Applied Thermal Engineering 122 (2017) 794–805

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Thermophysical properties of graphene nanosheets – Hydrogenated oil based nanofluid for drilling fluid improvements

Yee Ho Chai [a], Suzana Yusup [a],*, Vui Soon Chok [b], Sonny Irawan [c], Jespal Singh Deol Balbir Singh [d]

[a] Biomass Processing Lab, Center for Biofuel and Biochemical, Green Technology, Mission Oriented Research, Chemical Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia
[b] Chemical Engineering Department, Heriot-Watt University Malaysia, No. 1, Jalan Venna P5/2, Precinct 5, 62200 Putrajaya, Malaysia
[c] Petroleum Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia
[d] Graphene Nanochem Plc, Suite 0.2, Level 9, WORK@Clearwater Changkat Semantan, Off Jalan Semantan, Damansara Heights, 50490 Kuala Lumpur, Malaysia

HIGHLIGHTS

- Combination of hydrodynamic and acoustic cavitation for nanoparticle dispersion.
- Dispersion of graphene nanosheets at 25 ppm, 50 ppm and 100 ppm.
- Thermal conductivity and rheological properties of nanofluid are investigated.
- Brief evaluation of hydrodynamic cavitation process carried out in this study.

ARTICLE INFO

Article history:
Received 17 January 2017
Revised 29 March 2017
Accepted 4 May 2017
Available online 5 May 2017

Keywords:
Graphene nanosheets
Hydrogenated oil
Thermal conductivity
Rheological behaviour
Hydrodynamic cavitation

ABSTRACT

In this study, thermophysical properties of graphene nanosheets – hydrogenated oil based nanofluid was investigated for the improvement of drilling fluids. Graphene nanosheets powder were dispersed through two-steps method which utilizes hydrodynamic and acoustic cavitation (HAC) combination process. The weight concentrations of dispersed graphene nanosheets powder in this study are 25 ppm, 50 ppm and 100 ppm respectively. The thermophysical properties investigated include thermal conductivity and rheological properties of graphene nanosheet – hydrogenated oil based nanofluid. At the highest nanoparticle concentration, thermal conductivity (TC) enhancement is able to reach up to 14.4% at 50 °C while viscosity and shear stress values increased up to 33% at 30 °C. Both properties are observed to increase with respect to nanoparticle concentrations. The TC models were able to predict consistently with experimental data at lower nanoparticle concentration but underpredicted at higher nanoparticle concentration. The Bingham model has proven to fit well with the rheological data obtained in this study. Cavitation number, K and coefficient of discharge, C_D parameters used to evaluate hydrodynamic cavitation dispersion were found to be 1.025 and 0.3313 respectively. Both parameters had denoted that hydrodynamic cavitation had taken place in the system successfully.

1. Introduction

It is reported that >50% of the current world reserves are 4200 m below sea level with temperature and pressure exceeding 200 °C and 1600 bar respectively [1]. The stability of drilling fluids deteriorates when subjected to high temperature and high pressure (HTHP) applications. Drilling fluids subjected to HTHP applications often result in wear and tear of drilling tools and equipment [2]. Several main limitations include costly materials and treatment costs, increase in fluid density and inability to perform under HTHP conditions [3]. Singh and Ahmed [4] explained that the increased in surface interactions between particles allow heat to be conducted more efficiently. Not only that, the disposal of waste oil-based mud to the surroundings resulted in pollution of the oceans and killing off the coral reefs [3]. The need for a biodegradable and environmental friendly drilling fluid is inevitable to preserve the marine environment. The search of a base fluid that could biodegrade anaerobically led to the discovery of esters which would biodegrade with the presence of “built-in” oxygen

---

* Corresponding author.
E-mail addresses: yeeho.chai@gmail.com (Y.H. Chai), drsuzana_yusuf@utp.edu.my, drsuzana_yusuf@petronas.com.my (S. Yusup), V.Chok@hw.ac.uk (V.S. Chok), drsonny_irawan@utp.edu.my (S. Irawan), jespal@platinumgroup.com.my (Jespal Singh Deol Balbir Singh).

http://dx.doi.org/10.1016/j.applthermaleng.2017.05.012
1359-4311/

Nomenclature

μ	dynamic viscosity of liquid	n	shape factor of nanoparticle
μ_{max}	maximum velocity	p_{in}	inlet pressure
C_D	coefficient of discharge	p_{vap}	vapour pressure of liquid
$d_{orifice}$	orifice diameter	Re	Reynold's number
K	cavitation number	γ	shear rate
k_{bf}	thermal conductivity of base fluid	Δp	inlet and outlet pressure difference
k_{eff}	effective thermal conductivity of nanoparticle	ρ_l	density of liquid
k_{nf}	thermal conductivity of nanofluid	σ	shear stress
k_p	thermal conductivity of nanoparticle	σ_o	limiting shear stress
M	mass flow rate	φ	volume fraction of nanoparticle

present in the esters [5]. The challenges of vegetable oil or esters as drilling fluids are reported to have high viscosity properties and rapid deterioration at high temperature [6]. The application of graphene nanosheets as nanomaterials to improve the thermophysical properties of a biodegradable drilling fluid is proposed to overcome the limitations.

Nanofluids are a relatively new class of fluids which consist of base fluids having metallic or non-metallic nanoparticle suspensions with average sizes of 100 nm or less [7] that consist of condensed nanoparticles that act as a colloidal suspensions. Since the first synthesised carbon nanotube nanofluid by Stephen U.S. Choi in 1995, there has been an escalating number nanofluidics-related publications and its applications. Numerous nanofluids applications have revolutionised various industries globally including industrial with heat transfer applications [8], electronic cooling systems [9], cooling and lubrication of drilling fluids [10] and, etc. as nanofluids possess anomalous physical properties compared to its base fluids counter-part.

Graphite contains multiple layers of planar structures where each layers are termed graphene. First discovered by Novoselove et al. [11], the arrangement is usually honeycomb lattice structure with interplanar distance between each layer of graphene at approximately 0.335 nm and atomic separation of 0.142 nm. The thickness between each sheets are roughly distanced at 0.34 nm. Graphene has been reportedly to have high carrier mobility, high Young's modulus strength and high intrinsic thermal conductivity. The intrinsic value of thermal conductivity of a freely suspended single layer graphene at room temperature is valued between 2000 and 4000 W/m K [12]. Some has even reported up to as high as 5300 W/m K [13]. As graphene is a two – dimensional material, the heat transfer properties of graphene will be significantly different as compared to zero dimensional and one dimensional nanoparticles [14]. This anomalous heat transfer conductance enables graphene to be a potential source for the improvement of existing coolants.

Ahammed et al. [15] had carried out thermal conductivity comparisons between graphene against other metal oxide nanoparticles. They discovered that at very low volume concentration of 0.15 vol%, is are able to thermal conductivity enhancement by 37.2% at 50 °C with graphene-water. When compared to silver-water at similar temperature, graphene supersedes by 5.2%. Yu et al. [16] compared 5.0 vol% of graphene-ethylene glycol nanofluid against graphene oxide and discovered graphene to possess higher thermal conductivity enhancement by 42%. They deduced this to the presence of oxygen atoms and saturated sp^3 bonds which limited the thermal conductance across graphene oxide. Ma et al. [17] had investigated the effect of functionalized graphene nanosheets into silicon oil at 0.07 wt% up to 60 °C. The maximum thermal conductance enhancement achieved in their study was 18.9%.

However, the rheological aspect of the drilling fluids should also be considered. High viscosity properties of drilling fluids allows solid cuttings to be suspended whilst preventing sagging simultaneously [18] as excessive inclusion of nanoparticle concentrations prove to be disadvantageous. Vajjha and Das [19] discovered that the maximum theoretical particle loading allowable in a solution is 3 vol% where particle loadings greater than that will incur greater pressure drop and higher pumping operation cost.

In this study, graphene nanosheets was dispersed into hydrogenated oil – based drilling fluid via two – steps method which utilized hydrodynamic cavitation as the dispersion process. The thermophysical properties investigated in this study are thermal conductivity and rheological behaviour properties of graphene nanosheets – hydrogenated oil based nanofluids.

2. Experimental procedure

2.1. Materials

Hydrogenated oil-based drilling fluid and graphene nanosheets were procured from Platinum Green Chemicals Sdn. Bhd., Malaysia where the materials were used as received. Table 1 outlined the physical properties of the materials used in this study.

2.2. Nanofluid preparation

The dispersion of graphene nanosheets was carried out using a two – steps method that utilized hydrodynamic cavitation dispersion as shown in Fig. 1 to implode bubbles and break down agglomerates into smaller sizes. In this study, the dispersion of

Table 1
Summary of physical properties of hydrogenated oil-based drilling fluid and graphene nanosheets.

Hydrogenated oil		Graphene nanosheets	
Density (kg/m^3)	780 (at 15 °C)	Density (kg/m^3)	874.4
Viscosity (cP)	1.5–2.0 (at 40 °C)	Carbon content (%)	>99.8%
Flash point (°C)	90	Oxygen (%)	<0.05
Vapour pressure (kPa)	<0.1 (at 40 °C)	X-Y dimensions (μm)	0.06–0.1
		Z dimensions (μm)	0.002–0.005
		Thermal conductance (W/m K)	2800