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Experimental investigation on non-Newtonian behavior of Al_2O_3-MWCNT/5W50 hybrid nano-lubricant affected by alterations of temperature, concentration and shear rate for engine applications

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ABSTRACT

In the present study, rheological behavior of Al_2O_3-MWCNT (65%–35%)/5W50 hybrid nano-lubricant is experimentally evaluated with the aim of facilitating its applications in automotive industry. Aluminum oxide (Al_2O_3) nanoparticles with the mean diameter of 50 nm along with multi-walled carbon nanotubes (MWCNTs) with inner diameter of 3–5 nm and outer diameter of 5–15 nm were used as nano-dispersants. Dynamic viscosity of samples of hybrid nano-lubricant composed out of 0% up to 1% solid volume fraction was measured at temperatures between 5 and 55 °C and shear rates between 666.5 and 10,664 s^{-1}. As a result it was revealed that the hybrid nano-lubricant is a non-Newtonian fluid, also power law index signified shear thinning (pseudoplastic) behavior of the fluid. It was observed that increasing of solid volume fraction aggravates non-Newtonian behavior of the nano-lubricant; on the contrary, temperature increment had the reverse effect. For the purpose of forecasting viscosity of the hybrid nano-lubricant, a new correlation is proposed which is based on temperature and solid volume fraction. R-squared of the correlation outputs is 0.9923, this means that the correlation is capable of modeling viscosity behavior of the hybrid nano-lubricant.

1. Introduction

Many researches have been conducted over the last decade on nanofluids in order to identify the effects of dispersed nanoparticles on base fluid characteristics as well as improving heat transfer properties of fluids being used in engineering applications. Finding of the optimum condition of a fluid in terms of temperature and solid volume fraction is the greatest challenge which many scientists have faced in their studies on nanofluids. It has been showed that increasing of thermal conductivity of Al_2O_3/water would increase heat transfer causing wall temperature reduction [1–3]. Viscosity of Al_2O_3 nanoparticles dispersed in ethylene Glycol is increased as a result of solid volume fraction increment, on the other hand increasing of temperature would cause viscosity reduction. Relative viscosity in a constant solid volume fraction is independent of temperature; also viscosity at a constant temperature is independent of solid volume fraction [4]. Viscosity of turbine lubricant is not remarkably affected by dispersion of Al_2O_3 nanoparticles, because heat transfer improvement is less than the reverse effects on pressure drop induced by nanoparticles' presence [5]. In some researches, experimental correlations are proposed by which viscosity can be predicted in terms of temperature, size of nanoparticles and solid volume fraction [6, 7]. Examples of mathematical models which are proposed for the purpose of prediction viscosity of nanofluids are listed in Table 1.

It has been observed in some researches that thermal conductivity of nanofluids containing multi-walled carbon nanotubes (MWCNTs) linearly changes versus solid volume fraction variations. Also electrical conductivity, density and viscosity of nanofluids in presence of mufti-walled carbon nanotubes is significantly increased [22]. Thermophysical characteristics of nanofluids including viscosity and thermal conductivity depend on size of nanoparticles as well as solid volume fraction. Thermal conductivity and dynamic viscosity of nanofluids would be increased as a result of solid volume fraction increment. Moreover with decreased size of nanoparticles, thermal conductivity is enhanced but dynamic viscosity would be decreased [23–25]. Some of the studies that have been conducted on nanofluids containing Al_2O_3 are summarized in Table 2.

There are many papers in literature about measurement of thermophysical properties of different nanofluids [35–41] but in the present study, Al_2O_3-MWCNT (65%–35%)/5W50 hybrid nano-lubricant is evaluated in terms of rheological behavior for the first time. The main objective of this article is practical applications of the nano-lubricant in car engines. Viscosity of the hybrid nano-lubricant was measured at solid volume fractions of 0% up to 1% and at temperatures

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Nomenclature

T	Temperature (°C)
w	Weight (g)

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

between 5 and 55 °C. Dynamic viscosity of the hybrid nano-lubricant samples is predicted by a new correlation.

2. Experimentation

In order to prepare the hybrid nano-lubricant, 5w50 engine oil was used as base fluid. Multi-walled carbon nanotubes (MWCNTs) and Al_2O_3 nanoparticles were used with the ratio of 35% to 65% respectively. Mean diameter of Al_2O_3 nanoparticles is 50 nm and inner and outer diameter of multi-walled carbon nanotubes are respectively 3–5 nm and 5–15 nm.

The required weights of nanoparticles for making samples with solid volume fractions of 0.05%, 0.1%, 0.25%, 0.5%, 0.75% and 1% were calculated by using Eq. (1). Samples were prepared by two-step method, to do so multi-walled carbon nanotubes and Al_2O_3 nanoparticles were weighted and mixed in engine oil. Samples were blended for 2–3 h by a magnetic blender. Then samples were exposed to ultrasonic waves of 20 kHz produced by a 1200 W ultrasonic processor (Kimia Nano Danesh I.R. Iran) for 6–7 h. Second blending was carried out to achieve stabilized and homogenized samples of hybrid nano-lubricant. The prepared samples along with the base oil, MWCNT and Al_2O_3 nanoparticles are depicted in Fig. 1.

$$\varphi\% = \frac{\left(\frac{w}{\rho}\right)_{MWCNT} + \left(\frac{w}{\rho}\right)_{Al_2O_3}}{\left(\frac{w}{\rho}\right)_{MWCNT} + \left(\frac{w}{\rho}\right)_{Al_2O_3} + \left(\frac{w}{\rho}\right)_{5W50}} \tag{1}$$

Dynamic viscosity of the prepared hybrid nano-lubricant samples was measured by the use of a Brookfield viscometer manufactured by Brookfield engineering laboratories (USA). Accuracy and repeatability of the viscometer were respectively ±1.0% and ±0.2%. Viscosity

Table 1
Examples of experimental correlations for modeling viscosity of nanofluids.

	Authors	Years	(Vol.%)	Correlation
Theoretical correlations	A. Einstein [8]	1906	< 2	$\mu_{nf}=\mu_{bf}(1+2.5\ \Phi)$
	Mooney [9]	1951	–	$\frac{\mu_{nf}}{\mu_{bf}}=e^{\left(\frac{2.5\Phi}{1-k\Phi}\right)}$ 1.35 < k < 1.91
	H. C. Brinkman [10]	1952	–	$\mu_{nf}=\frac{\mu_{bf}}{(1-\Phi)^{2.5}}$
	Krieger and Dougherty [11]	1959	–	$\frac{\mu_{nf}}{\mu_{bf}}=\left[1-\frac{\Phi}{\Phi_m}\right]^{-2.5\Phi_m}$ $0.495<\Phi_m<0.54$
	Nielsen [12]	1970	< 2	$\mu_{nf}=(1+1.5\Phi)e^{\left(\frac{1}{1-\Phi_m}\right)}\mu_f$
	T. S. Lundgren [13]	1972	< 4	$\mu_{nf}=\mu_{bf}(1+2.5\Phi+6.25\Phi^2)$
	X. Wang et al. [14]	1999	–	$\mu_{nf}=\mu_{bf}(1+7.3\Phi+123\Phi^2)$
Experimental correlations	W. J. Tseng and C.-N. Chen [15]	2003	3–10	$\frac{\mu_{nf}}{\mu_{bf}}=0.4513e^{0.6965\Phi}$
	H. Chen et al. [16]	2007	0.5–8.0 wt%	$\mu_{nf}=\mu_{bf}(1+10.6\Phi+(10.6\Phi)^2)$
	Abedian et al. [17]	2010	–	$\mu_{nf}=\frac{\mu_{bf}}{(1-2.5\Phi)}$
	S. Aberoumand et al. [18]	2016	0–0.72 (wt)	$\mu_{nf}=\mu_{bf}(1.15+1.061\Phi-0.5442\Phi^2+0.1181\Phi^3)$
	M. Hemmat Esfe et al. [19]	2014	0–1	$\frac{\mu_{nf}}{\mu_{bf}}=0.9118e^{(5.49\Phi-0.00001359T^2)}+0.0303\ln T$
	M. Hemmat Esfe et al. [20]	2014	0–2	$\mu_{nf}=(15.89+614.4\Phi-14526\Phi^2)$
	M. Hemmat Esfe et al. [21]	2014	0–1	$\mu_{nf}=(1+11.61\Phi+109\Phi^2)\mu_{bf}$
	M. K. Meybodi et al. [6]	2016	0–4	$\frac{\mu_{nf}}{\mu_{bf}}=\frac{133.546-343.824e^{\left(\frac{\Phi}{s}\right)}+290.118\left(e^{\left(\frac{\Phi}{s}\right)}\right)^2-78.993\left(e^{\left(\frac{\Phi}{s}\right)}\right)^3}{0.911+32.3301\times\frac{\ln s}{T}-11.732\times\frac{(\ln s)^2}{T}}$

Table 2
A summary of studies conducted on nanofluids containing Al_2O_3 nanoparticles.

Nanoparticle	Base fluid	Concentration	Temperature	Diameter nm	Ref.
Al_2O_3	Water	0–2.5	25	–	[26]
Al_2O_3 & TiO_2	Water	3–14.3 wt	20–50	25	[27]
MWCNT	Water-ethylene glycol	0–1.8	0–40	30–40	[28]
Al_2O_3	Glycerol	0–5	20–70	–	[29]
Al_2O_3	90% ethylene glycol and 10% water	0–1.5	25	–	[30]
Al_2O_3	gear oil (SAE EP-90)	0–2	15–40	40	[31]
Al_2O_3 TiO_2	Methanol	0.01–0.15	1–20	–	[32]
Al_2O_3, CuO, SiO_2, TiO_2, and ZnO	Water propylene glycol	0.070–0	K 235–380	15	[33]
Al_2O_3 TiO_2	Distilled water	0.01–0.08	25–80	0–10,000	[34]
Al_2O_3 TiO_2	Oil	0.1%, −5%	20 °C to 60 °C.	5 nm to 250	[3]
Al_2O_3	Ethylene glycol	1%–4%	20 °C–60 °C	20 nm	[4]