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Pipeline transport of heavy crudes as stable foamy oil

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ABSTRACT

A new idea was proposed to transport heavy crudes as foamy oil at normal temperature. The effects of foaming agent type and concentration, foam stabilizer type and concentration, oil–water volume ratio and temperature on the formation and stability of foamy oil were evaluated. The foamy oil properties and drag characteristics of foamy oil flow in small diameter pipes were investigated. The results indicate that the prepared stable foamy oil could be characterized as non-Newtonian power law fluid. The predicted pressure drops were in good agreement with the measured ones. The significant dynamic viscosity reduction rates were obtained.

Introduction

The steady increase in global demand for oil and the depletion of conventional oil reserves has created a transition from conventional to non-conventional oil [1,2]. In this environment, heavy oil and oil sands are expected to become a major source of energy and could potentially extend the world's energy reserves by 15 years [3] if they can be recovered and transformed into final products at a rate and price competitive with other energy sources [4]. However, the high viscosity and complicated composition make heavy oil much difficult and expensive to be produced, transported and refined [5].

In recent years, because of the high cost of heavy oil thermal recovery technology [6–10], cold heavy oil production technology has been successfully applied in field and has achieved a good development effect [11–13]. Among the non-thermal recovery techniques, solution-gas drive is one of the most efficient ways [14]. This method involves simultaneous-mixture flow of gas as very tiny bubbles entrained in heavy oil, which was later defined as foamy oil flow [14]. Several heavy oil reservoirs in the west Canada [15], Venezuela [16], China [17] and Oman [18] under solution gas drive have shown high oil production rates, slower production decline rates and higher primary recovery due to the formation of foamy heavy oil [14,19–21].

Many efforts have been made on this promising heavy oil production method for its low cost and high oil recovery [24–30]. However, almost all related researches for foamy oil focus on underground parts, rarely involving subsequent process of above-ground gathering and transportation. Common approaches for heavy oil transportation mainly include heating, dilution, emulsification and upgrading [31–34]. But the oil are generally needed to be wholly treated, and meanwhile they have their respective adaptability and shortage. High energy consumption always follows the heating or upgrading method, and a large amount of light oil or diluent is generally required for the blending method, and low transport efficiency and large treatment volume of waste water have hindered the popularization and application of the emulsification method [33,35].

Considering the great flowability of foamy oil which have improved the production performance of heavy oil reservoirs, and the broad prospects of cold heavy oil production, an idea that heavy oil is transported in the form of foamy oil at normal temperature was proposed. In this study, the factors affecting the formation and stability of the foamy oil were evaluated based on the synergy of the foaming agent and foam stabilizer, the properties of foamy oil and the drag characteristics of foamy oil pipe flow were experimentally investigated, hoping to provide a possibility for the new technology of cold heavy oil transportation in the future.

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Materials and methods

Materials

The heavy crude oil sample, whose basic compositions and physical properties are listed in Table 1, was collected from J7 well area in Xinjiang oilfield in China. Nitrogen (N_2), which is a colorless, odorless, tasteless, nontoxic, noncorrosive and nonflammable inert gas at ambient temperature and pressure, was used to prepare foamy oil in this study. Moreover, the water used is tap water, which was from Chengdu water supply company. According to the company's water analysis report, the pH value and salinity are 7.32 and 132 mg/l, respectively.

The foaming volume and foam stability of the foamy oil were directly influenced by the type and concentration of foaming agent and foam stabilizer. There are four kinds of common foaming agents in industrial applications, i.e. the anionic, the cationic, the nonionic and the amphoteric, in which the amphoteric surfactant is rarely applied for its high cost. In this paper, two kinds of cationic, anionic and nonionic surfactants were selected as foaming agents, and two kinds of anionic and three kinds of nonionic surfactants were selected as foam stabilizers, which are shown in Tables 2 and 3 respectively.

Apparatus

The simulation installation of foamy heavy oil flow, as shown in Fig. 1, was designed and assembled by the pipeline testing system and purge system. It has a maximum operating pressure of 1.0 MPa and can work between 10 and 90 °C. The foamy oil was transported by a multiphase pump (Shanghai, China) with a maximum flowrate of 12 l/min, a maximum operating pressure of 3.0 MPa and a maximum operating temperature of 250 °C, which has great suction performance and small pressure fluctuation. There are three 0.82 m long PVC test pipes with different internal diameters (D) of 4, 5 and 8 mm respectively. The purge system mainly includes a compressor, an air tank (a maximum pressure of 0.8 MPa) and a rotameter etc. The foamy oil storage tank, waste liquid tank, and auxiliary piping were well insulated by glass wool and controlled by a temperature control system.

XP-300C image analytical system (Shanghai, China) was used to capture and analyze foam micrographs. Anton Paar Rheolab QC viscometer (Graz, Austria) was adopted to test the rheological behaviors of the foam and the oil. A combined device of a F-400 homo-mixer (Foshan, China) with a maximum stirring rate of 8000 rpm and a CWYF-2 high temperature-high pressure reactor (Nantong, China) with a maximum operating temperature and pressure of 600 °C and 50 MPa, was used to prepare foamy oil. A Shangping FA2104S electronic balance with an accuracy of 1/10,000 g (Shanghai, China) was used to weigh various samples. A Zhongxing digital thermostatic water bath (Shijiazhuang, China) was used as a temperature monitoring system when preparing foamy oil. Some measuring cylinders (1000 ml, 100 ml) and pipettes (100 ml) were used to evaluate the foam performance.

Experimental procedure

Preparation and performance evaluation of foamy oil

Based on Waring Blender method, 50 ml water with the required proportion of surfactants and 50 ml heavy oil was added to a stirring cup and evenly mixed by a glass rod as the foaming fluid. Then the mixture was stirred for 15 min at a stirring rate of 4500 rpm in the reactor at 20 °C and 0.1 MPa to prepare the desired foamy oil. Due to the poor flowability, the heavy oil was difficult to be wholly transferred from the measuring cylinder to the stirring cup after the volume was measured. Therefore, we measured the density of the heavy oil at 20 °C and weighed the mass of the oil in accordance with the required volume in the follow-up experiments.

The time for the bubbles coalescing to half of the original volume is recorded as the half-life $t_{1/2}$ of the foam system [35], and the foaming volume V_o and half-life $t_{1/2}$ were used as two indexes for evaluating foamy oil property. To evaluate the comprehensive influences on the foaming fluid foamability, its foam composite index (FCI) can be calculated by the formula of $FCI = 0.75V_o t_{1/2}$

Table 1
Basic properties and compositions of J7 crude oil.

Viscosity at 50 °C (mPa s)	Density at 20 °C (kg/m^3)	Bound water (wt.%)	Asphaltene (wt.%)	Wax (wt.%)	Resin (wt.%)
932	918.9	1.97	3.79	0.71	6.13

Table 2
Foaming agents used for foamy oil preparation.

Surfactant	Code	HLB value	Ionicity	Provider
Cetyl trimethyl ammonium bromide	CATB	16	Cation	Shanghai Chemical Reagent Plant
Cetyltrimethylammonium chloride	CATC	15.8	Cation	Shanghai Chemical Reagent Plant
Sodium benzenesulfonat	ABS	10.6	Anion	Chengdu Kelong Chemical Reagent Factory
Sodium dodecyl sulfate	SDS	40.0	Anion	Chengdu Kelong Chemical Reagent Factory
Coconutt diethanol amide	CDEA	15	Nonionic	Chengdu Kelong Chemical Reagent Factory
Octyl phenol ethoxylate	OP-10	14.5	Nonionic	Chengdu Kelong Chemical Reagent Factory

Table 3
Foam stabilizers used for foamy oil preparation.

Surfactant	Code	Main composition	MW	Ionicity	Provider
Carboxy methyl cellulose sodium	CMC	Carboxy methyl cellulose sodium	264.204	Anion	Chengdu Kelong Chemical Reagent Factory
Polyacrylamide	PAM	Polyacrylamide	3×10^8	Anion	Chengdu Kelong Chemical Reagent Factory
Hydroxyethyl cellulose	HEC	Hydroxyethyl Cellulose	2.5×10^5	Nonionic	Chengdu Kelong Chemical Reagent Factory
Dodecanol	Dod	1-Dodecanol	186	Nonionic	Chengdu Kelong Chemical Reagent Factory
SF-1 suspending agent	SF-1	Acrylic polymer	–	Nonionic	Guangzhou Feirui Chemical Ltd.

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