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Development of models to predict the viscosity of a compressed Nigerian bitumen and rheological property of its emulsions

O.S. Alade [a,b,*], B. Ademodi [b], K. Sasaki [a], Y. Sugai [a], J. Kumasaka [a], A.S. Ogunlaja [c]

[a] Resources Production and Safety Engineering Laboratory, Department of Earth Resources Engineering, Kyushu University, Fukuoka, Japan
[b] Petroleum and Petrochemical Engineering Laboratory, Department of Chemical Engineering, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria
[c] Department of Chemistry, Nelson Mandela Metropolitan University, Port-Elizabeth, South Africa

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ABSTRACT

The viscosity of a compressed Nigerian bitumen was measured over a temperature range of 85 °C to 150 °C. It was found that the viscosity at 85 °C and atmospheric pressure, increased from 1894 mPa s to 2787 mPa s at 7 MPa. At the temperature of 150 °C, the viscosity increased from 65 mPa s (at atmospheric pressure) to 71 mPa s at 7 MPa. Water-in-oil and oil-in-water emulsions were formed in a microreactor. The viscosity of original oil at 60 °C and shear rate of 0.14 s^{-1} increased from 34,535 mPa s to 46,130, 59,867, and 71,912 mPa s due to the formation of water-in-oil emulsions containing 15%, 35% and 55% w/w water dispersed in the oil phase, respectively. On the other hand, the viscosity at the same condition was found to have decreased to 239.9 mPa s and 1260 mPa s as a result of 55% and 70% w/w oil particle dispersed in the alcoholic-caustic solution containing hydrophilic polymeric surfactant. The flow activation energy E_a decreased with increasing water fraction (increased viscosity) for W/O emulsions and increased with increasing water fraction (decrease in viscosity) for O/W emulsions. Moreover, viscosity prediction models have been developed and verified using the experimental data.

1. Introduction

One of the most important parameters in engineering design and simulation for bitumen production and transportation is the viscosity (Zirrahi et al., 2014). Therefore, the need for its prediction for relevant applications in various processes such as mining, in situ recovery, production and transportation had led to development and verification of several models (Mehrotra and Svrcek, 1986; Puttagunta et al., 1993; Johnsen and Rønningsen, 2003; Al-Roomi et al., 2004; Behzadfar and Hatzikiriakos, 2014). In addition, development of models to predict effects of important variables such temperature and pressure on viscosity is vital to solving problems associated with recovery and production of bitumen which exists under pressure in the reservoir (Mehrotra and Svrcek, 1987; Puttagunta et al., 1993). In line with this, some recent efforts on bitumen recovery technologies including CO_2 injection, (Behzadfar and Hatzikiriakos, 2014), solvent injection (Kariznovi et al., 2013; Zirrahi et al., 2014) and solvent-steam co-injection (Nourozieh et al., 2015; Ma et al., 2016) had further contributed in the development of a number of important models to predict the viscosity of bitumen-gas and bitumen-solvent mixtures at various conditions.

Another important phenomenon which has effect on the process economy during heavy oil recovery, production, and transportation is the formation of water-oil emulsion (Bennion et al., 1993; Al-Bahlani and Babadagli, 2009; Wong et al., 2015; Wen et al., 2016). It has been documented that in-situ recovery methods including steam flooding, cyclic steam stimulation (CSS), steam assisted gravity drainage (SAGD), chemical assisted steam drive, and other hybrid recovery technologies employed in the EOR induce the formation of water-in-bitumen emulsion which exhibits higher viscosity compared to the original oil and thereby affects production flow (Bennion et al., 1993; Al-Bahlani and Babadagli, 2009; Zirrahi et al., 2014). Apart from the in-situ bitumen emulsification through steam condensation, the formation of heavy oil emulsion and micro-emulsion assisted by chemical surfactant is applicable in EOR (Fletcher et al., 2012; Nguyen and Balsamo, 2013), pipeline transportation (Martínez-Palou et al., 2011; Alade et al., 2016b), and emulsified fuel technology (Miller and Srivastava, 2000). Therefore, understanding of emulsification process and emulsion property is very essential in the mentioned aspects of bitumen development.

The rheological property of complex fluid such as heavy oil and its emulsions is one of the major properties relevant in production and transportation. Specifically, the rheological properties of crude

* Corresponding author at: Petroleum and Petrochemical Engineering Laboratory, Department of Chemical Engineering, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria.
E-mail addresses: oalade@oauife.edu.ng, aladeorimi@yahoo.com (O.S. Alade).

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Nomenclature

C_B	bitumen content (%w/w)
C_S	water content (%w/w)
D_{vm}	Percentage change in viscosity
d_v	Particle size of emulsions (μm)
K	Flow consistency index (mPa s^n)
K_O	Pre-exponential factor of flow consistency index (mPa s^n),
n	Flow behaviour index (dimensionless)
Nd	Number of data
P	Pressure (MPa)
Pr	Reference pressure (MPa)
R	Universal gas constant (8.3144598 J mol^{-1} K^{-1})
T	Temperature of compressed bitumen (°C)
T_e	emulsion shearing temperature (°C)
T_f	emulsion formation temperature (°C)
μ	Viscosity of compressed bitumen (mPa s)
μ_o	Temperature independent pre-exponential factor (mPa s)
μ_a	Apparent viscosity of emulsion (mPa s)
μ_{cal}	Calculated viscosity (mPa s)
μ_{exp}	Experimental viscosity (mPa s)
μ_p	Viscosity of compressed bitumen at reference pressure (mPa s)
Δμ	Viscosity difference (mPa s)
$\dot{\gamma}$	Shear rate (s^{-1})
β	Piezoviscous coefficient (MPa^{-1})
a, b, Θ, Ø, ϑ, α, Þ, ψ,ν, ω, X, Y	System specific adjustable parameters
A_0	Original bitumen
A_1, A_2, A_3	W/O emulsion (C_B=85%, 65%, and 45%, respectively)
B_1, B_2, B_3	O/W emulsion (C_B=40%, 55%, and 70%, respectively)
ARE%	Average percentage relative error
AARE%	Absolute average percentage relative error
SAR	Sum of absolute of residuals
R^2	Coefficient determination
W/O	Water-in-oil emulsion
O/W	Oil-in-water emulsion

oil have very useful applications in process design to handle the fluid, numerical modelling, simulation and optimisation (Ukwuoma and Ademodi, 1999; Evdokimov et al., 2004; Ghannam et al., 2012; Amir et al., 2015; Mortazavi-manesh and Shaw, 2016a). Thus, the studies of rheological properties of heavy oil including bitumen emulsions have been the focus of several researches (Al-Roomi et al., 2004; Ghannam et al., 2012; Al-Yaari et al., 2015; <mac_ce:cross-ref refid="bib9>Alade et al., 2016a, 2016b; Mortazavi-manesh and Shaw, 2016a, 2016b).

Agbabu is one of the important locations of the natural deposit of bitumen and heavy oil within the Okitipupa area of Ondo State, Nigeria, where an estimated 38–50 billion barrel of the oil has been reportedly deposited (Ademodi et al., 1987). Thus, Agbabu oil sand and/or natural bitumen had been the focus of geological investigations by several multinational companies (Ajayi, 1999). Prior to the present investigation, several researches and discussions (Oderinde and Olanipekun, 1990a; Ajayi, 1999; Fasasi et al., 2003; Adebiyi et al., 2006; Adebiyi and Omode, 2007; Ademodi et al., 2014; Adebiyi et al., 2015; Adebiyi and Akhigbe, 2015) have considered Agbabu location and/or Agbabu bitumen in various aspects of its development. However, the effect of pressure on the viscosity as well as the rheological studies of the oil is yet to receive significant attention. Similarly, studies on the emulsification of the oil, rheological property and development of models to predict the viscosity are rarely available in the literatures.

The foregoing has therefore informed the objective of the present study which primarily seeks to investigate the viscosity-pressure and temperature relationship of Agbabu bitumen, and rheological properties of its emulsions for the purpose of developing models to predict the viscosity. It is anticipated that such information would be relevant considering production, and emulsification aspects of recovery and transportation.

2. Materials and experimental methodology

2.1. Materials

Fresh sample of the oil sand was collected from a well located at Agbabu, Nigeria (latitudes 6° 39′ 40′ N and longitudes 4° 53′ 25′ E, Ondo state). Sample to be used for the experiment was heated briefly at 60 °C in an oven (OFW-300B) to liberate the free water content. As recommended by Dessouky et al. (2011), prolonged heating of the bitumen sample was avoided in order to minimise bitumen aging or oxidation. The micrographic image of the bitumen sample was consistently observed to ensure significant elimination of water during this process. Solution of the partially hydrolysed polymeric surfactant (1.0% w/w PVA 235) was supplied by the Kuraray Co., Ltd., Japan. Known volume of the surfactant (PVA 235) was diluted with filtered water to prepare a stock aqueous solution of 5000 ppm used in the experiments. Analytical grades of Alcohol and NaOH were supplied by Junsei Chemical Co., Ltd., Japan. Table 1 presents the properties of Agbabu oil sand and the surfactant.

2.2. Methodology

2.2.1. Viscosity-pressure-temperature study

The influence of pressure on viscosity of the dewatered bitumen was studied at the pressures (P) 0.1, 3, 5, 7 MPa and temperature (T) 85 °C to 150 °C using a high pressure and temperature Viscopro2000 Cambridge viscometer (Model SPL372) which is capable of measuring viscosity in the range of 0.2 mPa s to 20,000 mPa s and maximum temperature and pressure of 190 °C and 7 MPa, respectively. The operating principle is simply such that the instrument expresses the dynamic viscosity as a function of distance and time taken by the piston to move through the chamber. Temperature is measured with the platinum Resistance Temperature Detector (RTD) mounted at the base of the chamber. About 10 ml of heavy oil sample was fed into the sample container and was pushed to the sensor. The system was heated to increase temperature at the interval of 5 °C using the environment controlled oven; and pressure was increased by the use of Nitrogen gas as shown in Fig. 1 below.

2.2.2. Viscosity-pressure-temperature correlation

The viscosity-pressure and temperature relationship of the compressed bitumen was correlated by fitting the data to the following models:

1. Power law function (this study)

   i. $\mu = \nu T^{\theta} P^{\varnothing} \ldots$ (1)

2. Exponential function: Barus model (Barus, 1893; Behzadfar and