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Investigation of the viscosity and density of heavy oil/water blends at elevated temperatures and pressure; Part 1: Oil-only sample (absence of water)

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ABSTRACT

A proprietary cell was designed and fabricated to investigate the density and viscosity of fluid at high pressure and elevated temperatures. In the first part of this study the results of density and viscosity measurement of a heavy oil sample in the absence of water are presented and the results for water/oil blends will be reported in the second part. A heavy oil from a reservoir in Western Alberta was used and its density and viscosity were measured using a special blind cell and a custom made inline viscometer respectively at pressure of 13.76 MPa (2000 psig) and elevated temperatures of up to 300 °C. Hysteresis was observed on density and viscosity of the heavy oil when it was cooled down after being exposed to elevated temperatures.

1. Introduction

Thermal recovery methods for heavy oils rely on applying thermal energy to crude oil in order to reduce its viscosity and to enhance its mobility. In a high temperature environment which exist during a typical thermal recovery method crude oil is in direct contact with water. Due to elevated temperature in presence of agitation and mixing, dissolution of water in the oil phase will occur. Dissolution of water that has a lower viscosity than the heavy oil at existing temperature, can help lower the oil phase viscosity and increase the mobility of crude oil. As such, measuring the amount of water dissolution in crude oil at different temperatures gains importance in any thermal recovery. On the other hand determination of density and viscosity of the crude oil at elevated temperatures is necessary during the production of heavy crude oil. In this first part of the study the density and viscosity measurement results of the crude oil in the absence of water at elevated temperatures up to 300 °C and pressure of 13.76 MPa (2000 psig) are presented. Note that the operating range for conventional viscosity and density measuring devices is usually far less than the temperature range which was used in this study. This restriction also exists for conventional PVT cells and their operating temperature limit is usually below 200 °C.

Due to the above mentioned limitations on conventional PVT cells, a special “Bellows” cell, including the relevant auxiliary systems, was designed, fabricated and successfully commissioned at the In Situ Combustion Research Group at the University of Calgary. A literature review of some of the previous studies is presented in the next section followed by the details of the experimental setup used in the current study.

One of the earliest density and viscosity measurements on bitumen samples produced from Alberta oil sands was published by Ward and Clark at 1950 [1]. They measured the viscosity and specific gravity of dead Athabasca bitumen. Mehrotra and Svrcek [2–5] (1985, Part I, II and II, 1988a) conducted a series of experiments on bitumen samples which were produced from different reservoirs in Alberta such as Athabasca, Cold Lake, Peace River and Wabasca saturated with different types of solution gas. Their experimental setup consisted of a mixing cell, sample cell, a gear pump and a viscometer. Bitumen was saturated with solution gas by mixing and agitation inside the mixing cell and the viscosity of the sample was continuously measured where a constant viscosity was an indication of the equilibrium state. Then a sample cell was filled with the saturated oil and weighed. Since the volume of the sample cell was known by previous calibration, the density of the oil sample was calculated by dividing the mass of oil by the volume of sample cell. Later, a new setup was designed by Mehrotra [6] which consisted of an Anton Paar densitometer, Haake Rotovisco viscometer, a diaphragm pump and a mixing cell. The reported densities and viscosities were at temperatures and pressures up to 120 °C

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and 10 MPa respectively.

Sayegh et al. [7] reported liquid density and solubility data on mixtures of heavy oil and carbon dioxide. Their experimental setup consisted of a blind cell and a window cell both equipped with a floating piston. Two capillary viscometers and a digital densitometer were used to measure the viscosity and density respectively. The maximum temperature and pressure at which the measurements were taken, were 140 °C and 13 MPa respectively.

Badamchi Zadeh et al. [8] reported density and viscosity measurement results on a dead oil sample of Athabasca bitumen. Densities were measured at temperatures ranging from 10 to 50 °C and the pressure of up to 3.540 MPa. Reported viscosity measurements were at atmospheric pressure at the temperature interval of 103–147 °C. An Anton Paar densitometer and a Cambridge viscometer were used to conduct the density and viscosity measurements respectively.

Abedi et al. [9] introduced a specially designed cell which was designed to study the phase behavior of organic fluids and to determine the density and composition of individual phases at elevated temperatures. This cell had a variable volume ranging from 10 cm^3 to 175 cm^3 and its upper operating temperature and pressure was 452 °C and 28 MPa respectively. The cell, was made transparent for X-rays which allowed the observation of the number of co-existing phases and their volume measurement as well as their individual densities without sampling. A stainless steel bellows was used to vary the volume of the cell. Several papers were published by different authors who used the above mentioned cell to study the phase behavior of different mixtures. One of the published studies using this cell which involves a heavy oil, is the study which was conducted by [10]. They reported density measurements of water saturated Athabasca bitumen over the temperature range of 104–370 °C at pressures up to 16 MPa.

Kariznoevi et al. [11] published results for density and viscosity measurements of Athabasca bitumen at temperatures up to 200 °C and pressure up to 10 MPa. Their experimental setup was designed to study the phase behavior and solubility of the mixtures of different hydrocarbons and water with heavy oil. For measuring the density and viscosity of different fluids, they used an Anton Paar densitometer and a Cambridge viscometer. This experimental setup later used by Zirrahi to study the phase behavior of water/solvent/bitumen. In this study the author reported results for viscosity and density measurements on MacKay River bitumen. The measurements were conducted at pressures ranging from 1.12 MPa to 10.43 MPa.

2. Experimental setup

The schematic of the experimental setup is shown in Fig. 1. The cell is a cylindrical-shaped blind chamber which is made of Inconel 718. There are two inlet/outlet ports at the top and bottom of the cell which can be used as injection or withdrawal points In order to perform the mixing of the fluids inside the cell, there are two Inconel 718 bellows installed on either end of the inner-chamber of the cell. Each bellows can move left and right and simultaneous opposite expansion/contraction of both bellows can create the agitation and mixing operation inside the cell. Moving of the bellows is induced by appropriate flow of a high temperature hydraulic oil which can be injected/withdrawn from the chambers attached to the bellows using a double-barrel Quizix (QX6000-20 K) pump. Each barrel is connected to one of the bellows and can be operated independently to either expand or contract the corresponding bellows. For the sake of simplicity, this pump will be referred to as the hydraulic fluid pump in this paper.

The total volume of the cell depends on the location of each bellows. In fact, the volume of the cell decreases with expansion of both bellows and it increases when both bellows are contracting. Therefore, the instantaneous volume of the cell is a function of the location of both bellows at any given time. To determine the instantaneous location of the bellows, an Inconel rod is attached to the inner head surface of each bellows and it extends through opposing walls of a temperature-controlled oven. Each rod is enclosed in type 316 stainless steel tubing, which is part of the hydraulic reservoirs that activate the bellows. A small magnet is installed at the end of each rod which is external to the oven. Ring magnets are located on the external side of each section of stainless steel tubing and they are activated by the internal magnets to provide a direct indication of the location of the corresponding bellows. An aluminum disk is installed on each external ring magnet to make them easier to track. To determine the location of each external magnet laser detectors are installed on each arm of the cell. The laser detectors precisely measure the distance between the laser source and corresponding aluminum disks and through the calibration curves which will be explained later, the volume of the cell can be determined. To measure the viscosity of the fluid inside the cell, an in-line viscometer is attached to the top inlet/outlet port of the cell. The viscometer is a custom-made high temperature viscometer from Cambridge (Visco Pro 2000) and it is rated for temperatures of up to 315 °C. The P-V-T cell and viscometer are installed inside an oven with accurate temperature control and forced-air convection capability. The oven is made by CSZ and it can maintain the assigned temperature set point to less than ± 0.1 °C.

3. Calibration of the cell

An essential step in making the cell ready to perform any measurement was calibration of the cell. In fact, the major direct outputs expected from the bellows cell at a specified operating condition include either the absolute value of the inner volume of the cell or its change due to any external disturbance such as temperature variation. With the current design, the volume of the cell was measured using two laser beam sources/detectors as explained in more details in the previous section. Laser detectors can only measure the linear movement of the bellows in both directions and the measured values were converted to associated absolute/differential volume. In order to perform this conversion, calibration curves were determined by measuring the extent of linear movement associated with withdrawal/injection of a known volume of a calibration fluid out of/into the cell at any specified temperature and pressure. In this study distilled water was used to calibrate the cell due to easy handling capability and the availability of accurate experimental density/temperature/pressure data. Two types of calibration curves were determined:

3.1. Laser readings versus volume change inside the cell

This type of calibration curve is required to convert the linear movement of each bellows to the corresponding volume change inside the cell. The curves were determined by recording the laser values associated with injection/withdrawal of a known amount of distilled water into/out of the cell. Fig. 2 presents the calibration curve for the right bellows at the pressure of 2000 psig and room temperature.

3.2. Total volume of the cell versus temperature

For a known mass of fluid inside the cell at a constant pressure, the cell volume changes with temperature. A calibration curve for the laser reading versus temperature was derived for only one of the bellows. Calculation of the volume of the cell at any temperature during an experiment required that the second bellows was returned to its initial position at the start of the temperature ramp. Fig. 3 shows the total volume of the cell and corresponding laser readings at different temperatures. To test the accuracy of the determined calibration curves the densities of distilled water at temperatures up to 300 °C and a pressure of 2000 psig were measured. The measured densities along with the reference values are listed in Table 1. Note that the reference values of water densities were obtained from the databank provided by National Institute of Standards and Technology, [14]. Considering the relative error between the measured and reference values for the density of

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