Physica E 90 (2017) 194–203

Contents lists available at ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Experimental investigation, model development and sensitivity analysis of rheological behavior of ZnO/10W40 nano-lubricants for automotive applications

Mohammad Hemmat Esfe[a,*], Seyfolah Saedodin[b], Mousa Rejvani[b], Jalal Shahram[b]

[a] *Department of Mechanical Engineering, Khomeinishahr Branch, Islamic Azad University, Isfahan, Iran*
[b] *Faculty of Mechanical Engineering, Semnan University, Semnan, Iran*

ARTICLE INFO

Keywords:
Nano-lubricant
Rheological behavior
Shear thinning
Sensitivity
ANN modeling

ABSTRACT

In the present study, rheological behavior of ZnO/10W40 nano-lubricant is investigated by an experimental approach. Firstly, ZnO nanoparticles of 10–30 nm were dispersed in 10W40 engine oil with solid volume fractions of 0.25–2%, then the viscosity of the composed nano-lubricant was measured in temperature ranges of 5–55 °C and in various shear rates. From analyzing the results, it was revealed that both of the base oil and nano-lubricants are non-Newtonian fluids which exhibit shear thinning behavior. Sensitivity of viscosity to the solid volume fraction enhancement was calculated by a new correlation which was proposed in terms of solid volume fraction and temperature. In order to attain an accurate model by which experimental data are predicted, an artificial neural network (ANN) with a hidden layer and 5 neurons was designed. This model was considerably accurate in predicting experimental data of dynamic viscosity as R-squared and average absolute relative deviation (AARD %) were respectively 0.9999 and 0.0502.

1. Introduction

In many industrial applications, it is needed that heat transfer enhances while heat conduction surface is decreased and the flow of coolant fluids such as water, oil and Ethylene Glycol is reduced. To do so, nanofluids have been introduced which were able to full fill the expectations [1]. The so called nanofluids are built from dispersion of tiny particles (smaller than 100 nm) in a base fluid [2]. Nanofluids have unique thermophysical characteristics that can make them preferable over generic fluids.

Nanofluids have many applications in automotive industry, though lubrication of internal parts of engines for the purpose of reducing friction is the most important one. According to the researches that have been conducted, presence of nanoparticles in oils may enhance their lubricating properties compared to base fluid; this would result in heat transfer enhancement inside the engine and increasing the durability of the parts [3–7].

Thermal conductivity and viscosity are thermophysical characteristics of nanofluids that have been studied by many scientists. From many researches it is proven that if temperature and solid volume fraction rises, thermal conductivity of nanofluid would be enhanced [8–13]. Also some papers reported that using smaller nanoparticles helps thermal conductivity enhancement [11–13]. Viscosity plays an important role in rheological behavior of a fluid [14–16]. Viscosity is a force resisting against fluid to flow. Temperature and nanoparticles loading and size can affect viscosity thus rheological behavior of a nanofluid. Regarding to recent researches, viscosity of nanofluid is enhanced by increment of solid volume fraction, temperature reduction and increasing of nanoparticles size [17–20]. Since last decade artificial neural network has been used by many scientists to predict experimental thermophysical data including thermal conductivity and viscosity. Artificial neural network is one of the most powerful methods of data modeling which is capable of predicting nanofluids behavior with the lowest error [21–25].

Rheological behaviors of nanofluids are quite different from each other and a specific behavior cannot be determined for all nanofluids. Viscosity of Ag-heat transfer oil was studied by Aberoumand et al., nanoparticles loadings up to 0.72 wt% were studied at temperatures between 25 and 80 °C [26]. From the results it was indicated that the base fluid exhibit Newtonian behavior while adding even a few amount of nanoparticles changes it to non-Newtonian. The behavior of non-Newtonian fluids are not studied extensively yet. A summary of researches conducted on rheological behaviors of nanofluids is presented in Table 1.

* Corresponding author.
E-mail address: M.hemmatesfe@gmail.com (M. Hemmat Esfe).

http://dx.doi.org/10.1016/j.physe.2017.02.015
Received 30 December 2016; Received in revised form 1 February 2017; Accepted 20 February 2017
Available online 21 February 2017
1386-9477/

Nomenclature

T	Temperature (°C)
w	Weight (gr)

Greeks symbols

$\dot{\gamma}$	Shear rate (s^{-1})
μ	Dynamic viscosity (poise)
ρ	Density (kg/m^3)
τ	Shear stress ($dyne/cm^2$)
φ	Nanoparticle volume fraction

Subscripts

nf	Nanofluid
bf	Base fluid

The main purpose of this paper is to study rheological behavior of ZnO/10W40 nano-lubricant affected by temperature and volume fraction variations. Identification of this nano-lubricant's characteristics are essential for its applications as a lubricant in the automotive industry, beside this subject is not investigated in any other article yet. In this study the experimental data are modeled by a new correlation and artificial neural network.

2. Experimentation

In order to prepare the nano-lubricant, Zinc oxide nanoparticles (ZnO) with the size of 10–30 nm were dispersed in 10W40 engine oil. The characteristics of ZnO nanoparticles are listed in Table 2.

Table 3 presents the characteristics of 10W40 oil.

For the purpose of identifying morphology and structural specifications of ZnO nanoparticles, X-ray diffraction was utilized; the results are depicted in Fig. 1.

The nano - lubricant was made by two-step method; ZnO nanoparticles with volume fractions of 0.25%, 0.5%, 0.75%, 1%, 1.5% and 2% were weighted using Eq. (1) prior to being dispersed in 10W40 engine oil.

$$\varphi = \frac{\left(\frac{w}{\rho}\right)_{ZnO}}{\left(\frac{w}{\rho}\right)_{ZnO} + \left(\frac{w}{\rho}\right)_{10W40}} \quad (1)$$

In this equation ρ is density, φ is solid volume fraction of nanoparticles and w is weight of nanoparticles. The suspensions of nanofluids were blended for 2 h by magnetic blender. The samples were homogenized and stabilized by ultrasonic processor (Kimia Nano Danesh (KND), I.R Iran) with power of 1200 w and 20 kHz frequency was utilized. The result of preparing nanofluids by this method was:1- Stabilized suspensions up to 72 h, 2- Excellent uniformity and homogeneity of samples, 3- Agglomerations and aggregation of nanoparticles were removed. Different samples of composing nano-lubricant are illustrated in Fig. 2.

After nano-lubricants preparation, their dynamic viscosity was measured in temperature ranges of 5 up to 55 °C and in shear rates between 666.5 and 11997 s^{-1}. Brookfield viscometer made by Brookfield engineering laboratories (USA) was used for viscosity measurements. The accuracy of this apparatus was ± 1.0% and its repeatability was ± 0.2%. The viscometer was calibrated by measuring Ethylene Glycol and Glycerin's viscosities at room temperature. Some of the measurements are listed in Table 4.

3. Result and discussion

Ostwald–de Waele relationship is used for identification of the rheological behavior of fluids, this equation is as follows:

$$\tau = m\dot{\gamma}^{n} \quad (2)$$

Where n is power law index, m is consistency index and τ stands for shear stress. The viscosity of the fluids which follow power law is defined by following equation:

$$\mu = m\dot{\gamma}^{n-1} \quad (3)$$

In this equation μ represents the apparent viscosity and $\dot{\gamma}$ is shear rate. N determines rheological behavior of fluids as if it is equal to 1 then the fluid is Newtonian while n values, not equal to one represent non-Newtonian fluids. In order to obtain n and m indexes, logarithmic diagram of shear stress-shear rate is drawn and then the indexes are calculated by below equation:

$$Ln(\tau) = Ln(m) + nLn(\dot{\gamma}) \quad (4)$$

3.1. Rheological behavior of base oil

In the present study, firstly 10W40 base oil rheological behavior is studied. In Fig. 3, variations of shear stress and apparent viscosity versus shear rate are illustrated. With regard to this figure, when temperature is constant shear rate increment leads to apparent

Table 1
A summary of researches conducted on rheological behavior of nanofluids.

Particle	Base fluid	Conc. (%)	Temp. (°C)	Shear rate range	Rheological behavior	Ref.
CuO **Al2O3** **TiO2**	Oil	1 & 2	15.6	100–1000	Shear thinning	Jamal-Abad [27]
MWCNT	Poly α-olefin (PAO6)oil	0.12	Ambient temperature	100	Newtonian (< 0.09 vol%) Shear thinning (0.09 & 0.13 vol%)	Yang et al. [28]
TiO_2	Water	5–12	25	10–1000	Shear thinning	Tseng and Lin [29]
MWCNT-SiO2	EG-water	0.0625 – 2	27.5–50	0.612–122.3	Shear thinning	Eshgarf and afrand [30]
CuO	Oil (SN- 500)	0.2–2 wt%	24–70	1–17	Newtonian	Saeedinia et al. [31]
Al_2O_3	EG-water	0.1–1.5	10–50	3–74	Bingham plastic	Kole and Dey [3]
Fe_2O_3	Glycerol	0.25–0.8	30	0.01–264	Shear thinning	Abareshi et al. [32]
Graphite	Oil	0.17–1.36	30–60	0.1–10000	Shear thinning	Wang et al. [33]
SiO2	Paraffinic mineral oil	1 & 2	25–140	1–1000	Newtonian	Anoop et al. [34]