Journal of Natural Gas Science and Engineering xxx (2015) 1–8

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Experimental and theoretical investigation on Nano-fluid surface tension

Hemat Ranjbar [a, b, *], Mohammad Reza Khosravi-Nikou [a], Amir Safiri [a], Samaneh Bovard [a], Ali Khazaei [a]

[a] Faculty of Gas Engineering, Petroleum University of Technology (PUT), Ahvaz, Iran
[b] Sirri Island Gas Gathering and NGL Recovery, Iranian Offshore Oil Company, National Iranian Oil Company, Iran

ARTICLE INFO

Article history:
Received 5 October 2015
Received in revised form
3 November 2015
Accepted 5 November 2015
Available online xxx

Keywords:
Nano-fluid
Surface tension
Thermodynamics model
Triethylene glycol

ABSTRACT

Effect of γ-Al_2O_3 and MgO nanoparticle on surface tension of Tri Ethylene Glycol (TEG) was studied for different nanoparticle concentrations. Furthermore, the effect of nanoparticle size on the Nano-fluid surface tension was investigated. Results showed that surface tension increases for some particle concentrations and decreases for some others; in other words, a certain particle concentration could not be determined as the boundary for the increase or decrease of surface tension. Moreover, Sorbitan oleate was added to TEG solution to investigate the changes in surface tension that may occur due to the addition of surfactants. It is shown that by increasing surfactant concentration, Nano-fluid surface tension would decrease. The effect of nanoparticle size on surface tension was analyzed as well. Using experimental data, five empirical and thermodynamic-based models; i.e., Redlich–Kister (RK), Malanovsky-Marsh (MM), Jufu et al. (JBZ), Chunxi et al. (CWZ) and Santos et al. (SFF) were evaluated for surface tension estimation, and it was found that SFF method is the best method to correlate nano fluid surface tension in this study.

1. Introduction

Water molecules are probably the most common unfavorable component found in untreated natural gas. Thus, it is unavoidable to dry natural gas to a specific point, since water molecule can clog the pipeline by forming clathrate hydrates; and it can engender other severe problems for consumers (Rahimpour et al., 2013). In oil and gas industry, Tri-ethylene glycol is used to “dehydrate” natural gas (Ranjbar et al., 2015). Foaming of glycol is a problem frequently encountered by conventional TEG dehydration units (Gandhidasan, 2003; Shucheng et al., 2006). It can increase glycol loss and reduce the plant capacity (Fransen et al., 2009). Presumably, changing the surface tension of TEG offers the potential to overcome these drawbacks. The authors recommend that one can investigate the effect of surface tension on foam formation of TEG by addition of nanoparticles to TEG.

Nanofluids are innovative liquids containing stable nanoparticles which are dispersed uniformly in the base fluid and having an average size less than 100 nm (Das et al., 2008). They are expected to have different thermo-physical properties, such as thermal conductivity (Patel et al., 2003) and specific heat (Vajjha and Das, 2009), as compared to conventional fluids. Furthermore, nanoparticles can influence the physical properties of the fluid such as viscosity (Prasher et al., 2006), surface tension (Tanvir and Qiao, 2012), and wettability (Sefiane et al., 2008). Nano-fluid technology has fostered extensively within the last decades and proved its essential applications in petroleum industries (Hemmati et al., 2012). In oil production it is attractive to change the water wettability and surface tension in a manner that oil reservoir is preferentially water-wet (Donaldson and Alam, 2008).

In the literature, there are limited authors who have investigated the effect of nanoparticles on the surface tension of Nano-fluids (Khaleduzzaman et al., 2013; Khanafer and Vafai, 2011). In a work conducted by Golubovic et al. (2009), it was discovered that there was a small change in surface tension of water when low concentrations of Al_2O_3 and BiO_2 nanoparticles were used. In addition, Kim et al. (2007) and Godson et al. (2010) elucidated that Nano-fluids' surface tension increases linearly with the increase of Nano-fluid concentration. In another research by Moosavi et al. (2010), it was observed that the addition of ZnO nanoparticles

* Corresponding author. PUT, Ahvaz 61981-44471, Iran.
E-mail address: ranjbar.hemat@gmail.coml (H. Ranjbar).

http://dx.doi.org/10.1016/j.jngse.2015.11.010
1875-5100/

Table 1
Experimental and literature data of density and viscosity of TEG (Begum et al., 2013; Francesconi et al., 2004).

Temperature (K)	Density (Kg/m^3)		Viscosity (Pa s*10^{+3})	
	Present study	Literature data	Present study	Literature data
298.15	1119.8	1119.8	3.677	3.682
303.15	1116.1	1115.8	3.051	2.919
308.15	1112.0	1112.6	2.311	2.336
313.15	1107.9	1108.4	1.903	1.898
318.15	1103.8	1104.0	1.618	1.559
323.15	1099.6	1100.0	1.283	1.299

could increase the surface tension of ethylene glycol as the base fluid. They ascribed their results to nanoparticle agglomeration at the surface of ethylene glycol. Murshed et al. (2009) and Kumar and Milanova (2009) clarified that surface tension of water-based Nano-fluids increases when carbon nanotubes are added to the water.

Among these findings, different results were obtained when Murshed et al. (2008) evaluated water−TiO_2 Nano-fluid. They observed that the surface tension of this Nano-fluid is considerably less than those of the base fluid. They attributed this to the Brownian motion of nanoparticles, and the interaction of nanoparticles and molecules of liquid which causes a reduction in cohesive energy at the interface. In addition, Chen et al. (2011) obtained that the surface tension of laponite and distilled water constantly reduces with the increasing the concentration of nanoparticles. Similarly, the findings of Jeong et al. (2008) indicated that the surface tension of alumina−water Nano-fluids dropped with nanoparticle concentration. Moreover, Vafaei et al. (2009) indicated that the surface tension of Bi_2Te_3/water Nano-fluid decreased to a minimum value and then increased with the addition of more nanoparticle. They assumed that this type of change in surface tension to be a consequence of nanoparticle assembly at the liquid−gas interface.

Accordingly, there exist different results concerning the variation of surface tension due to the addition of nanoparticles. It is not certainly determined whether nanoparticles can increase the surface tension or decrease it. Generally, changes in the surface tension of Nano-fluids depend on the base fluid and nanoparticles used; and hence, should be considered thermodynamically.

Chunxi et al. (2000) formulated a thermodynamic model for the prediction of surface tension of binary liquid solutions, including aqueous systems, based on the Wilson equation (Wilson, 1964). In addition, Jufu et al. (1986) proposed a procedure for the surface tension correlation of nonpolar fluid according to the density functional theory. Sprow and Prausnitz (1966) introduced a valuable thermodynamic model from the Butler equation (Butler, 1932). This simple model has suitable results for utterly asymmetric systems possessing high values of surface tension. Sonawane and Kumar (1999) also used the Butler equation as their framework and suggested an accurate equation to determine the surface tension of multicomponent systems with largely various molecular sizes.

Marsh (1977) developed a general model to represent various thermodynamic excess functions for a mixture. By making some simple assumptions, Redlich and Kister (1948) derived their equation from the Marsh's general model. Santos et al. (2003) evaluated the performance of binary systems of water/methanol, water/ester and ester/methanol with respect to the above mentioned thermodynamic-based models. They also used Butler equation to derive a simple equation for asymmetrical binary liquids possessing large values of excess surface tension.

In summary, the purpose of this article is to determine the effect of the addition of MgO and Al_2O_3 (for different concentration and size of nanoparticles) on the surface tension of TEG. After that, thermodynamic models are evaluated to find the best models for surface tension of nano fluid estimation.

2. Material and methods

Triethylene glycol (TEG) was obtained from Sigma−Aldrich with purity of more than 99 %wt. First; the samples were dehydrated by passing through molecular sieves. In order to be sure about purity of samples, experimental density and viscosity were compared with the related literature data in the range of 298.15−323.15 K. One could see from Table 1 that there is an acceptable agreement amongst the measured values and literature data (Begum et al., 2013; Francesconi et al., 2004).

Two types of γ-Al_2O_3 nano particles with *APS* 20 nm and 80 nm (SSA > 138 m^2/gr and SSA > 58 m^2/gr, respectively) and Magnesium Oxide (MgO) nano particle with APS 20 nm and SSA > 60 m^2/gr purchased from US Research Nanomaterial's, Inc., which are used without any purification. Figs. 1 and 2 show transmission electron microscopy (TEM) images of $\gamma-Al_2O_3$ and MgO nano particles, respectively.

To prepare the sample, 15 ml of pure TEG was used as the base fluid. Then, $\gamma-Al_2O_3$ and MgO nanoparticles were added to it at different concentrations. To disperse particles uniformly in the base fluid, an ultrasonic processor from Hielscher Company (Model UIP500hd), which generates a series of ultrasonic waves, was used (Fig. 3 a). The solution of the base fluid and nanoparticles was

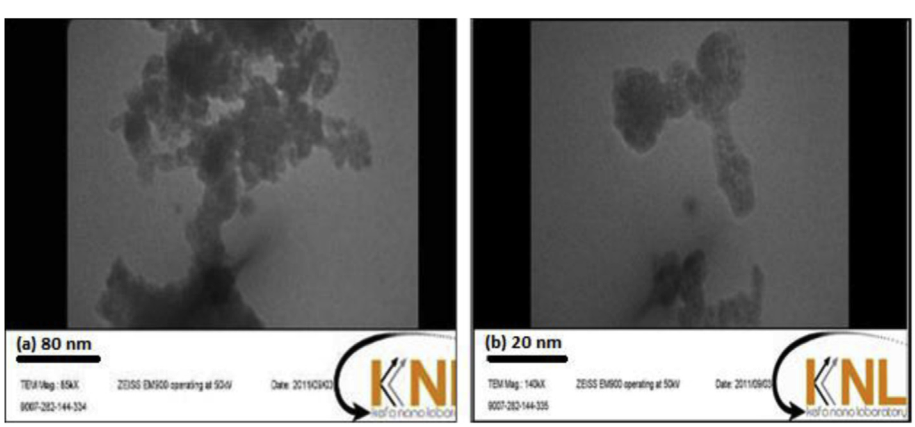

Fig. 1. TEM image of γ-Al_2O_3 nano particles (APS = 80 (a) and 20 nm (b)).