International Journal of Thermophysics (2021) 42:137
https://doi.org/10.1007/s10765-021-02890-1

Experimental Investigations on Stability and Viscosity of Carboxymethyl Cellulose (CMC)-Based Non-Newtonian Nanofluids with Different Nanoparticles with the Combination of Distilled Water

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Received: 17 April 2021 / Accepted: 27 June 2021 / Published online: 6 July 2021

Abstract

This paper presents the experimental analysis of stability and rheological studies of three different types of nanoparticles (Al_2O_3, CuO, and TiO_2) with carboxymethyl cellulose (CMC)-based nanofluids. The two-step method was adopted for the preparation of nanofluids. In the present study, nanoparticles were characterized by X-ray diffraction (XRD) analysis. The sedimentation tests and UV–Vis absorbance tests were performed to predict the stability of nanofluids. For all prepared nanofluids when CMC concentration was zero, TiO_2 nanofluids was found to be more stable in the visual tests for a period of 18–20 days and CMC (0.4 % by weight) -based TiO_2 nanofluid took 28–30 days to sediment. For rheological study of nanofluids, viscosity was measured under the influence of increasing particle concentration (0.01 % to 0.04 %) and increasing temperature (25 °C to 55 °C). The experimental results reveal that on increasing particle concentration the viscosity of nanofluids increases by 27 %, 21.5 % and 17.4 % for TiO_2, Al_2O_3 and CuO nanofluids respectively as compared to the base fluid. While on the increasing temperature from 25 °C to 55 °C, the viscosity of nanofluids decreases by 11 %, 12 % and 9 % for Al_2O_3, CuO, and TiO_2, respectively. Moreover, from the shear stress vs. shear rate trends, it was concluded that all three nanofluids exhibit pseudoplastic or shear-thinning nature.

Keywords Nanoparticles · Non-Newtonian nanofluids · Shear rate · Temperature · Viscosity

Abbreviations

w	Weight, (g)
K	Shape factor

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D	Average particle size, (nm)
Al_2O_3	Aluminium oxide
CuO	Copper oxide
TiO_2	Titanium oxide
CMC	Carboxymethyl cellulose
n	Flow behavior index
m	Consistency index

Symbols

	Density of fluid, (kg·m^{-3})
ϕ	Nanoparticle volume concentration
τ	Shear stress
μ	Dynamic viscosity, (Pa-s)
β	Peak width at half the maximum height
	Shear rate, (1·s^{-1})
λ	Wavelength, (Å)
θ	Diffraction angle

Subscripts

bf	Base fluid
nf	Nanofluid
np	Nanoparticle

1 Introduction

Nowadays, the concept of nanofluids is being extensively used in many industries including engine cooling, electronic devices, internal combustion engines, food industries, heat exchangers. [1–4]. In recent decades, nanofluids are also being used as cooling and lubricating fluids [5–9]. Therefore, to predict the mechanical and thermal properties of nanofluids, independently both phase's solid (nanoparticle) and liquid (base fluid) should be investigated. So far, lot of metal, metal oxides and hybrid combinations of nanoparticles added in various base fluids, these fluids suggested as working fluids and lubricants for milk industries, melts of polymers, oil industries, bio-fluids, paints, tars and in various thermal devices [10, 11]. Most of the investigators have studied various characteristics of fluid flow and heat transfer through nanofluids in the last two decades [12] and concluded nanofluids are having high heat transfer rate than conventional fluids. Though, this enhanced heat transfer rate of nanofluids countered by adding more pumping power for the circulation of nanofluids. Therefore, it is most important to investigate the rheological studies of these fluids.

For estimating required pumping power, it is very important to understand the behavior of nanofluids. A large number of studies have been reported on viscosity and rheological behavior of nanofluids [13–15]. These studies concluded that base fluids are less viscous than nanofluids. The viscosity of nanofluids increased on increasing the particle concentration by volume. But most of the studies are limited to Newtonian nature of base fluids [16]. While some studies are on non-Newtonian behavior of nanofluids [17–19] and a few researchers reported that viscosity diminishes with an increase in particle size. Furthermore, the viscosity of nanofluid was investigated with temperature variations [20–23]. Results reveal that the viscosity of nanofluids decreases with the rise in temperature. Saeedi et al. [17] experimentally investigated the rheological behavior of CeO_2-ethylene glycol nanofluids at different temperatures ranges from 25 °C to 50 °C with 5 °C intervals. They used six different volume concentrations (0.05, 0.1, 0.2, 0.4, 0.8, and 1.2 %) of nanoparticles. They found from rheological results that maximum increment in viscosity occurs at the temperature of 25 °C and particle concentration of 1.2 %. Jamshidi et al. [18] carried out a study on the effects of temperature on the viscosity of nanofluids undergoing heating and cooling process. Beheshti et al. [19] examined the rheological behavior and thermophysical properties of oxidized CNT-based nanofluids. They also measured the viscosities of pure oil at different temperatures and found a decreasing trend in viscosities as the temperature increases. Sundar et al. [20] experimentally investigated the viscosity of ethylene glycol-based aluminium oxide nanofluids. They found nanofluids with higher viscosities exhibit enhanced thermal conductivity. Hemmat Esfe et al. [21] examined the rheological behavior of ethylene glycol-based hybrid nanofluid. They found that the change in sensitivity of nanofluids enhanced with the change in particle concentration. While the changes in sensitivity is quite low with variation in temperature. Moreover, they create a third- power correlation for predicting the viscosities of hybrid nanofluid for a given value of operating temperature and particle concentration. Minakov et al. [22] investigated the rheological behavior of ethylene glycol and engine oil-based nanofluids with the variation in particle size from 0 nm to 150 nm. They concluded that the non-Newtonian nature on increasing particle concentration, described by Herschel-Bulkley fluids. Liu et al. [23] experimentally investigated the rheological study of liquid paraffin base nanofluids containing multiwall carbon nano tube particles. They found that the behavior of consistency index is decreasing with increasing temperature and decreasing with particle volume concentration.

Base fluids with suspended nanoparticles, subjected to several forces such as buoyancy force, gravitational force, Van der Waal attractive force and electrostatic repulsive force. The Vander Waal attractive force and gravitational force trying to pull the fluid particles together and settle down the particles. These two forces are against the stability of nanofluids and the performance of nanofluids is highly depend on the stability of nanofluids. The poor stability of nanofluids can hinder its thermophysical properties which leads to the poor performance of nanofluids in several applications such as biomedical field, heat exchangers, engine cooling. [24].

Ijam et al. [25] experimentally investigated the thermo- physical properties of nanofluids and conducted visualization test to check the stability of nanofluids. They found that nanofluids were stable for more than 2 months of time. Moreover, they developed a correlation for predicting the electrical conductivity and thermophysical properties. Ranjbarzadeh et al. [26] conducted experiments to investigate the synthesis of graphene oxide nanoparticles, stability of hybrid nanofluids and the variation in viscosity with different parameters. Furthermore, they developed a correlation to predict the viscosity at different particle concentration and working temperature. Shanbedi et al. [27] investigated stability and thermophysical properties for different surfactant-based nanofluids. They observed that the shear stress and viscosity increases for CNT-based nanofluids as the concentration of surfactant increased.

It was concluded from the literature survey that very few researchers have shown their interest towards the rheological investigations of Al_2O_3, CuO, and TiO_2 nanoparticles with CMC-based nanofluids. On the other hand, in the past, most of the study was concentrated on the Newtonian behavior of the nanofluid. Though, due to certain applications of working fluids in different industries like; polymers industries, food industries, pharmaceutical industries, oil industries, bio-fluids, and chemical industries, the behavior of working fluids are in non-Newtonian in nature. Thus, the objective of the present study is to analyze the viscosities and stability of CMC-based non-Newtonian nanofluids. For the present study three different types of nanoparticle; Al_2O_3, CuO, and TiO_2 have been employed in the four different volume concentrations (0.01 %, 0.02 %, 0.03 %, and 0.04 %) for the analysis. Also, CMC (0.4 wt% or 4:1 $g \cdot kg^{-1}$ of water) is used to give a pseudoplastic nature to the base fluid (distilled water). The main focus of the rheological studies is to emphasize the viscosity of fluids, so that pumping power or pressure losses may be optimized. Which is the main concern for the design of the heat exchanger or any thermal device based on fluid flow. Further, the objective behind the selection of such nanoparticles is the low cost and easy availability. Therefore, the combination of nanofluids with these particles can be easily replaced with conventional fluids. For the present study, first of all, the nanoparticles were characterized using XRD tests. Secondly, the stability of with and without CMC-based non-Newtonian nanofluids were done using sedimentation tests and UV–Vis. absorbance test at different intervals of time. Then, the rheological behavior of viscous nanofluids was investigated at different temperatures and particle concentration.

2 Experimental Procedure

2.1 Materials

In the present study three different types of nanoparticles Al_2O_3, CuO, and TiO_2 have been used as nano–additive in the base solution containing deionised water and CMC, 0.4 % by weight. Particles purchased from PLATONIC NANOTECH PRIVATE LIMITED, India. The thermophysical properties of nanoparticles provided by the supplier is presented in Table 1. The value of these properties is in good agreement with previous studies [28, 29]. Also, the CMC was provided by AXAR CHEMICAL, India. The manufacturer properties of CMC are presented in Table 1. MALVERN PANALYTICAL X-ray diffractometer (XRD) was used for characterization of nanoparticles. A dynamic shear rheometer (ANTON PAAR SMART PAVE 102) was used for viscosity measurements at different temperature and shear rates.

Table 1 Thermophysical properties of nanoparticles

Properties	Al_2O_3	CuO	TiO_2	CMC
CAS number	1344-28-1	1317-38-0	13 463-67-7	9004-32-4
Purity	99.9 %	99.9 %	99.9 %	99 %
Average particle size	30–40 nm	40–60 nm	30–50 nm	1.5–3.5 μm
Specific surface area	60–80 $m^2 \cdot g^{-1}$	30–50 $m^2 \cdot g^{-1}$	200–230 $m^2 \cdot g^{-1}$	–
Molecular weight	101.96 $g \cdot mol^{-1}$	79.545 $g \cdot mol^{-1}$	79.8658 $g \cdot mol^{-1}$	263.20 $g \cdot mol^{-1}$
Melting point	2055 °C	1350 °C	1843 °C	274 °C
True density	3.97 $g \cdot cm^{-3}$	6.4 $g \cdot cm^{-3}$	4.23 $g \cdot cm^{-3}$	0.7 $g \cdot cm^{-3}$
Specific heat	765 $J \cdot kg^{-1} \cdot K^{-1}$	530 $J \cdot kg^{-1} \cdot K^{-1}$	680 $J \cdot kg^{-1} \cdot K^{-1}$	4179 $J \cdot kg^{-1} \cdot K^{-1}$ (1 % in water)
Thermal conductivity	38–43 $W \cdot m^{-1} \cdot K^{-1}$	30–33 $W \cdot m^{-1} \cdot K^{-1}$	8–12 $W \cdot m^{-1} \cdot K^{-1}$	–
Morphology	Spherical	Spherical	Spherical	–

2.2 Preparation of Nanofluids

The two-step method was employed to prepare the nanofluids in the present study [30]. This method is most commonly used to synthesize the nanofluids because of low processing cost and easily availability. At first, the mass of each nanoparticle has been calculated by following equation [31].

$$\phi(\%) = \frac{\left(\frac{w}{\rho}\right)_{np}}{\left(\frac{w}{\rho}\right)_{np} + \left(\frac{w}{\rho}\right)_{bf}} \times 100 \tag{1}$$

where ϕ, w and ρ are represents volume fraction (%), mass (g) and density ($g \cdot cm^{-3}$) respectively. The consequent mass of nanoparticles necessary to attain exact solid volume fractions, were weighted in a digital weighing machine (ACZET CY124C) with a 0.001 g precision. Then solid volume fraction directly dispersed in to base fluid contain CMC 0.4 % (by weight). The CMC is used for present study create a non-Newtonian nature to the base fluid.

The Magnetic stirrer (VELP SCIENTIFICA) was used to stirrer the base fluid embedded with nanoparticles for 1 h at 1500 rpm for the complete mixing of nanoparticles into the base fluid. After that stirred nanofluid was supplied to Ultrasonication bath (BIOGEN) of 200 W at a frequency and temperature of 40 kHz and 30 °C, respectively, for the complete homogeneity of particles throughout the solution. Also, to remove agglomeration of particles due to adhesive forces between the nanoparticles.

2.3 Stability Measurement

The literature review reveals that a lot of methods exist to predict the stability of nanofluids, mainly including sedimentation test, zeta potential test, viscosity test, UV–Vis absorbance spectroscopy test. For the present study the sedimentation test and UV–Vis. absorbance test has been performed to predict the stability of nanofluids. Prediction of the stability of nanofluids can be visually observed that shows the clustering of nanofluids in the liquid at the bottom part of the tube as depicted in Fig. 1 in the sedimentation test. Poor dispersion ability and low stability of nanofluids will lead to the settling down of nanoparticle in the base fluid. The simplicity and adequate performance of the method make it more favorable for the stability prediction. In the present work, three different types of nanoparticles (Al_2O_3, CuO, and TiO_2) were used at four different particle concentrations (0.01, 0.02, 0.03 and 0.04 % by volume). Visual observation test was performed for two different natures of nanofluids, Newtonian and non-Newtonian nanofluids. In the present study, the samples of nanofluids were kept in 15 ml transparent tubes and observed at equal intervals.

UV–Vis absorption is another method to find out the stability of water-based nanofluids. UV–Vis spectrometer (LABINDIA T60) was used to perform experiments over a range from 190 nm to 900 nm of wavelengths. Figure 2 shows the absorption test of nanofluids just after preparation, after 15 and 30 days of preparation. It is clear from the graph the freshly prepared nanofluids have higher absorbance. The absorbance measured just after the preparation of nanofluids

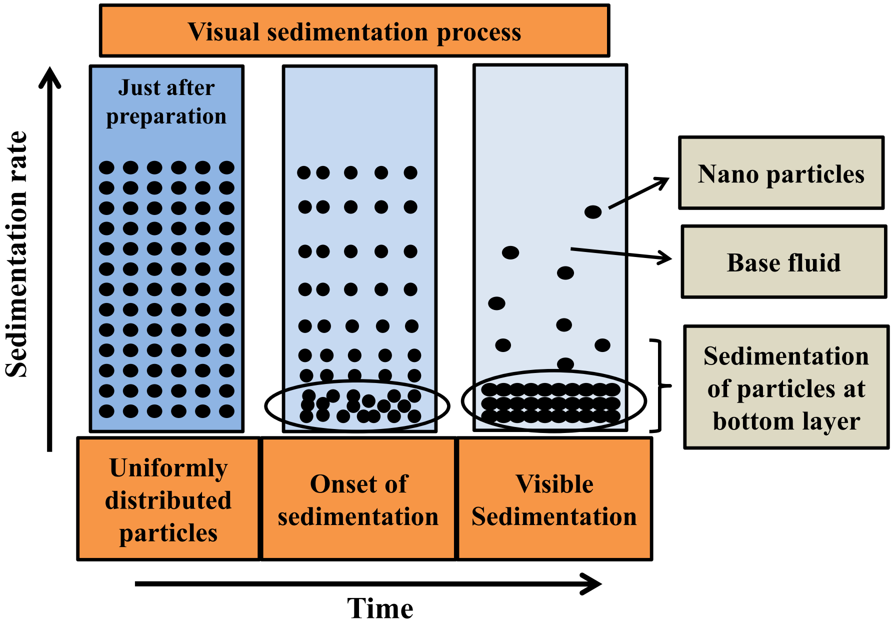


Fig. 1 Schematic diagram of sedimentation test

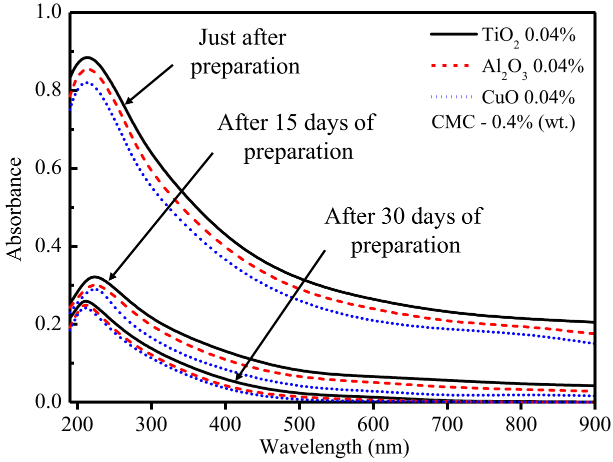


Fig. 2 UV–Vis. absorption test of nanofluids just after preparation, after 15 and 30 days of preparation at 0.04 % by vol. concentration containing CMC 0.4 % by weight

taken as a reference line. The sedimentation in freshly prepared nanofluids is negligible, because of the uniform distribution of particles throughout the colloidal solution. But after some time, agglomeration and sedimentation of nanoparticles starts within the base fluid. This will affect the rate of absorbance measured by the spectrometer. Thus, the fall of absorbance can be related to sedimentation and agglomeration of Al_2O_3, CuO and TiO_2 nanoparticles. Similar observations for TiO_2/water-based nanofluids were reported by Chang et al. [32].

2.4 Characterization of Nanoparticles

2.4.1 X-Ray Diffraction Characterizing

X-ray diffraction (XRD) is a most utilizing technique for the common characterization of nanoparticles. XRD analysis of the powdered nanoparticle provides important information such as sample purity, phase identification and crystallite size [33]. XRD pattern of Al_2O_3, CuO and TiO_2 nanoparticles have been shown in Fig. 3a–c, respectively. On comparing the XRD results of Al_2O_3, CuO and TiO_2 nanoparticles with Sammaiah et al. [34] and Asadi et al. [35], it was found that similar trends for diffraction pattern have been obtained in the present study. Figure 3 displays the XRD pattern of nanoparticles, major reflection values of 2° θ were observed in diffraction patterns.

The sharp and narrow diffraction peaks the Al_2O_3, CuO and TiO_2 nanoparticles ensures that they have a very good crystalline phase structure. The average size of the crystals obtained from the peak values by equating XRD data in Scherrer equation [35].

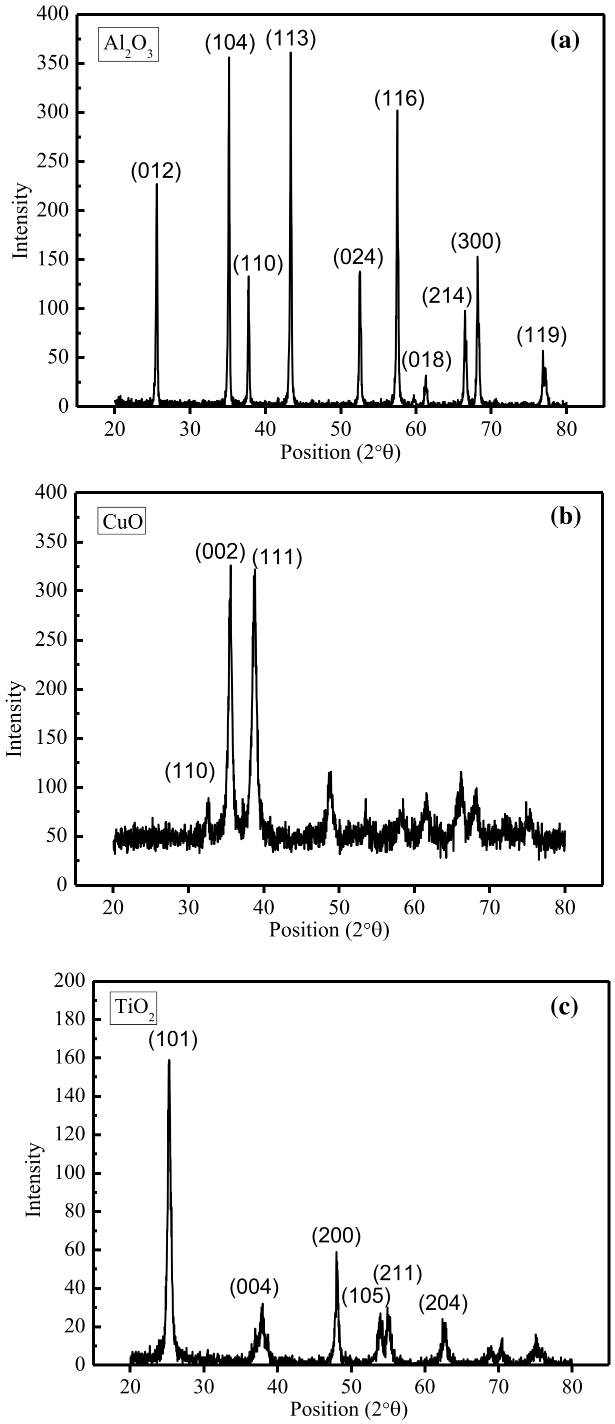


Fig. 3 XRD spectrum of (a) Al_2O_3 (b) CuO and (c) TiO_2 nanoparticles

$$D = \frac{K\lambda}{\beta \ \mathrm{COS}\theta} \tag{2}$$

where D is the average size of nanoparticle in nm, λ demonstrate the wavelength of X-ray in Å, β is the peak width at half the maximum height, θ is the diffraction angle at which peak occurs and K is the shape factor ($K = 0.89$). By using Eq. (2) the average size was obtained 40.17, 54.72 and 38.52 nm of Al_2O_3, CuO, and TiO_2 nanoparticles, respectively.

2.5 Viscosity Measurement

In the present study, the ANTON PAAR SMART PAVE 102 Rheometer was used to measure the viscosity of CMC-based nanofluids at variable temperatures from 25 °C to 55 °C and shear rate from 0 s^{-1} to 100·s^{-1}. The rheometer was calibrated before the measurements, as per the instructions in the user guide provided by the manufacturer. Moreover, the precision of the measured value was ± 1 % and repeatability ± 0.2 %. Rotational tests were performed to study the non-linear behavior of nanofluids. The value of torque varies from 2 N-m to 50 N-m for all measurements, and the tests were repeated three times for each of the samples. The estimated viscosity uncertainty is in the range of ± 2 %. The trends for measured viscosity and shear stress at a different shear rate and temperature of nanofluids are in the same order as reported by previous studies [21, 22, 26, 31, 35].

3 Results and Discussion

In this section, sedimentation test and rheological studies of different viscous nanofluids from Figs. 4, 5, 6, 7, 8, 9, 10, 11 and 12 were described. The various parameters were used in measuring the stability and viscosity of Al_2O_3, CuO and TiO_2 nanoparticle-based nanofluids. The results were examined concerning different parameters, including time, shear stress, shear rate, temperature and volume concentration of the nanofluids.

3.1 Sedimentation Test

Sedimentation test is one of the easiest and cheapest method to check the stability of nanofluids. Stability is one of the most important parameters while the preparation of nanofluids, as it decides the quality of nanofluids. For the present study, four different concentration (0.01, 0.02, 0.03 and 0.04 % by volume) of each nanoparticle with and without CMC concentration (0.4 % by weight) were checked for sedimentation of nanofluids at equal interval of time (in days) as shown in Figs. 4, 5, 6. Figure 4a and b show the samples just after the preparation of nanofluids. It is clear from the figures that the particles and CMC were uniformed distributed throughout the colloidal solution when all the samples are synthesized under same process and at the same interval of time. Figure 5a and b captured after the 15 days of the

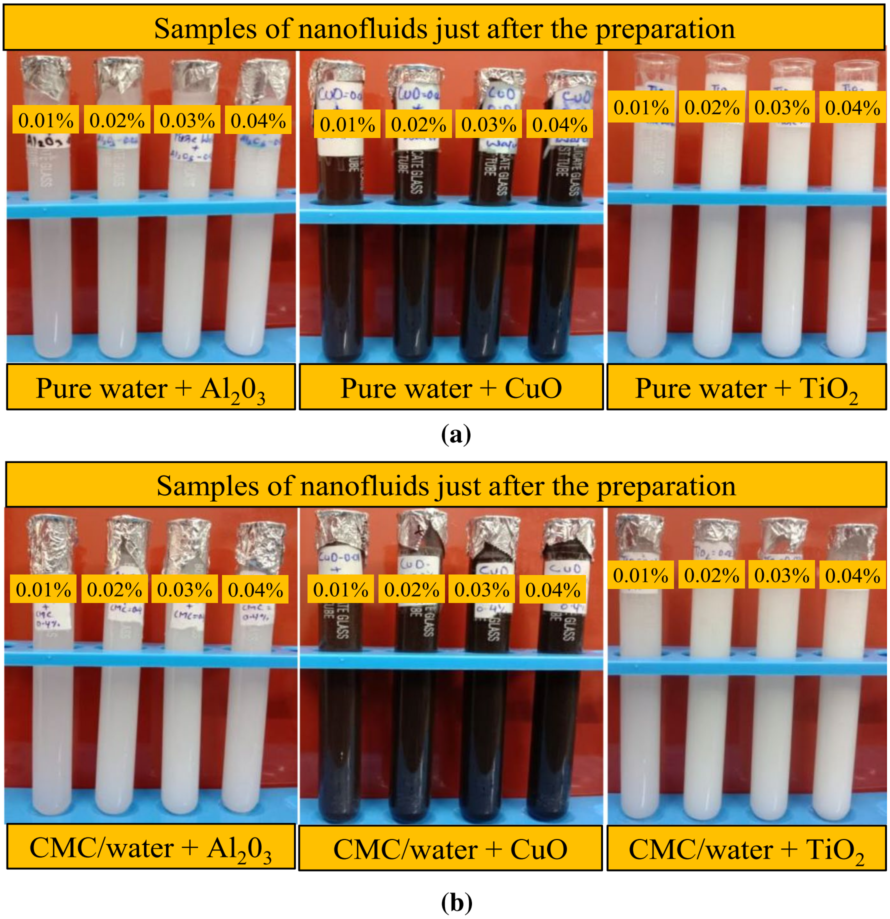


Fig. 4 Nanofluids just after the preparation (a) Pure water-based nanofluids (b) CMC-based nanofluids

preparation. It is observed from Fig. 5a that CuO-based nanofluids show near about full sedimentation of copper oxide nanoparticles in the colloidal solution, this might be occurring due to the greater dominant nature of gravitational forces and Van der wall attractive forces. The Al_2O_3-based nanofluids at higher concentration of particles seem to be more stable as compared to CuO nanofluids. While the TiO_2 nanofluids shows maximum stability as compared to Al_2O_3 and CuO nanofluids because of the less agglomeration of particles and higher repulsive forces between each nanoparticle in colloidal solution.

Figure 5b shows the sedimentation of CMC base nanofluids, captured after 15 days of the preparation. The CMC-based nanofluids observed to be more stable as compared to the nanofluids without CMC as CMC acts as a surfactant. Adding surfactants to the base fluid is the most common, simplest and effective chemical method to enhance the stability of nanofluids [36]. It is due to the

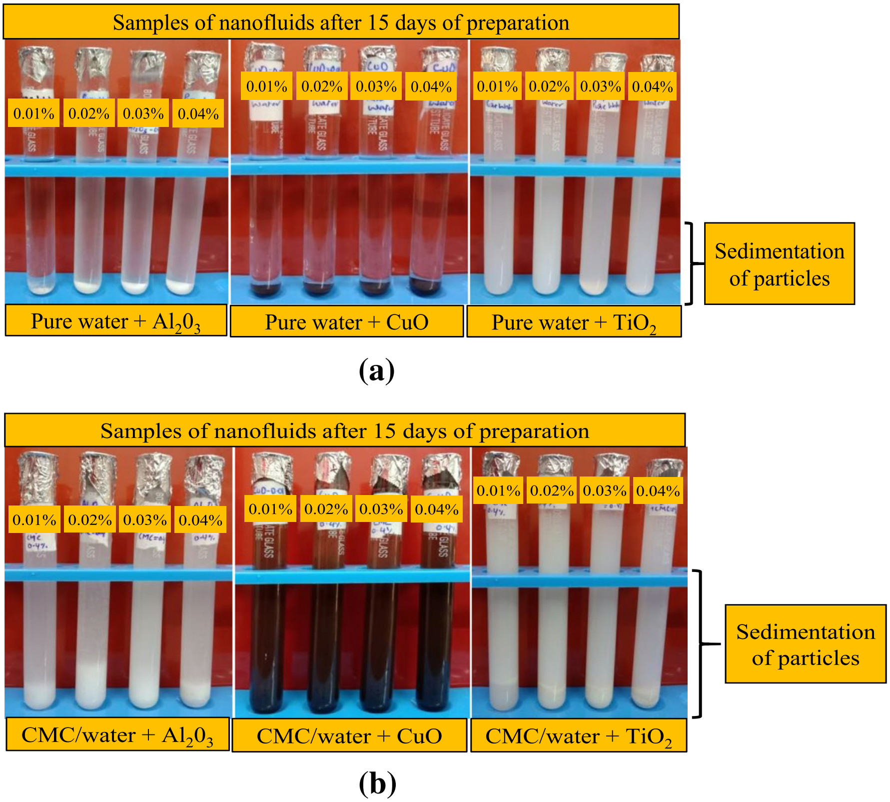
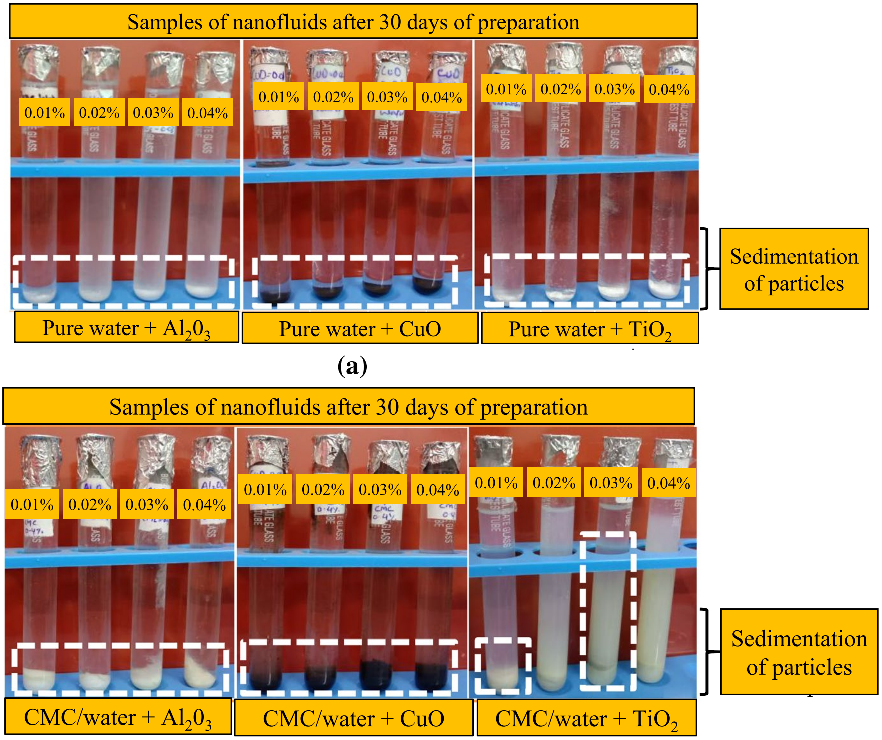


Fig. 5 Sedimentation of nanofluids after the 15 days of preparation (a) pure water-based nanofluids (b) CMC-based nanofluids

fact that surfactants are amphiphilic in nature, consisting of extended hydrophobic portions such as long-chain hydrocarbons and hydrophilic polar head group, which makes them behave like a co-polymer.

Figure 6a and b show the sedimentation of water-based and CMC-based nanofluids, respectively. It is clear from the figures that all the nanofluids show full sedimentation of nanoparticles in colloidal solutions after the 30 days of preparation except CMC-based TiO_2 nanofluids at higher concentrations. The time taken by the nanoparticles to settling down is given in Table 2.

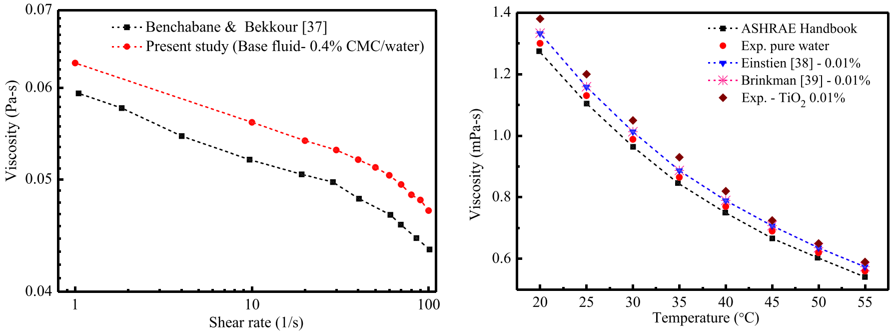
Moreover, the stability of nanofluids was monitored by UV–Vis. absorption test, which detects a decrease in the absorbance peaks. Figure 2 clearly shows that the absorption peaks of freshly prepared stable nanofluids are higher than the nanofluids in which particles are the onset of sedimentation or settle down. The detailed discussion has been presented in Sect. 2.3.



(a)

(b)

Fig. 6 Sedimentation of nanofluids after the 30 days of preparation (a) pure water-based nanofluids (b) CMC-based nanofluids



(a) **(b)**

Fig. 7 (a) Validation of present work with Benchabane and Bekkour [37] for 0.4 % (by weight) CMC aqueous solution. (b) Validation of pure water viscosity with ASHRAE handbook data [31] and comparison of TiO2 0.01 % results with Brinkman and Einstein models of viscosity for 0.01 particle concentration

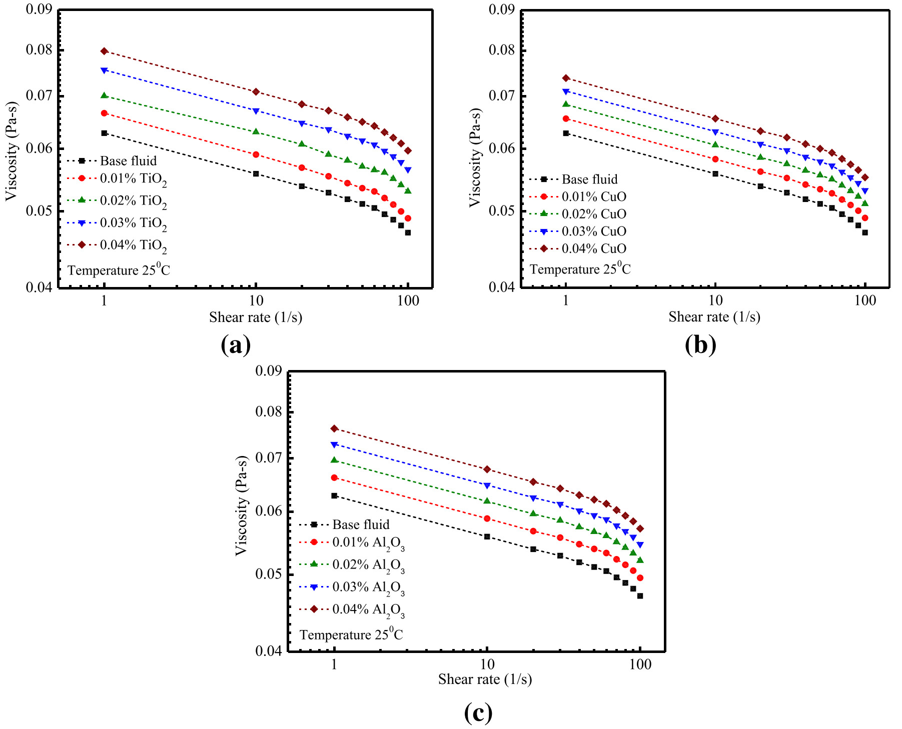


Fig. 8 Variation in viscosity with shear rate for CMC-based nanofluid at different nanoparticle concentrations of (a) TiO_2, (b) CuO and (c) Al_2O_3

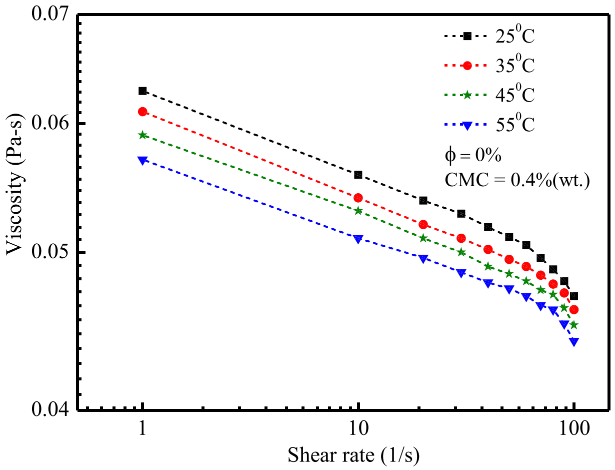


Fig. 9 Variation in viscosity of base fluid (deionised water + CMC 0.4 % wt.) at different temperatures

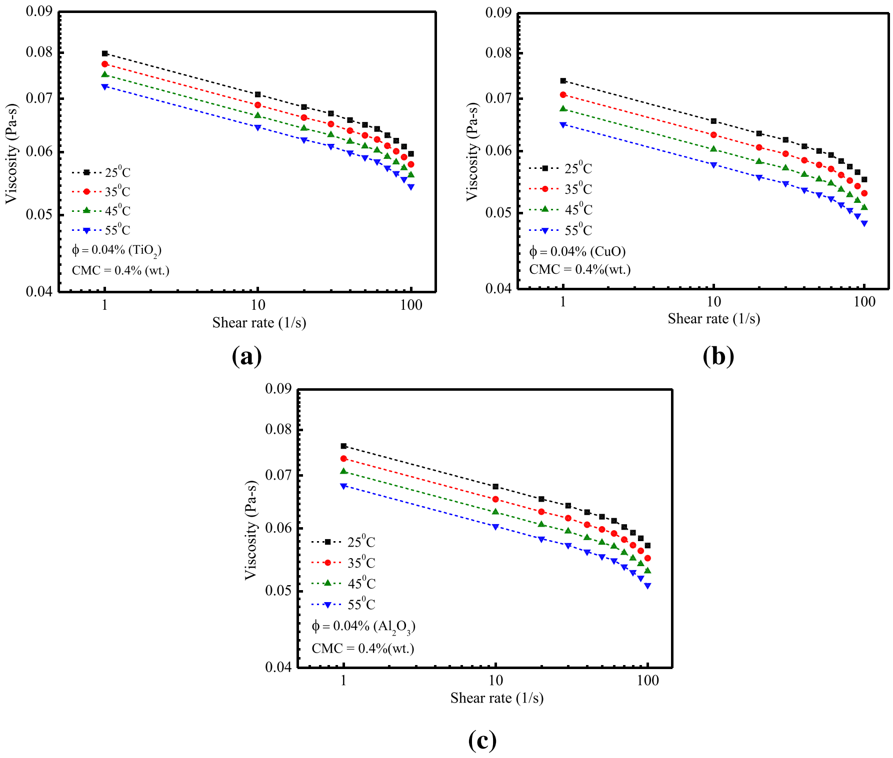


Fig. 10 Viscosity versus shear rate at different fluid temperatures of CMC-based nanofluids with different nanoparticles (a) TiO_2, (b) CuO and (c) Al_2O_3

3.2 Validation and Base Fluid Behavior

In order to determine the precision of the rheometer, the validations were performed for the viscosity of 0.4 % CMC aqueous solution at different shear rates ranges between 0 and 100 s^{-1}. The results were compared with Benchabane and Bekkour [37] with a maximum variation of 8 %, which is illustrated in Fig. 7a. Also, the viscosity of pure water has been compared with ASHRAE Handbook data [31] at different temperatures, ranges from 20 °C to with 55 °C as shown in Fig. 7b with a maximum deviation of 4 %.

From the literature, there are some promising viscosity models to calculate the viscosity of nanofluids. The viscosity of TiO_2 0.01 vol% without CMC is compared with the Einstein model (Eq. 3) and Brinkman model Eq. 4 for 0.01 % of particle concentration. Figure 7b shows clearly that both the models have similar trends with a maximum deviation of 7 % when compared to TiO_2 0.01 % nanofluid. The following models have been used for the validation of viscosity of nanofluids.

1. Einstein model [38] has been used for calculating the viscosity as it is applicable for less than 2 vol% of particle concentration.

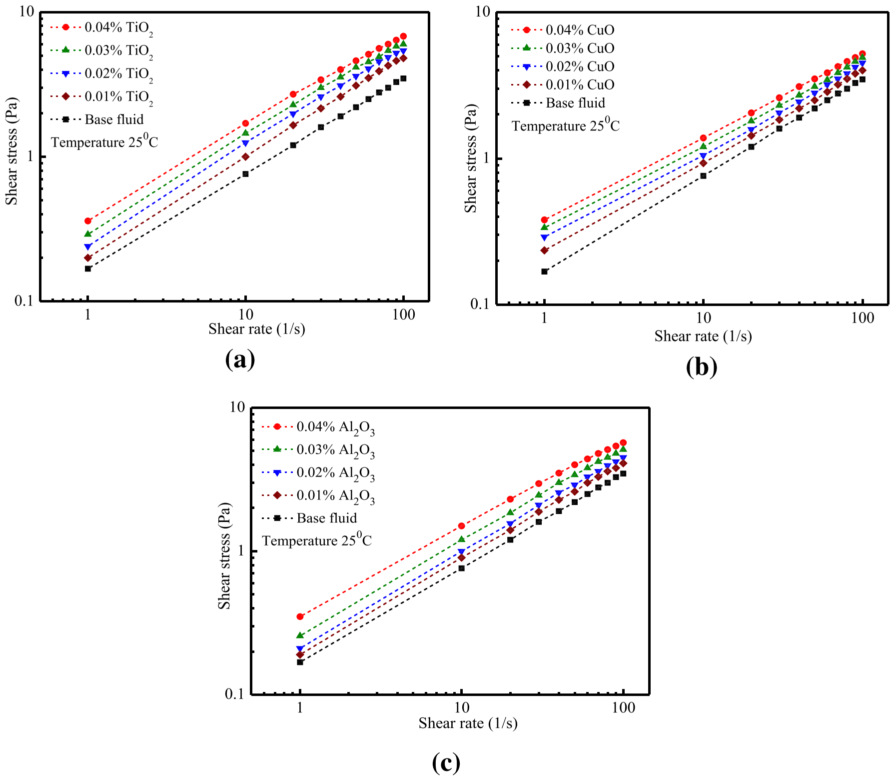


Fig. 11 Variation in shear stress with shear rate for different particle concentration of TiO_2 (a), CuO (b) and Al_2O_3 (c) nanofluids at a temperature of 25 °C

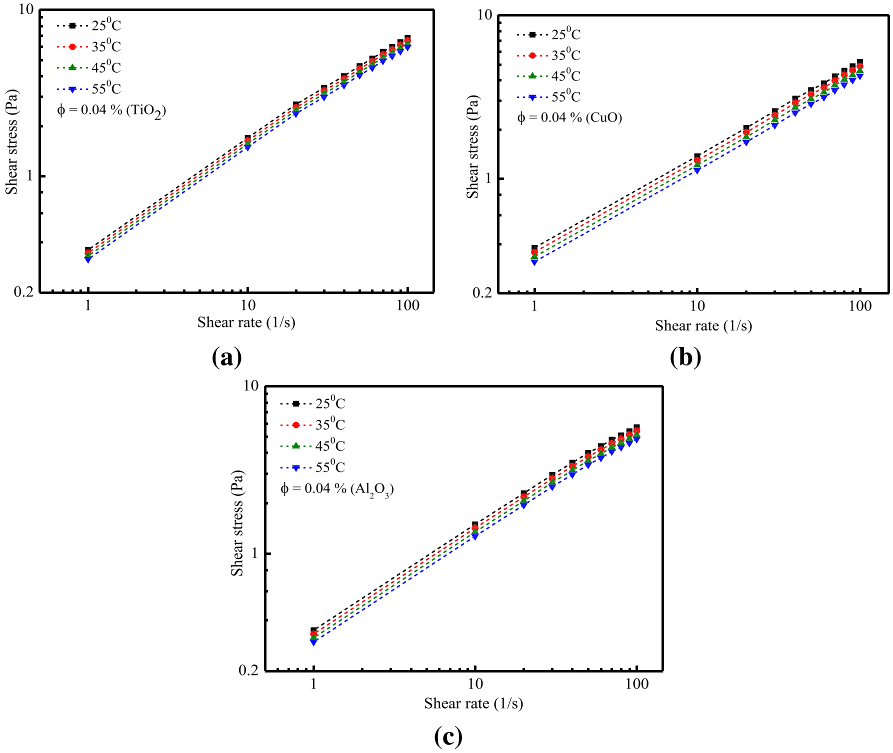
$$\frac{\mu_{nf}}{\mu_{bf}} = (1 + 2.5\phi) \tag{3}$$

2. Brinkman model [39] is the modification of Einstein model and it is applicable for less than 4 vol% of particle concentration.

$$\frac{\mu_{nf}}{\mu_{bf}} = \frac{1}{(1 - \phi)^{2.5}} \tag{4}$$

3.3 Effect of Particle Concentration on Viscosity of Nanofluids

In this section, the viscosity of the base fluid and different nanofluids is investigated with different particle concentrations (0.01 %, 0.02 %, 0.03 % and 0.04 % by vol.) at 25 °C of temperature and plotted on a log–log scale. Figure 8 shows the viscosities of TiO_2, CuO and Al_2O_3 nanofluids at different particle concentration with the change in shear rate ranges from 0 s^{-1} to 100 s^{-1}. It is clear from Fig. 8 that the



(a) (b) (c)

Fig. 12 Variation in shear stress with shear rate for different temperatures of TiO_2 (a), CuO (b) and Al_2O_3 (c) nanofluids at a particle concentration of 0.04 %

Table 2 Stability time (in days) of nanofluids

Nanoparticles	Stability time of nanofluids (in days)	
	Pure water-based nanofluids	CMC-based nanofluids
Al_2O_3	10–12	22–24
CuO	8–10	19–21
TiO_2	18–20	28–30

viscosity of all the nanofluids increases with the increase in particle concentration. Moreover, the viscosity of all the nanofluids decreases as the shear rate increases.

The comparison of viscosities of different CMC-based TiO_2, Al_2O_3 and CuO nanofluids with base fluid has been done at a mean value of the shear rate of 50 s^{-1}. It can be concluded from Fig. 8, that the value of viscosities was found 64.9, 62.09 and 60.04 mPa-s for TiO_2, Al_2O_3 and CuO nanofluids respectively at a shear rate of 50 s^{-1} and particle concentration of 0.04 %. At the same time, the increment in viscosities was measured 27 %, 21.5 % and 17.4 % for TiO_2, Al_2O_3 and CuO-based nanofluids respectively as compared to the base fluid. It is clear from Fig. 8, that all the nanofluids follow similar trends and exhibit pseudoplastic or shear thinning nature. The following reasons are responsible for this phenomenon.

1. The specific surface area of TiO_2 nanoparticles is greater than Al_2O_3 and CuO nanoparticles. Therefore, TiO_2 contains more particles than Al_2O_3 and CuO for the same concentration. The higher concentration of nanoparticles in a base fluid produces a resistance to flow by lowering the kinetic energy of fluid molecules. It may reduce the ability of random movement of particles between the fluid layers. Thus, the TiO_2 nanofluids have greater viscosities than CuO and Al_2O_3 nanofluids for the same concentration.
2. The nanoparticles in CMC-based nanofluids form clusters because of the Van der Waal attractive forces between the particles and fluid molecules. These clusters of nanoparticles resist the motion of fluid molecules results in the enhancement of viscosity.
3. The nanoparticles in the base fluid are of different sizes and exhibits different attraction forces between particles and fluid molecules. Thus, as the shear rate increases, the agglomerated clusters of nanoparticles and attraction forces between them breaks down, as a result, the viscosity of nanofluids decreases.

3.4 Effect of Temperature on Viscosity of Base Fluid and Nanofluids

To predict the rheological behavior of nanofluids, the viscosity of base fluid was measured at different shear rates ranges between 0 and 100 s^{-1}. All graphs were plotted on a log–log scale. Figure 9 shows the variation in viscosity of the base fluid (deionised water containing CMC 0.4 % by wt.) with the variation in the shear rate at different temperatures. It is clear from the figure that the viscosity of base fluid decreases with the rise in the value of the shear rate. It was also observed that the viscosity changes when the base fluid temperature rises from 25 °C to 55 °C. From the trends, it can be observed that the deionised water with 0.4 % of CMC shows non-Newtonian behavior.

Figure 10 shows the effects of temperature on viscosity of TiO_2, CuO and Al_2O_3 nanofluids at a particle concentration of 0.04 %. Similar trends were observed for all three types of nanofluids, as the temperature increases the viscosity of nanofluids decreases. The comparison of viscosities of different nanofluids with temperature has been made at a mean value of the shear rate of 50 s^{-1}. From Fig. 10, it is concluded that the decrement in viscosities from 25 °C to 55 °C for TiO_2, CuO and Al_2O_3 nanofluids were found 9 %, 12 % and 11 % respectively at a shear rate of 50 s^{-1}. The following reasons are responsible for the same.

1. The colloidal solution of nanofluids exhibits adhesive forces between the fluid molecules and nanoparticles. On the increasing temperature, the fluid molecules and nanoparticles have greater thermal energy and this energy is sufficient to overcome these adhesives forces. It breaks the adhesive bonds between fluid molecules and nanoparticles.

2. Second reason is the Brownian motion of particles. When the temperature increases the kinetic energy of fluid molecules are also increased. The fluid molecules and nanoparticles are allowed to random movement. Hence, the random movement of fluid molecules and nanoparticles declines the resistance to flow, this leads to decrease the viscosity.

3.5 Rheological Study of Nanofluids

In this section, the rheological behavior of CMC-based nanofluids was discussed on the basis of shear stress with the variation in shear rate. Behavior of fluids can be divided in two parts. First is Newtonian behavior, for Newtonian fluids the shear stress is directly proportional to the shear rate and the viscosity is constant for a particular fluid. While for non-Newtonian fluids, viscosity is a function of temperature and shear rate ( ) and shear stress (τ). One of the most popular and reported models for non-Newtonian fluids is power law model given in Eq. 5.

$$\tau = m\dot{\gamma}^{n} \tag{5}$$

Also, the apparent viscosity (μ) defined by the given equation:

$$\mu = m\dot{\gamma}^{n-1} \tag{6}$$

where m is the consistency index and n is the flow behavior index.

If the value of flow behavior index is less than unity ($n<1$), the fluid is shear thinning or pseudoplastic characteristics. If this value is greater than unity ($n>1$), the fluid is shear thickening or dilatant behavior. For the Newtonian fluids, the value of flow behavior index remains unchanged ($n=1$).

Figure 11 plots over a log–log scale and shows the variation of shear stress with the shear rate at a fixed temperature of 25 °C for TiO_2, CuO and Al_2O_3 nanofluids. It is observed from the results that the value of shear stress of base fluid increases with the increase in particle concentration. Therefore, it can be concluded that on increasing particle concentration the movement of fluid layers resist each other. Which indicates that more power is required to flow nanofluids at higher concentrations. The above discussion reveals that on increasing particle concentration the viscosity of nanofluids increases, as a result, the non-Newtonian behavior of fluids increases.

Figure 12 plots on log–log scale and shows the shear stress variation with the shear rate at different temperature ranges from 25 °C to 55 °C. The graph shows that the value of shear stress increases with shear rate. While the value of shear stress decreases with the rise in temperature. The changes in shear stress from 25 °C to 55 °C was found 22 %, 17.6 % and 13.8 % for CuO, Al_2O_3 and TiO_2 nanofluids respectively at a mean value of the shear rate of 50 s^{-1}. The above findings clearly state that the value of shear stress changes with temperature, this supports the non-Newtonian behavior of nanofluids. Moreover, the value of flow behavior (n) was calculated using the power law model. It was found less than one (<1) for all the nanofluids. Therefore, it can be stated that the nanofluids utilized in the present study have a shear thinning or pseudoplastic nature.

4 Conclusions

The present experimental study covers the characterization of nanoparticles, stability and rheological behavior of non-Newtonian nanofluids. The key outcomes of the present work can be concluded as follows:

1. XRD analysis was performed to know the particle size of nanofluids. From the XRD analysis the diffraction angle of each peak and the conforming crystalline plane was obtained. From the analysis, it was concluded that the particle size was less than 100 nm.
2. Sedimentation visual test was performed to predict the physical stability of nanofluids. By the visual observations, it was found that the addition of CMC to the base fluid enhances the stability of nanofluids. Sedimentation time observed by direct visualization was 19–21 days, 22–24 days and 28–30 days for CuO, Al_2O_3 and TiO_2 nanofluids, respectively.
3. The UV–Vis absorption tests were performed to ensure the stability of nanofluids. It was observed that freshly prepared nanofluids give higher absorbance peaks. While the samples of nanofluids after 30 days of preparation shows lower peaks of absorption.
4. The increment in viscosities was measured 27 %, 21.5 % and 17.4 % for TiO_2, Al_2O_3 and CuO-based nanofluids respectively as compared to the base fluid. Moreover, when the temperature rises from 25 °C to 55 °C the viscosity of nanofluids decreases by 11 %, 12 % and 9 % for Al_2O_3, CuO and TiO_2 nanofluids, respectively.
5. The variation of shear stress with shear rate confirms the rheological behavior of nanofluids. The results reveal that the trend of the outcomes is in good agreement with power law model of non-Newtonian fluids and confirms that the nanofluids are non-Newtonian in behavior. Moreover, the value of flow behavior index was found less than the unity. This showed that the nature of nanofluids is shear-thinning.

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