Flow Characteristics of Crude Oil with Additive

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Chetan Badgujar
Kansas State University

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Praveen Kumar and Chetan Badgujar

Abstract In the present work, flow characteristics of high sulfur crude oil (HSCO) with the addition of low sulfur crude oil (LSCO) were studied. LSCO was mixed in high sulfur crude oil in concentration of 10–15% by volume. The rheological characteristics of the heavy crude oil suspension were determined using ISO-certified Rheometer for the range of shear rate varying from 0 to 500 s^{-1}, and temperature range varies from 25 to 45 °C. The rheological characteristics of the HSCO include steady-state flow behavior, yield stress, and thixotropic characteristic, etc. Optical microscopy and dynamic light scattering were used to analyze the size of wax crystals and crystal size distribution, respectively. The average size of wax crystals was 2550 nm for 100% HSCO which further reduced to 350 nm after adding 15% LSCO. HSCO shows the non-Newtonian flow characteristics at low temperature and decreases with increase in temperature. Rheological results of HSCO show that there is a reduction in viscosity with the addition of LSCO. The LSCO as an additive in HSCO can be beneficial for design of crude oil transportation pipeline.

Keywords Crude oil · Dynamic light scattering (DLS) · Optical microscopy (OM)

1 Introduction

The present investigation deals the rheological characteristics of HSCO with LSCO. Largest reserves of HSCO are present inside the earth, but due to complex property of hydrocarbon its production and extraction process in small fraction are difficult. Viscosity is a major problem for crude oil, so various methods are adopted for reduction in viscosity such as thermal enhanced oil recovery (EOR) methods. Production and thermal recovery method are the commonly used to study the behavior of HSCO with and without emulsions in pipeline. Rheological

P. Kumar (✉) · C. Badgujar
Indian Institute of Technology Delhi, New Delhi, India
e-mail: praveen.dimenssion@gmail.com

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characteristics such as steady-flow behavior, yield stress behavior, and thixotropic behavior of heavy oil and its emulsion are measured with the help of rheometer. The elastic behavior of non-Newtonian fluid follows the Hooke's law [1]. It indicates that shear stress is directly proportional to shear rate within elastic limit, in contrast to a non-Newtonian fluid under shear stress. HSCO viscosity behavior exhibits frequency or dependence of time which was measured by researchers [2–5]. Temperature also plays an important role in the viscoelasticity of HSCO. The constituent of crude oil has polar fraction (asphaltenes, resins, and wax) behaving as solid, while HSCO with large amount aromatics component behaves like liquids. The flow characteristics of crude oil in pipeline show variations from one crude well to the other [6]. The flow characteristic of crude oil also depends on age and depth of crude oil well [7]. HSCO exhibits the non-Newtonian flow characteristics due to difficulty of its transportation at very long distances [8]. During the transportation from sea to refinery, wax substance deposits on the pipeline wall cause the reduction in flow diameter of pipeline. This leads to blockage of transportation pipeline and failure of valve. The most important data required for designing a transportation system are the rheological characteristics of the suspension at various operating conditions. Rheological characteristics of the HSCO depend on several parameters such as flash point, pour point, specific gravity, operating temperature, yield stress, and thixotropic structure [9, 10]. Investigators [6–8, 11–15] also studied the rheological characteristics of HSCO with the addition of different types of additives. A small proportion of the some drag reducing agents is able to reduce the viscosity of the HSCO which helps in the improvement of pipeline flow characteristics. The viscosity of crude oil reduced in water emulsion [11]. The literature indicates that the addition of different types of additives can be helpful in improving flowability of HSCO. The aim of this investigation is to investigate the rheological behavior and microstructure of HSCO and its emulsions with LSCO.

2 Materials and Methods

In the present investigation, HSCO and LSCO were supplied from Indian Oil Corporation Limited (IOCL), Panipat, India, which were mixed with low sulfur crude oil with the help of magnetic stirrer. A magnetic stirrer was operated at 1500 rpm for each emulsion with a time duration of 1 h. The concentration of LSCO in HSCO was taken as 10 and 15% (by volume). The physical parameters, namely density, viscosity, pour point, basic sediment, and water percentage, were tested according to the norms of American Society for Testing and Materials (ASTM) methods. The rheological characteristic of crude oil and its emulsions (with low sulfur crude oil) was evaluated using ISO-certified Rheometer (Rheolab QC, APC Ltd., Germany).

3 Experiments

The physical parameters and testing method of HSCO and LSCO are represented in Table 1. In the present study, CR mode of rheometer is used to determine the viscosity (v) and a shear rate of HSCO and its emulsions which represent their flow behavior.

4 Results and Discussion

4.1 Steady-Flow Behavior

Steady-flow behavior of (in terms of viscosity) samples of HSCO at three different concentration levels of LSCO, i.e., 10 and 15% (by volume), was observed at three different temperature levels which are shown in Fig. 1. It was further revealed that HSCO shows non-Newtonian shear thinning behavior while increasing the temperature from 25 to 45 °C. However, the viscosity of crude oil decreases with increase in temperature of crude oil from 25 to 45 °C. It was also revealed that viscosity difference between crude oil and emulsion samples was smaller at a high shear rate and larger at the low shear rate.

This happens due to the fact that the component of high molecular weight like waxes, resins, and asphaltenes, etc. does not form complex bond at high temperature which results in viscosity reduction [15]. For LSCO, the viscosity reduction in HSCO was found from 5.8 to 5.1 mPa.s at 25 °C, as shown in Fig. 1a. While HSCO with 15% LSCO was used, the viscosity drops from 5.8 to 5.3 mPa.s, as shown in Fig. 1b. It can be observed that viscosity reduction also remains significant at lower temperatures. Dynamic viscosity reduction (DVR %) of HSCO was reduced more economically by using light crude oil which can be confirmed from Table 2. Figure 1c represents the flow behavior of HSCO. It was observed that HSCO shows non-Newtonian shear thinning behavior while increasing the temperature from 25 to 45 °C. This happens due to the fact that the component of

Table 1 Physical properties and test method

S. No.	Parameter	Units	Method	HSCO	LSCO
1	Density	kg/m^3	ASTM D1250	874.6	837.6
2	Basic sediment and water	wt%	ASTM D4007	0.125	0.10
3	Water	wt%	ASTM D4928	0.06	0.04
4	Sulfur	wt%	ASTM D4294	2.58	0.18
5	Viscosity	Pa.s	Rheometer	0.006	0.0054
6	Pour point	°C	ASTM D97	55	53
7	Color	–	–	Black	Black

Weight percentage (wt%)

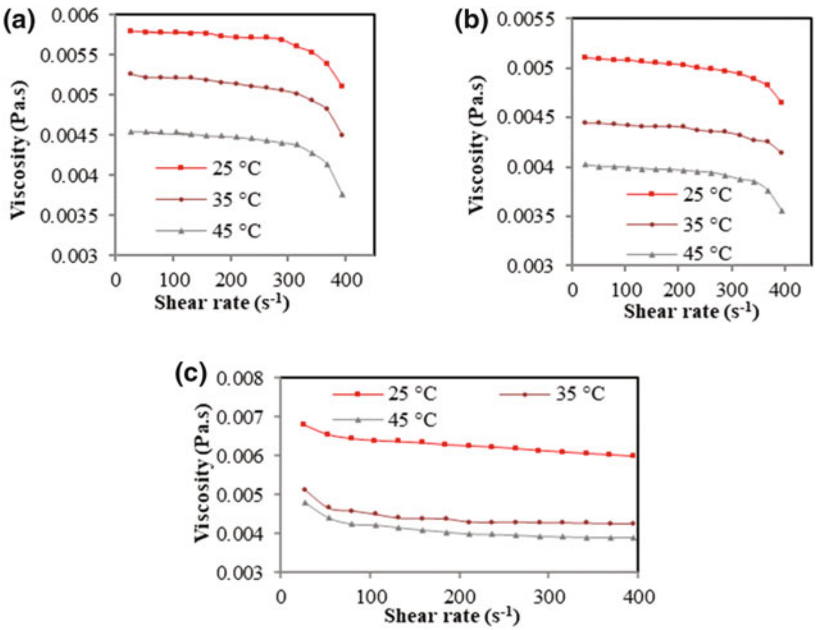

Fig. 1 Viscosity behavior of **a** 90% HSCO–10% LSCO, **b** 85% HSCO–15% LSCO, and **c** 100% HSCO, at different temperatures

Table 2 Properties of crude oil at a shear rate of 500 s^{-1}

Sample	25 °C		35 °C		45 °C	
	Viscosity (mPa.s)	DVR (%)	Viscosity (mPa.s)	DVR (%)	Viscosity (mPa.s)	DVR (%)
S1	5.8	–	5.6	3.4	4.3	25.8
S2	5.4	6.9	5.2	10.3	4.1	29.3
S3	5.3	13.8	4.2	27.5	4.0	31.0

S1 100% HSCO; S2 90% HSCO–10% LSCO; S3 85% HSCO–15% LSCO

high molecular weight like waxes, resins, and asphaltenes, etc. does not form complex bond at high temperature which results in viscosity reduction [11].

4.2 Yield Stress Behavior

In the following study, the yield stress of the samples was determined from shear stress to shear rate curve obtained from rheometer. The controlled stress (CS) mode of rheometer is used to measure the yield stress which produces high precision results as compared to controlled rate (CR) mode, as recommended by [16].

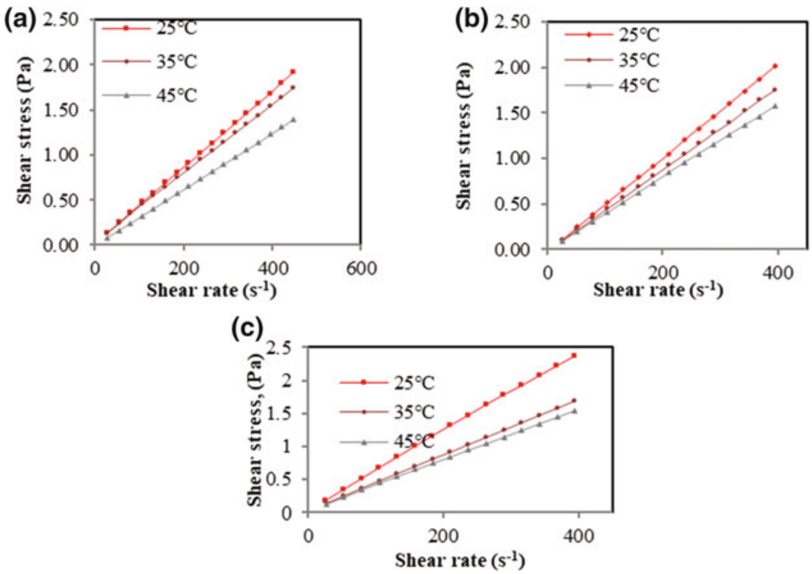

Fig. 2 Yield stress behavior of **a** 90% HSCO–10% LSCO, **b** 85% HSCO–15% LSCO, and **c** 100% HSCO, at different temperatures

Yield stress of each sample was recognized/identified with the help of Bingham model. As per the observation, yield point decreases with increase in temperature. Figure 2a indicates that apparent yield stress diminishes with the addition of 10% of LSCO in HSCO. This happens due to the elimination of stresses from crude oil with the addition of surfactant which tends toward decrease in viscosity of crude oil; while 15% of LSCO was added more, the stresses in HSCO were eliminated due to change in inner mechanism of crude oil, as shown in Fig. 2b. The small variation in stress level causes a significant change in mechanical properties of structured fluid. However, the material tends to deform elastically below the specified stress level. This happens due to reason that beyond this stress level the applied stress produces continuous deformation in the fluid which results in smooth flow of crude oil emulsion [17]. The shear stress to shear rate response at different temperatures is represented in Fig. 2c. The yield point of HSCO shifts from 1.6 to 1 Pa with increase in temperature from 25 to 45 °C.

4.3 *Thixotropic Behavior of Crude Oil and Its Emulsions*

The thixotropic behavior of HSCO and HSCO–LSCO mixture was investigated in the present study to determine the magnitude of change in microstructure from one state to other and vice versa. Thixotropic experiments were carried out on HSCO

Table 3 Hysteresis area at different temperatures

S. No.	Temperature (°C)	Hysteresis area (Pa.s^{-1})		
		S1	S2	S3
1	25	226	195	130
2	35	196	192	126
3	45	89	0	0

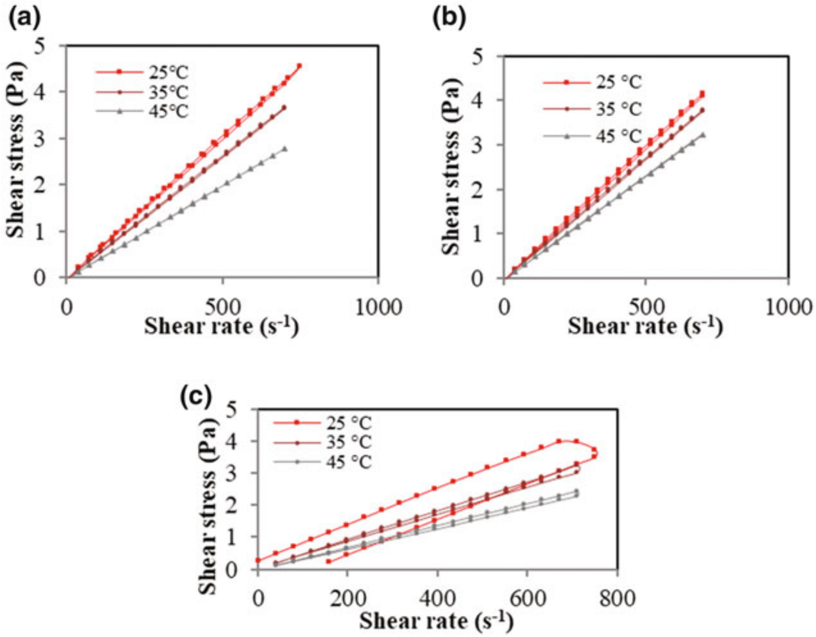

Fig. 3 Thixotropic behavior of **a** 90% HSCO–10% LSCO, **b** 85% HSCO–15% LSCO, and **c** 100% HSCO, at different temperatures

for the up- and down-cycle of 100 s which was required to break the thixotropic structure of HSCO. The shear rate ramped up 0.8–700 s^{-1} within 100 s and quickly ramped down from 700 to 0.8 s^{-1} in equal time. The value of thixotropy in terms of energy per unit volume was calculated from the hysteresis loop area which enclosed between the up-curve and down-curve rheograms [18–21]. Hysteresis loop area of HSCO and its emulsions is summarized in Table 3. It was found that the mixing of LSCO in HSCO depletes the thixotropic behavior and results in the reversal of processes which makes the up- and down-curve to coincide for the concentration of 10 and 15%, respectively, which is shown in Fig. 3a, b. An identical up- and down-curve was noticed at temperature of 25 and 35 °C which indicates the unnoticeable thixotropic behavior of HSCO. The thixotropic behavior of HSCO at different temperatures is shown in Fig. 3c.

4.4 Dynamic Light Scattering (DLS)

Dynamic light scattering instrument (Model ZEN3600, Malvern Instruments Ltd., Malvern, UK) was used to measure the particle size by diffusing scattered light through the crude oil. Zetasizer system of DLS instrument had analyzed the diameter of particle crystals by calculating Brownian motion and then interpreted their diameter using recognized theories.

Zetasizer module determines the size distribution of wax particles with the help of relation between diffusion speed and size. The size of particles can be found by analyzing their movements. When the position of wax particles from each other appears same and their movements were minimum, then it denotes the existence of larger-sized wax particles. When a movement of particles becomes arbitrary from each other, then it denotes toward their small size. In the present study, DLS instrument was used to perform the quantitative analysis of the micrographs of pure crude oil and its emulsions with LSCO and natural surfactant. Figure 4 represents the DLS graphs of pure crude oil and its emulsions. From Fig. 4a, it is found that the radius of HSCO wax crystals lies in the range of 2000–3100 nm. The average size of wax crystals seems to be larger, i.e., approximately 2550 nm, which would abstract the smooth flow in the pipeline. Figure 4b represents the DLS graph of 85% HSCO and 15% LSCO mixture, and the radius of the wax crystal was found in the range approximately 350 nm.

4.5 Optical Microscopy (OM)

Optical microscopy (OM) was used to analyze the change of wax crystal size before and after the addition of LSCO. A simple polarized light-based inverted microscope (Model MA100, Eclipse, Nikon Metrology, Europe) was used to perform the optical microscopy at 25 °C. Microscopic images of HSCO are shown in Fig. 5a which explained that the larger-sized spherical globules appeared in HSCO. Larger-sized globulite structure adheres to the smooth flowability in the pipeline. The effect of the addition of LSCO in HSCO decreases the size of wax particles, as shown in Fig. 5b. The addition of LSCO dispersed the globulite structure of wax particles into the rod-like structure. Therefore, the flowability of HSCO increases with the addition of LSCO. Hence, LSCO acts as a better wax inhibitor.

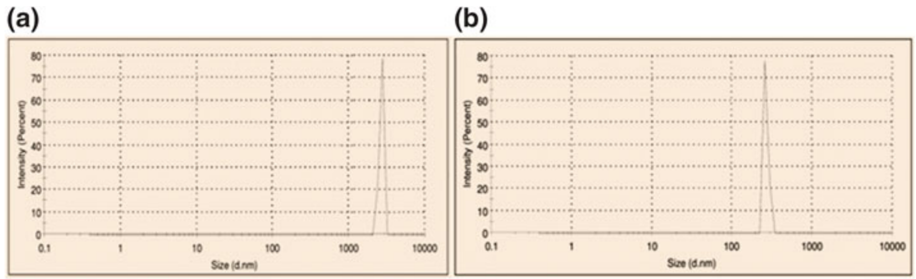

Fig. 4 Average particle size of **a** 100% HSCO paraffin crystals range from 2000 to 3100 nm and **b** 85% HCSO–15% LSCO crystal ranging from 210 to 350 nm

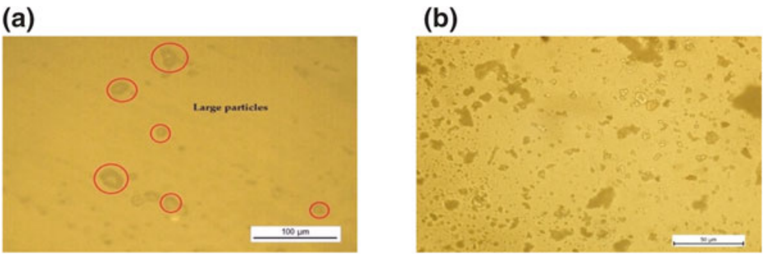

Fig. 5 Optical microscopic images of **a** 100% HSCO and **b** 85% HSCO + 15% LSCO

5 Conclusions

In the present study, the rheological behavior and microstructure of HSCO and its emulsions were investigated. LSCO was used as additives for HSCO at three concentrations. Dynamic light scattering (DLS) and optical microscopy (OS) of crude oil and its emulsions were performed. Rheological results reveal that the presence of LSCO in HSCO approximately eliminates its thixotropic behavior. HSCO shows the non-Newtonian shear thinning characteristics. As the temperature increases, the viscosity of crude oil decreases and shows the Newtonian flow behavior at 45 °C. The addition of LSCO as an additive in HSCO can be useful for the design of crude oil pipeline transportation system. It was found that the HSCO with HSCO–LSCO mixture has a lesser degree of aliphaticity as compared to pure HSCO. Optical microscopy also confirms that the addition of LSCO causes a drastic change in shape of HSCO wax crystals from globules to a rod-like structure which improves its flowability.

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