 nanofluids represent a contrary trend; where the viscosity decresed with the increased in particle size. Other researchers such as Lu and Fan [16] and Anoop *et al*. [17] established similar results for Al_2O_3-water nanofluids. This explained that such trend in nanofluid behavior is due to the occurrence of higher interface resistance with fluid layer due to the presence of more surface area in case of smaller particles rather than bigger ones.

4.0 CONCLUSION

The rheological characteristics of ZnO and Al_2O_3 non-Newtonian nanofluids were investigated experimentally. Results have shown that the viscosity of dielectric nanofluids increased, at high shear rates, under an applied electric field. This phenomenon can be manipulated to improve the oil recovery in reservoir environment at a high flux and flow resistance. It is also observed that the particle size might have optimum point regarding the measurement for viscosity of nanofluids. In addition, this study also presents the comparative analysis of simulated and experimental result of a solenoid modeled to be used in conjunction with viscometer. It is noted that the solenoid used as a transmitter, has been best to propagate at an optimum voltage of 1.5 V with a designed frequency of 167 MHz. Further trails are planned in subsea environment to study the workability of proposed EM system and its effect on electrorheological properties of nanofluid.

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