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Investigation on drag characteristics of heavy oil flowing through horizontal pipe under the action of aqueous foam

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ABSTRACT

As a promising drag reduction method for heavy crude oil flow, water–annulus technology has been developed to make the oil flow more easily through a pipeline. But this core–annular flow always shows unstable structure and higher water cut required due to density difference and oil–water interaction. In order to decrease the water cut as much as possible, we focus on the experimental study of the drag characteristics of the flow with annular foam and core heavy oil in this work. An aqueous foam solution system AFS–2 was evaluated using Waring Blender method. A foam injecting system was designed and assembled to investigate the flow patterns and drag characteristics of Tahe heavy crude oil flowing through a horizontal pipe under the action of two kinds of AFS–2 foams with different air volume fraction. The effects of air volume fraction in the foams and the flow rates of the oil and foam on the flow patterns and pressure gradients along the pipe test section were discussed. Based on the oil–foam stratified flow theories, a model for pressure gradient prediction of the oil flowing through the wet foam–annulus was established and modified. The results indicate that the dry foam cannot achieve a desired drag reduction effect, but the drag reduction efficiency is generally more than 70% when the volume flow ratio of wet foam to oil is more than 0.1. The drag reduction mechanism can be attributed to a composite layer with top foam and bottom inhomogeneous foam or foam drainage, isolating or lubricating the inner–pipe wall. The relative errors of pressure gradients between calculated and experimental results are generally higher than 300%, but these can be reduced to less than 10% while the oil flow friction item of the model is multiplied by a modified coefficient β of 0.1907. To a certain extent, this work has verified the drag reduction of foam or foam drainage for heavy oil flow.

1. Introduction

The pipeline transportation of heavy crude oil is an important process from well head to users. The design and operation of the gathering system and long distance transportation for the heavy oil have faced great challenges due to its high viscosity and serious adherence to the pipe–wall. Some drag–reduction methods for the heavy oil flow, mainly including heating, dilution, emulsification and upgrading (Rafael et al., 2011; Abdurahman et al., 2012; Weissman et al., 1996), have to be used to realize its economic and safe transportation. However, these methods are generally used to wholly treat the oil, and they have 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. Therefore, a promising method of core–annular flow (CAF) has been developed to isolate or weaken the interaction between the oil and inside pipe–wall with a light fluid.

An interfacial drag reduction method of piping oil was proposed (Isaacs and Speed, 1904), which perhaps is the origination of CAF or lubricated pipeline and has been widely reviewed over the past years (Bai and Joseph, 2000; Ghosh et al., 2009; Rafael et al., 2011). These studies mainly include numerical simulation, experimental investigation and theoretical analysis for flow pattern, pressure drop and CAF stability. Some studied results show that the lowest pressure gradients were achieved when the injected water rate was between 30% and 40% (Glass, 1961), and the

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optimum flow rate ratio of water/oil was 0.5 for laminar water–annulus and approximately 0.11 for turbulent one (Liu and Zhang, 1990), and there was a drag reduction over than 90% while an annular water layer formed at pipe–wall (Bensakhria et al., 2006). CAF has been applied in petroleum industry to reduce the pressure drop along heavy oil pipeline. Shell Oil Co. widely publicized the use of CAF in viscous oil pipeline without heating or insulation in 1972. However, the water–annulus structure in CAF transportation always is unstable due to density differences between oil and water, which greatly restricts its wide application.

Aqueous foam is a non–equilibrium dispersion system of gas bubbles in a relatively smaller volume of liquid, and evolves over time by gravitational drainage, coarsening and film rupture (Magrabi et al., 1999). Foam has been widely applied in drilling, well cementing, profile control and water shut–off, well testing and flooding–oil production due to its favorable pseudoplasticity, good emulsifiability and oil–carrying capability, excellent selectivity between oil and water (Fan, 1997; Yang et al., 2002). The injection of microbubbles could reduce the production rate of turbulence kinetic energy and enstrophy (Ferrante, 2004). The foam would self–lubricate and lead to a lubricated laminar flow (Briceno and Joseph, 2003). We noticed that aqueous foam injected into the boundary between oil flow and inside pipe–wall could weaken the oil adherence to the pipe–wall and reduce its flow drag (Jing et al., 2013) and simulated the influence of the diameter and inclination of pipe on heavy oil–aqueous foam flow patterns and pressure drops (Zhu et al., 2011).

This work focuses on the experimental study of the drag behaviors of the oil–foam flow. An aqueous foam liquid system with high foaming ability and stability was screened out to investigate the flow patterns and drag characteristics of heavy oil flowing through a horizontal pipe under the action of both dry and wet foams. A model for pressure gradient prediction of the oil flowing through the wet foam–annulus was established and modified.

2. Materials and methods

2.1. Materials

The crude oil sample, whose basic compositions and physical properties are listed in Table 1, was collected from the gathering station of the 12th oil block in Tahe oilfield. Moreover, the water used in this study 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.

Table 1
Basic properties and compositions of Tahe crude oil.

Basic properties		Composition (wt%)	
Density at 20 °C (kg/m^3)	933	Bound water	5.3
Viscosity(mPa s)			
20 °C	986	Wax	0.3
30 °C	577	Resin	4.2
40 °C	337	Asphaltene	9.7

According to the related studies, the foaming agents used for the preparation of aqueous foam almost involve all kinds of surfactants, which includes the common chemicals such as sodium dodecyl sulfate, sodium benzenesulfonat and fatty alcohol polyoxyethylene ether sodium sulfate (Zhao, 1992; Zhou and Tan, 1999; Guo et al., 2000; Zhou and Liu, 2001). Therefore, there are 6 kinds of surfactants selected as foaming agents in this study, as shown in Table 2, and their ionicities and HLB values are also listed.

However, the stability of foam prepared by any foaming agent is often difficult to meet the application requirements, appropriate foam stabilizers are always need to be added into the surfactant solution to improve its foam stability. The mixture of PAM and HXYP chemicals can greatly enhance the foam stability of the anion foaming system XN due to their synergistic effect (Su et al., 2007). The addition of the anion copolymer SF–1 crosslinked by acrylic acid and esters can significantly increase the stability of the foam prepared by associative foaming agent MF–1 solution (Zhang, 2004) due to the basic balance of solution viscosity and the compatibility with various surfactants. Dodecanol was used to stabilize the foam prepared by SDS solution (Dame et al., 2005) due to its high–level fatty alcohol with solubilization, arranging at equal intervals with surfactant molecules and reducing the repulsive force between surfactant molecules. In order to obtain aqueous foam system with excellent foaming ability and high half-time, dodecanol, SF–1 and PAM were selected as foam stabilizers in this study, as shown in Table 3.

2.2. Apparatus

The installation of heavy oil–aqueous foam flow simulation, as illustrated in Fig. 1, was designed and assembled by foam generator and container, foam–annulus generator, instruments and other power equipments, stainless steel tubes and fittings. In which, the foam generator with foam solution, air inlets and foam outlet is an airtight cylindrical vessel filled with wire mesh; the foam container (Volume = 16 l) with a piston is a specially–made cylindrical vessel; the foam–annulus generator consists of inner cylinder (oil flow channel) and outer annular cylinder (foam flow channel); the visual pipe section (L=1.5 m, D=25 mm) is made of organic glass; the pipe–loop (L=42 m, D=25 mm), including test section (L=3 m, D=25 mm), is made of 304 stainless steel.

XP–300C image analytical system (China) was used to capture and analyze foam micrographs. Anton Paar Rheolab QC viscometer (Austria) was adopted to test the rheological behaviors of the foam and the oil. Haake RS600 rheometer (Germany) was used to evaluate the elastic behavior of the foam. TX–500C interface tensiometer (America) was applied to measure the interfacial tensions of surfactant solutions. The GJ–1 Homo–mixer with a

Table 2
Surfactants used for foaming agents and interfacial tensions (IFT) for 0.5% surfactant solutions and Tahe crude oil at 20 °C.

Name	Code	Ionicity	HLB value	IFT(m N/m)	Provider
Sodium dodecyl sulfate	SDS	Anion	40.0	0.4453	P1
Sodium benzenesulfonat	ABS	Anion	10.6	0.2070	P1
Agent 3#	3#	Amphoteric ion	/	0.1850	P2
Cetyl trimethylammonium bromide	CTAB	Cation	15.8	0.0603	P3
Tween 80	Tween 80	Nonion	15.0	4.3616	P4
Sodium Oleate	SO	Anion	18.0	1.2963	P5

Note: [P1]Chengdu Kelong Chemical Reagent Factory; [P2]Chengdu Fuji Technology Limited Company; [P3]Shanghai Chemical Reagent Plant; [P4]Guangzhou Xingang Chemical Plant; [P5]Shanghai First Reagent Plant.