

Experimental Investigation of Viscosity of Glycerol Based Nanofluids Containing Carbon Nanotubes

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ABSTRACT

The addition of solid nanoparticles to liquids provide significant enhancement of heat transfer and hydrodynamic flow. The viscosity of nanofluids is important for nanofluid transport related to flow dynamics and heat transfer. The aim of the paper is to investigate experimentally the viscosity of nanofluids prepared with glycerol base and nitrogen-doped bamboo shaped multi-walled carbon nanotubes (MWCNTs). The samples are prepared with 0.1, 0.2, 0.5 and 1.0 wt.% MWCNTs. The viscosity of glycerol and MWCNTs nanofluid suspensions are measured at various temperatures and rotational speeds (shear rates). The influence of nanotubes amount, temperature and rotational speed on the viscosity is investigated.

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1. INTRODUCTION

The development of nanofluids is a novel problem. They have many applications in cooling and thermal management technologies, power generation, nuclear systems, chemical processors, air conditioning, microelectromechanical systems, friction reduction, etc. Nanofluids are prepared with metallic or non-metallic nanoparticles, having diameter from 1 to 100 nm, dispersed in a base fluid. Most commonly used base fluids are water, oil, paraffin, ethylene glycol, glycerol, etc. The investigation of properties of these nanofluids has been the area of many experiments [1-3]. The most important properties are thermal conductivity, heat capacity, viscosity

and density. The traditional coolants have low thermal conductivity. Nanofluids offer a solution to improve the heat exchange. Comparing the heat transfer of conventional fluids with nanofluids the thermal conductivity is high.

Nanoparticles applied in the nanofluids can be metals (Cu, Au), oxide ceramics (Al₂O₃, CuO, TiO₂, ZnO, Fe₂O₃, Fe₃O₄), carbide ceramics (SiC, TiC) and non-metals like diamond, fullerene and carbon nanotubes. For the practical applications it is important to know the effect of nanoparticles on the thermophysical properties. The viscosity is an essential property. It describes the internal resistance of a fluid to flow and it is related to the pumping power. Several review papers dealt

with the experimental determination of the nanofluid viscosity, and it is found that volume or mass fraction, temperature, particles shape and size affect the viscosity [4-7].

Chen et al. [8] investigated the rheological behaviour of TiO₂ – ethylene glycol nanofluids. The experimental results show that the nanofluids are Newtonian, the viscosity strictly depends on the temperature and TiO₂ nanoparticles amount, while the relative viscosity is independent of the temperature. In the another similar study, Chen et al. [9] also examined the rheological behaviour of TiO₂ – ethylene glycol nanofluids and studied the effects of particles shape, particles amount and temperature on the viscosity. It was observed that the nanofluids show shear thinning for the particles amount above 2 wt.%, and that temperature increase imposes a stronger shear thinning. Zhang and Han [10] investigated viscosity of two different nanofluids: hydrophilic TiO₂ – water and hydrophilic-lipophilic TiO₂ – water nanofluids. They depicted that the viscosity of nanofluid decreases with the increase of temperature and increases with the increase of nanoparticles amount. The same dependence between viscosity and temperature /nanoparticles amount was shown by Sharifpur et al. [11]. They investigated Al₂O₃ – glycerol nanofluids in the temperature range 20 – 70 °C, and for three particle sizes 19, 139 and 160 nm. It is interesting that the smallest nanoparticles showed the highest shear resistance.

There are many attempts to give the empirical models which link the viscosity of nanofluids (η_{nf}) with the viscosity of base fluid (η_{bf}) and the volume fraction (Φ) of dispersed particles. Some of the most popular models developed for nanofluids are presented below [3,12]:

Einstein model (1906)

$$\eta_{nf} = \eta_{bf}(1 + 2.5\Phi),$$

Brinkman model (1952)

$$\eta_{nf} = \eta_{bf}(1 - \Phi)^{-2.5},$$

Krieger-Dougherty model (1959)

$$\eta_{nf} = \eta_{bf} [1 - (\Phi/\Phi_m)]^{-[\eta]\Phi_m},$$

Frankel-Acrivos model (1967)

$$\eta_{nf} = \eta_{bf} \frac{9}{8} \left[\frac{(\Phi/\Phi_m)^{1/3}}{1 - (\Phi/\Phi_m)^{1/3}} \right],$$

Nielsen model (1970)

$$\eta_{nf} = \eta_{bf}(1 + 1.5\Phi)e^{[\Phi/(1-\Phi_m)]},$$

Batchelor model (1977)

$$\eta_{nf} = \eta_{bf}(1 + 2.5\Phi + 6.2\Phi^2),$$

where $[\eta]$ is intrinsic viscosity and Φ_m is maximum particle volume fraction. It is necessary to note that the applicability of these models depend on the volume fraction, the shape and size of solid particles, etc.

During the past decades, many of the studies are devoted to the investigation of the rheological behaviours of nanofluids that contain carbon nanotubes (CNTs). Both single walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) can be dispersed in the base fluid. The thermophysical properties of nanofluids containing CNT have been investigated in several studies [6,13,14], where the enhancement of thermal conductivity was observed with the addition of MWCNTs, while the viscosity of nanofluids exhibited non-Newtonian shear thinning behaviour.

Tribological properties of glycerol nanofluids were also studied. In their paper Shi et al. [15] compared the lubricating properties of pure glycerol and glycerol aqueous solutions with rapeseed oil, serving as a reference lubricant. The authors found that the coefficient of friction of pure glycerol is substantially lower than that of rapeseed oil, although the viscosity of pure glycerol is higher than that of rapeseed oil. Even the wear was lower in case of pure glycerol. The viscosity of pure glycerol decreases with increasing water content. Coefficient of friction of glycerol solutions is also lower than that of pure glycerol, but the wear is lower in case of glycerol solutions. Chen et al. [16] investigated glycerol solution and glycerol solution with nanodiamonds particles and showed that in both cases superlubricity can be achieved, with the coefficient of friction of approximately 0.006. They also showed that presence of nanodiamonds particles, due to the rolling effect of the nanodiamonds, significantly reduce the wear of both contact bodies. Finally, Tuan et al. [17] showed that coefficient of friction for glycerol containing 1 wt.% CNT could be below 0.06, while the addition of CNT has no effect on wear or it is even detrimental.

The aim of the paper is to investigate experimentally the viscosity of glycerol based nanofluids containing 0.1, 0.2, 0.5 and 1.0 wt.% MWCNTs. The viscosity of glycerol and MWCNT nanofluid suspensions are measured at various temperatures and shear rates. The influence of the nanotubes amount, temperature and shear rate on the viscosity is investigated.

2. EXPERIMENTAL DETAILS

2.1 Materials

Glycerol of purity 99.5 % was used as a base fluid. Glycerol or glycerine is chemically produced from propylene, but it can also be obtained from vegetable oils. It is one of the important by-products of biodiesel production.

The multi-walled, bamboo-shaped carbon nanotubes (Fig. 1) were used as additive. This type of material is the most widely produced by the catalytic chemical vapour deposition (CCVD) process. Nickel nitrate hexahydrate salt was used as a catalyst during the CCVD synthesis, and MWCNTs are produced using appropriate carbon source under appropriate conditions [18]. The diameter of produced MWCNTs was in the range 10 – 30 nm, with variable length.

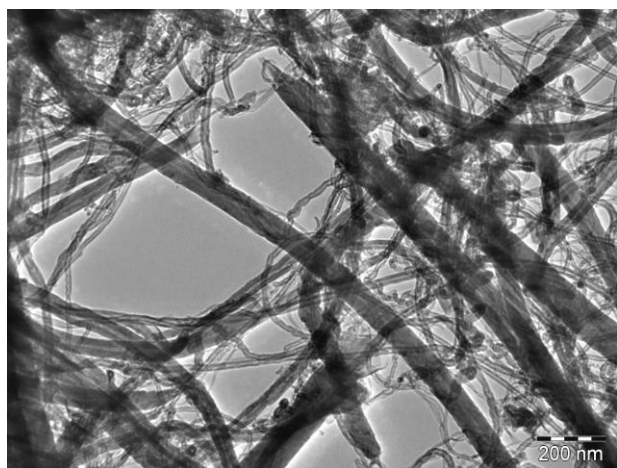


Fig. 1. SEM image of the MWCNTs used in the study.

The glycerol based nanofluids were formulated with 0.1, 0.2, 0.5 and 1.0 wt.% MWCNTs, measured with accuracy of 0.1 mg. No dispersant or surfactant was used. The glycerol-MWCNTs mixture was stirred with mechanical blender to make nanofluids with different mass fractions. For each measurement, a 42 millilitre sample was prepared.

2.2 Viscosity measurement

Viscosity measurements were performed using a rotational rheometer “50 RCOxp” (Fann Instrument Company). The instrument consists of two coaxial cylinders. Radius of the sample cup (rotating cylinder) is 18.415 mm and radius of the bob (static cylinder) is 15.987 mm with height of 76.2 mm.

Each sample was tested at four different temperatures (23, 30, 40 and 55 °C) with various rotational speeds applied (20, 40, 60, 80, 100, 120, 150, 200, 250, 300, 350 and 400 rpm). At each temperature, the rotational speed was increased from 20 to 400 rpm, while the pressure of tested fluids was set to 1 psi (approx. 6.9 kPa), throughout the measurement.

During the experiments, following data were measured/calculated: temperature [°C], rotational speed [rpm], viscosity [Pas], shear rate [s^{-1}] and shear stress [Pa]. In order to achieve a higher confidence level in evaluating test results, five replicate tests were run for each experiment.

3. RESULTS AND DISCUSSION

The viscosity of glycerol and MWCNTs nanofluid suspensions are measured at various temperatures and rotational speeds in order to investigate the influence of temperature, rotational speed and nanotubes amount on their rheological behaviour.

3.1 Effect of temperature on the viscosity

The influence of temperature on the viscosity was the same for all samples and rotational speeds. That is why, as a representation of this behaviour, viscosity of tested samples as a function of temperature was presented only at some rotational speeds (Fig. 2).

As it can be noticed on Fig. 2 the viscosity of glycerol and MWCNTs nanofluid suspensions exponentially decreases as the temperature increases. This is expected behaviour for glycerol. For nanofluid suspensions, the Brownian movement gets stronger with the increase in temperature, so the distance between molecules increases, resulting in less attraction between molecules. Since the interaction between nanoparticles and

molecules, and molecules and molecules decrease with the increase in temperature, therefore, the viscosity decreases with increasing the temperature.

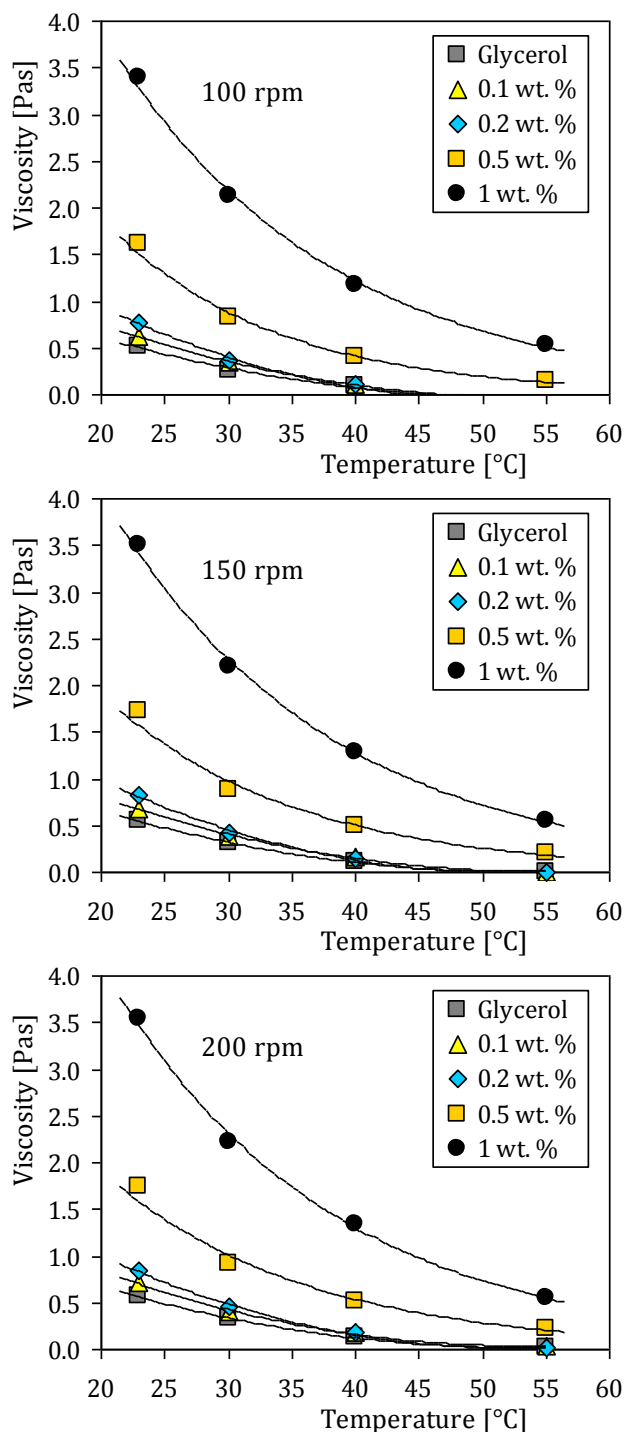


Fig. 2. Viscosity of tested samples with different amount of MWCNTs as a function of temperature at different rotational speeds (100, 150 and 200 rpm).

3.2 Effect of rotational speed on the viscosity

The influence of rotational speed on the viscosity was similar for all samples, so only

viscosity of nanofluid sample with 1 wt.% MWCNTs as a function of rotational speed is presented (Fig. 3).

Figure 3 shows that the impact of rotational speed on the viscosity can be noticed only at lower rotational speeds (up to 150 rpm). In addition, at the highest test temperature of 55 °C, the viscosity hardly changes when rpm increases.

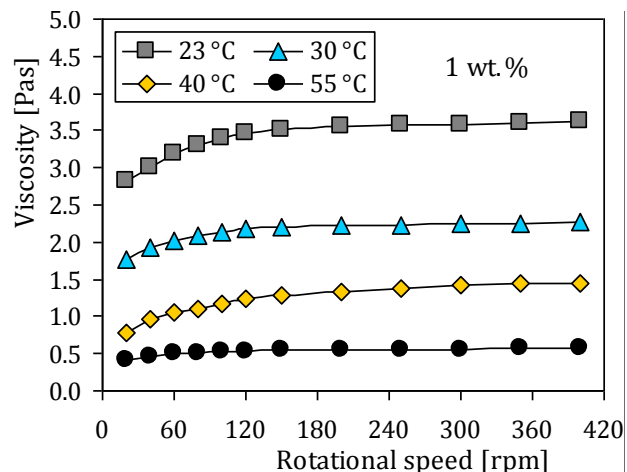


Fig. 3. Viscosity of nanofluid sample with 1 wt.% MWCNTs at different temperatures as a function of rotational speed.

3.3 Effect of MWCNTs amount on the viscosity

The influence of MWCNTs amount on the viscosity was also similar for all temperatures and rotational speeds. As a representation of this behaviour, viscosity of tested samples at rotational speed of 200 rpm as a function of MWCNTs amount is presented (Fig. 4).

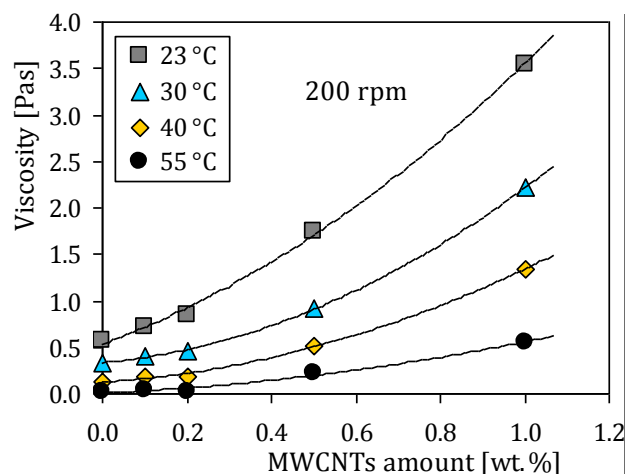


Fig. 4. Viscosity of tested samples at rotational speed of 200 rpm, and different temperatures as a function of MWCNTs amount.

Figure 4 shows exponentially increasing viscosity trends, i.e. the viscosity of MWCNTs nanofluid suspensions exponentially increase as the amount of MWCNTs increases. It is also interesting to notice that the differences in viscosities between glycerol and nanofluids with lower amount of MWCNTs (0.1 and 0.2 wt.%) are relatively small, especially at higher temperatures, suggesting that this amount of MWCNTs is small to significantly change the viscosity.

3.4 Shear stress – shear rate relation

The results for each temperature and rotational speed (shear rate) presented in Figs. 5 and 6 are a set of 30 measurements (readings) during a period of 30 seconds (data are saved every second).

The relation between shear stress and shear rate of Newtonian fluids is linear, i.e.

$$\tau = \eta \cdot \gamma,$$

where τ is shear stress, η is dynamic viscosity and γ is shear rate.

The obtained experimental results show that the glycerol base fluid is Newtonian fluid, since the shear stress is linearly proportional to shear rate. This can be noticed on Fig. 5 where the shear stress – shear rate relations for each temperature is approximate with a linear function. The R^2 (R-squared) values were in the range 0.9931 – 0.9999 and show acceptable goodness of fit ($R^2 = 1$ is a perfect fit).

On the other hand, the obtained experimental results show that nanofluid suspension with 1 wt.% MWCNTs behaves as non-Newtonian fluids, i.e. shear stress is not linearly proportional to shear rate (Fig. 6). In fact, its shear stress – shear rate relations can be characterized by a power-law fluid or Ostwald-de Waele model:

$$\tau = k \cdot \gamma^n,$$

where τ is shear stress, k is flow consistency index, γ is shear rate and n is flow behaviour index.

In the case of nanofluid suspension with 1 wt.% MWCNTs, the shear stress – shear rate relations

for each temperature is approximate with a power law function. The R-squared values were in the range 0.9974 – 0.9988, which represents the acceptable goodness of fit.

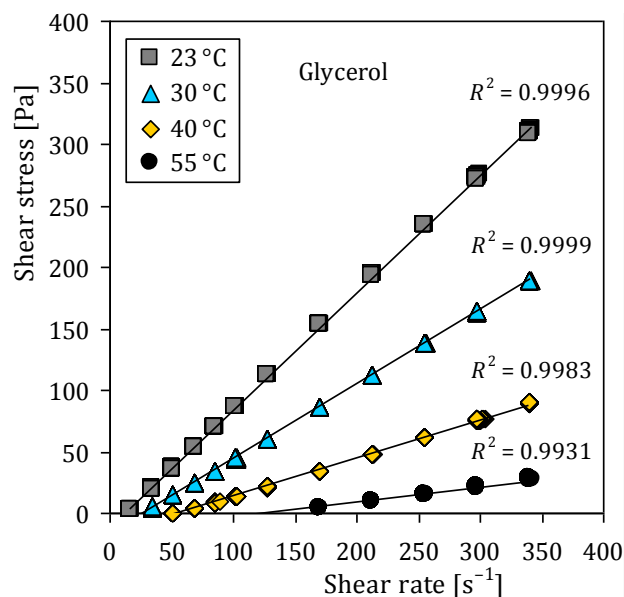


Fig. 5. Shear stress as a function of shear rate for glycerol.

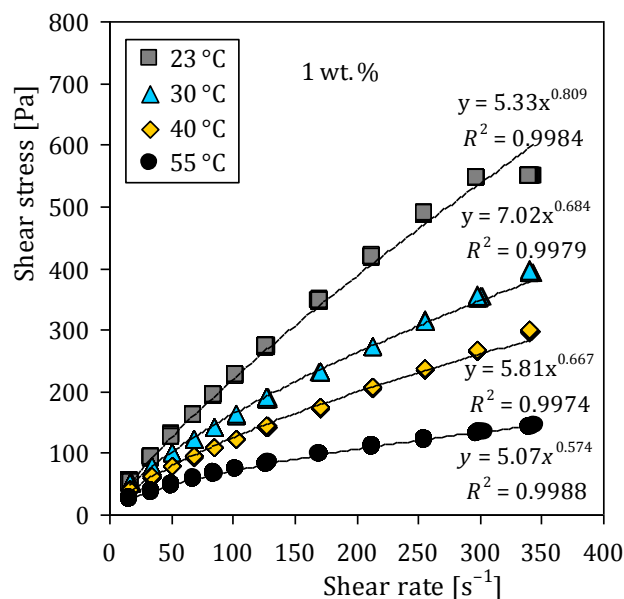


Fig. 6. Shear stress as a function of shear rate for nanofluid sample with 1 wt.% MWCNTs.

All values of the flow behaviour index (n) were lower than 1 (Fig. 6), which means that shear thinning behaviour occurs, i.e. the fluid is a pseudoplastic. The flow behaviour index decreases with increasing the temperature. In addition, thixotropic transient behaviour [19] was not noticed during the stepwise increase in shear rate at constant temperature, i.e. during testing.

4. CONCLUSIONS

Experiments were carried out on glycerol and glycerol based nanofluids containing 0.1 – 1.0 wt.% MWCNTs, at various temperatures (23 – 55 °C) and rotational speeds (20 – 400 rpm), in order to investigate rheological behaviour of these fluids.

The viscosity of all tested fluids decreases exponentially, as the temperature increases. The viscosities also increase, at a fixed temperature, with the increase of the rotational speed (shear rate), but it is obvious only at lower rotational speeds (up to 150 rpm).

The amount of MWCNTs shows noticeable influence on viscosity, regardless the applied rotational speed. All tested fluids show exponentially increasing viscosity trends with the increase of MWCNTs amount. Viscosities of nanofluids with lower amount of MWCNTs (0.1 and 0.2 wt.%) are similar to the viscosity of glycerol, while the other nanofluids show significantly higher viscosities, especially on lower temperatures.

The shear stress is linearly proportional to the applied shear rate for glycerol, confirming it is a Newtonian fluid. On the other hand, nanofluids containing MWCNTs show non-Newtonian, shear thinning behaviour, i.e. the fluids are pseudoplastic. This shear thinning behaviour of nanofluids also depends on the temperature.

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