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Study on A Method for Measuring the Viscosity Of High Water-Content Heavy Oil-Water Mixture

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Abstract **-** In Chinese heavy oil fields, the significant increase of water content in the produced fluids has made high water-content heavy oil-water mixture more common. In the measurement of viscosity of high water-content heavy oil-water mixture, the rotational viscometer method (RVM) cannot be applied, and the current stirring method has a problem that heavy oil is unable to be stirred uniformly at low speeds and deviates from actual operating conditions at high speeds. A stirring method with alternating high and low stirring speeds was designed in this study. The high-low speed stirring method (HLSSM) utilizes a short window period during high speeds when oil and water were coarsely dispersed to realize the viscosity measurement at low speeds. Comparison experiments indicate that the viscosity measured by this method reflects the shear-thinning behavior of non-Newtonian fluid, which is consistent with theoretical expectations. Furthermore, compared with the flow loop method (FLM), the average relative deviation for Oil A is 6.16%, with an average absolute deviation of 3.23 mPa·s, and for Oil B, the average relative deviation is 2.61%, with an average absolute deviation of 3.69 mPa·s, demonstrating that the testing accuracy meets the engineering requirement. This method not only shares the advantages of simple operation and continuous measurement with RVM but also overcome the issue of high cost associated with FLM.

Keywords**:** high water-content heavy oil-water mixture; viscosity measurement; high-low speed stirring method

1. Introduction

The increasing energy demand in the early 21st century has led many countries to focus on the development of heavy oil [1,2]. For China, most of the heavy oil fields have entered the middle to late stage of exploitation. The water content of produced fluids has significantly increased, making high water-content heavy oil-water mixture more common [3,4]. Viscosity is the most important parameter of flow characteristics. However, oil is difficult to emulsify in water generally, which makes the fluid in the pipeline exists in a suspension system of water-in-oil emulsion coexisting with free water even under high water-content conditions [5]. For this system, oil and water phases are easily stratified, resulting the system non-uniform and unstable. This makes the conventional rotational viscometer method (RVM) unsuitable for measuring its viscosity [6]. The viscosity measurement method based on flow loop can calculate viscosity through pressure drop inversion. The flow pattern of the fluid is close to the actual pipeline, resulting in high accuracy [7]. However, the flow loop method (FLM) has the problems of complicated experimental apparatus, long time consuming and high oil consumption, which is not suitable for popularization. Therefore, it is necessary to explore a method applicable for the measurement of viscosity of high water-content heavy oil-water system.

The viscosity measurement method based on stirring can maintain the uniformity of the mixture, thereby correlating parameters such as shaft torque of the stirrer and stirring speed to calculate viscosity [8]. Compared with RVM and FLM, the stirring method not only shares the advantages of simple operation and continuous measurement with RVM but also overcome the issue of high cost associated with FLM. Therefore, the stirring method has been favored by researchers in viscosity measurements of non-uniform mixing systems. The stirring method was initially used to study the stability of water-in-oil emulsions and their rheological properties [9,10]. Yu et al. refined the theory of stirring viscosity measurement and proposed a calculation method for viscosity and shear rate of fluid in stirring tank under different flow patterns [8]. This has significantly advanced the study of viscosity of such oil-water mixtures with a wide range of applications [11-14]. However, it is worth noting that this method did not take into account the effect of properties of experimental mediums. On the one hand, heavy oil has the characteristics of high density and high viscosity [15]. According to the theory of stirring viscosity measurement, a higher stirring speed is required to form a uniform coarse dispersion system of heavy oil in water. On the other hand, the shear rate of the fluid in the stirring tank is approximately a quadratic function of the stirring speed, and an increase in stirring speed leads to a multiplicative increase in the shear rate [11]. For example, for low-viscosity waxy oil, typically only a stirring speed of around 200 revolutions per minute (rpm) is required for uniformization. For heavy oil, the stirring speed needs to exceed 1000 rpm, leading to nearly a tenfold increase in the shear rate. The key of the stirring method lies in utilizing the "shear rate" as a "bridge" to simulate actual pipe flow. This alteration results in a significantly higher shear rate in the stirring tank compared to the actual pipeline, rendering the measured viscosity lacking practical significance.

According to the limitations of the aforementioned methods, a stirring method with alternating high and low stirring speeds was designed in this study. It utilizes a short window period during high speeds when oil and water were coarsely dispersed to realize the viscosity measurement at low speeds. Additionally, compared with FLM, the applicability of this method for measuring the viscosity of high water-content heavy oil-water mixture was validated.

2. Materials and methods

2.1. Materials

Two types of heavy oil, obtained from an oil field in China, was used for experiment. The oil samples were labeled as Oil A and Oil B, with their physical properties outlined in Table 1.

Table 1: Basic physical properties of the oil samples.

Items	Oil A	Oil B
Pour point (°C)	5	8
°API	23.52	19.82
Specific gravity at 20 °C	0.9128	0.9351
Viscosity at 50 °C (mPa·s)	497	1004
Wax content (wt.%)	1.8	<1
Saturates content (wt.%)	33.93	31.35
Aromatics content (wt.%)	26.35	26.96
Resins content (wt.%)	17.48	18.97
Asphaltenes content (wt.%)	2.22	2.73

2.2. Experimental apparatus

2.2.1. Apparatus of high-low speed stirring method

An apparatus of high-low speed stirring method (HLSSM) is used for measuring the viscosity of oil-water mixture. The apparatus, as shown in Fig. 1, is mainly composed of four parts: a) A stirring unit, connected by a stirrer (IKA MINISTAR-20), two shaft couplings, a torque sensor (CYN-023) and an impeller. The stirring speed range of the stirrer is 10 to 2000 rpm. A flat impeller is chosen for better oil-water mixing effect; b) A stirring tank, made of transparent acrylic material for easy observation. It is externally attached with a water jacket; c) A torquemeter, connected to the torque sensor, for measuring the torque of the stirring shaft. Its measuring range is 0 to 5 N·cm and the accuracy is 0.005 N·cm; d) A circulating water bath, connected to the water jacket of the stirring tank to control the temperature of the mixture. Its temperature control accuracy is 0.01 °C.

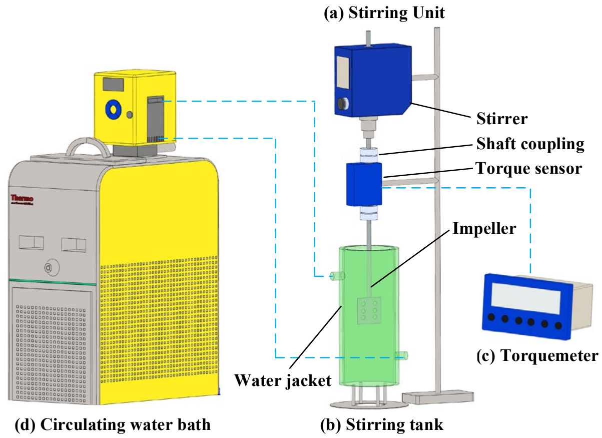


Fig. 1: Schematic diagram of apparatus of HLSSM.

2.2.2. Flow loop apparatus

In this study, the flow loop apparatus is used to validate the accuracy of HLSSM. The apparatus, as shown in Fig. 2, consists of oil-water mixing tank, circulating water bath, screw pump, stainless steel pipeline, mass flowmeter, temperature sensor and differential pressure sensor. The total length of the pipeline is 12 m with an inner diameter of 29 mm, including a test pipe section of 1 m. In the experiment, the oil-water mixture to be tested is poured into the tank, and the stirring impeller in the tank is initiated to make the mixture uniformly mixed. The screw pump is then activated to pump the fluid into the pipeline. Simultaneously, the temperature of the oil-water mixing tank and the pipeline is accurately controlled by the circulating water bath. Finally, after the flow is relatively stabilized, the pressure gradient of the test pipe section is recorded. The viscosity of the mixture is back-calculated according to Darcy's formula and the formula for friction factor.

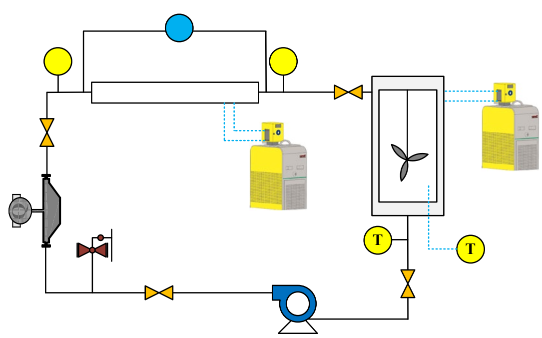


Fig. 2: Schematic diagram of flow loop apparatus.

2.3. Experimental principle

Considering the high viscosity characteristics of heavy oil, a high-speed stirring condition should be pre-determined before viscosity measurement, where the oil-water mixture can maintain coarse dispersion. Furthermore, the dispersion state needs to be maintained for a period in order to take advantage of this window to measure viscosity using a low stirring speed. An oil-water mixture with 120 ml of 80% water content was tested at five low speeds (200 to 600 rpm) and one high speed (2000 rpm). The experimental temperature was kept constant at 50 °C and the stirring time was 10 min. Cui et al. evaluated the stability of the oil-water mixture, finding that the volume of free water precipitated from the mixture follows a logarithmic function over time [16]. Therefore, in this study, the stratification of the mixture was observed after 2 min of standing at the end of the stirring. If no significant stratification occurred, it is considered that the stirring condition can maintain the stability of the oil-water mixture for a short window period. As shown in Fig. 3, the stratification occurred rapidly after 2min of standing within the range of 200 to 600 rpm, while at 2000 rpm, the oil droplets were uniformly distributed in the water without significant stratification.

Fig. 3: Stratification status of the mixture after standing for 2 min.

Based on the results of the oil-water dispersion experiment, the above stirring condition should be applied beforehand to uniformly mix the oil-water mixture. Additionally, several low stirring speeds need to be selected for shear tests because the shear rates at these low speeds approximate those in actual pipeline flow. The viscosity measurement procedure is illustrated in Fig. 4. First, it is stirred at 2000 rpm for 10 min, and then changed to 200 rpm for 2 min. It is subsequently stirred at 2000 rpm for 10 min, then changed to 300 rpm for 2 min. And so on, until the 2000-rpm stir is 10 min and the 600-rpm stir is 2 min, so as to realize an alternating viscosity measurement procedure between high-speed stirring dispersion and low-speed shear test.

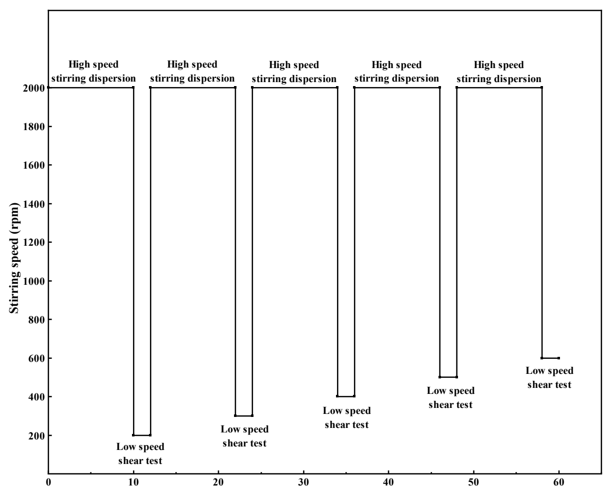


Fig. 4: Viscosity measurement procedure.

Two crucial issues in the application of the method involve determining the relationship between fluid viscosity and stirring shaft torque, as well as calculating the average shear rate of the fluid in the stirring tank. In terms of viscosity measurement, the relationship between viscosity, stirring speed and torque has been summarized in previous studies [8]. This relationship depends on the flow pattern in the stirring tank, and the flow pattern can be determined by stirring Reynolds number, defined as follows:

$$Re = \frac{D^2 n \rho}{\mu} \tag{1}$$

Where D is impeller diameter, m; n is stirring speed, r/s; ρ is liquid density, kg/m^3; μ is liquid viscosity, Pa·s.

When $Re \le 10$, the fluid in the stirring tank is in laminar flow. In this case, there is a linear relationship between viscosity and torque, as follows:

$$\mu = \frac{AM}{N} \tag{2}$$

Where A is torque constant; M is shaft torque, N·m; N is stirring speed, r/s.

When $10 < Re < 10000$, the fluid in the stirring tank is in transition flow. In this case, there is a power function relationship between viscosity and torque, as follows:

$$\mu = aM^{b} \tag{3}$$

Where a and b are parameters of the stirring system. For a specific stirring system, the values of a and b are only related to the stirring speed and not to the fluid properties.

From Eqs. (1) and (2), the parameters A, a, and b are independent of the fluid properties at a certain stirring speed. The torque of stirring shaft can be measured using several kinds of fluid with known viscosity, and the $\mu - M$ relationship at a given stirring speed can be calibrated by regression analysis.

The viscosity of non-Newtonian fluid varies with shear rate, so it is also necessary to calculate the fluid average shear rate corresponding to different stirring speeds. In this paper, the average shear rate of fluid in the stirring tank is calculated according to the equation proposed by Zhang et al. [17], as shown below. Thus, the $\mu - \bar{\dot{\gamma}}$ relationship is established.

$$\bar{\dot{\gamma}} = \sqrt{2\pi MN / (\mu V)} \tag{4}$$

Where V is volume of fluid in the stirring tank.

3. Results and discussion

3.1. Calibration of stirring system

14 kinds of Newtonian fluid with known viscosity were used to calibrate the stirring system. The relationship between viscosity and torque was fitted at five speeds respectively, as shown in Table 2. It can be seen that there are both laminar flow and transition flow conditions in the stirring tank during the calibration experiments. Therefore, linear fitting and power function fitting were used in the laminar and transition flow regions, respectively. The maximum experimental relative deviation of both is less than 8%, indicating that the relationship between viscosity and torque is consistent with the theory.

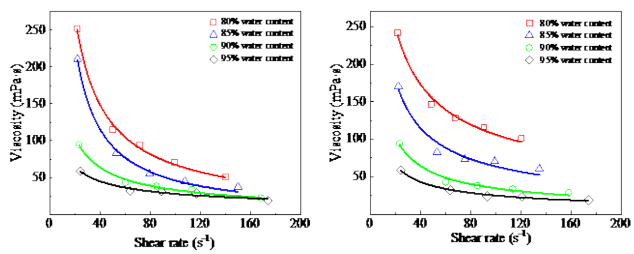
Table 2: Calibration results of stirring system.

Stirring speed (rpm)	Equation	Relative deviation (%)
200	$\mu = 2490.71M + 81.83$ ($Re \le 10$)	6.6
	$\mu = 5509.19M^{1.1597}$ ($10 < Re < 10000$)	5.7
300	$\mu = 2057.15M - 122.57$ ($Re \le 10$)	6.5
	$\mu = 4090.23M^{1.6191}$ ($10 < Re < 10000$)	4.9
400	$\mu = 1701.81M - 226.37$ ($Re \le 10$)	5.9
	$\mu = 2248.73M^{1.4865}$ ($10 < Re < 10000$)	3.5
500	$\mu = 1433.33M - 202.67$ ($Re \le 10$)	7.6

600	$\mu = 1250.05M^{1.5688}$ (10<*Re*<10000)	5.8
	$\mu = 1215.08M - 79.27$ (*Re*≤10)	3.9
	$\mu = 980.67M^{1.7871}$ (10<*Re*<10000)	6.9

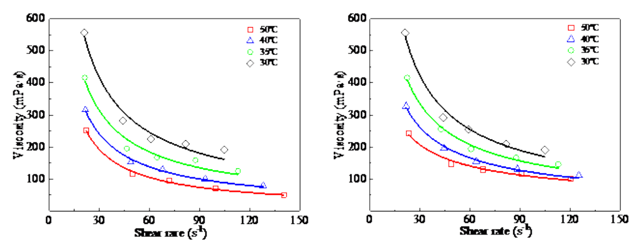
3.2 Reliability validation of the method

The flow characteristics of the mixture at different temperatures and water contents were measured by HLMMS. The flow characteristic curves for different water contents at 50 °C are shown in Fig. 5. The flow characteristic curves for different temperatures at 80% water content are shown in Fig. 6. It can be seen that the viscosity decreases with the increase of water content or the increase of temperature. The viscosity measured by this method shows the property of decreasing with the increase of shear rate, and this property is weakened with the increase of water content or temperature, which is due to the weakening of the influence of the oil phase viscosity on the viscosity of the mixture.



(b) Oil B

Fig. 5: Flow characteristic curves for different water contents at 50 °C.



(a) Oil A

(b) Oil B

Fig. 6: Flow characteristic curves for different temperatures at 80% water content.

Furthermore, the accuracy of the HLMMS was validated in comparison with FLM and the current stirring method. In FLM, the average shear rate in the pipeline is calculated based on energy dissipation rate, as shown below [18]. The current stirring method is a direct viscosity measurement method by using the same stirring system and stirring speed as HLMMS. The measurement results at 50°C and 80% water content are illustrated as an example, and the comparison results of the three measurement methods are shown in Fig. 7.

The flow characteristic curves of oil-water mixture determined by HLSSM are in general agreement with those determined by FLM. The average relative deviation for Oil A is 6.16%, with an average absolute deviation of 3.23 mPa·s, and for Oil B, the average relative deviation is 2.61%, with an average absolute deviation of 3.69 mPa·s, demonstrating that the testing accuracy meets the engineering requirement.

In addition, comparing the results of the current stirring method with those of FLM, it can be seen that the viscosities measured by the current stirring method are small and the relative deviations are large. This is due to the fact that oil and water are not sufficiently dispersed by the direct method of viscosity measurement with low stirring speeds. Most of the impeller is located in the water phase, resulting in only a small portion of oil affecting the torque, therefore the results are small. It is not feasible to measure the viscosity of high water-content heavy oil-water mixture by the current stirring method.

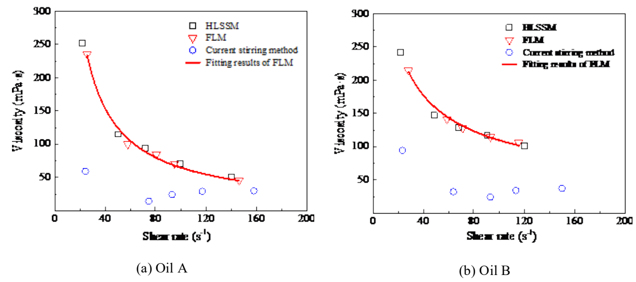


Fig. 7: Comparison results between HLSSM, FLM and the current stirring method

4. Conclusion

In the measurement of viscosity of high water-content heavy oil-water mixture, the current stirring method has a problem that heavy oil is unable to be stirred uniformly at low speeds and deviates from actual operating conditions at high speeds. A stirring method with alternating high and low stirring speeds was designed in this study. The HLSSM utilizes a short window period during high speeds when oil and water were coarsely dispersed to realize the viscosity measurement at low speeds. Comparison experiments indicate that the viscosity measured by this method reflects the shear-thinning behavior of non-Newtonian fluid, which is consistent with theoretical expectations. Furthermore, compared with FLM, the average relative deviation for Oil A is 6.16%, with an average absolute deviation of 3.23 mPa·s, and for Oil B, the average relative deviation is 2.61%, with an average absolute deviation of 3.69 mPa·s, demonstrating that the testing accuracy meets the engineering requirement. This method not only shares the advantages of simple operation and continuous measurement with RVM but also overcome the issue of high cost associated with FLM. Additionally, this method can be generalized for viscosity measurements in non-uniform mixtures with high viscosity of the dispersed phase.

The procedures of HLSSM are concluded as follows.

(1) **Preparatory experiment on stirring dispersion effect.**

According to the viscosity of the fluid to be tested, dispersion properties and the torque measurement range of the stirrer, the type and size of the stirring tank and stirring impeller should be appropriately selected. The mixture is stirred at the experimental temperature to observe the dispersion effect. A suitable stirring speed and stirring time should be determined, so that the mixture can maintain a 2–3 min window period of coarse dispersion, without obvious stratification. This stirring condition is the condition of high-speed stirring dispersion.

(2) **Calibration of stirring system.**

The stirring speed of low-speed shear test is determined by the shear rate range of actual pipeline, and the stirring time is fixed at 1–2 min, which is to ensure that the mixture is within the window period of coarse dispersion. Using several kinds of Newtonian fluid of different viscosity, the stirring shaft torques are measured at the calibrated stirring speed. The relationship between viscosity μ and torque M at different stirring speeds is established by regression analysis.

(3) **Collaborative measurement alternating high-low speeds**

High-speed stirring condition is collaborated with low-speed stirring condition for viscosity measurement. That is, the mixture needs to be dispersed in the high-speed stirring condition before testing the torque in each low-speed stirring condition. And the stable torque M at low speed is recorded.

(4) **Calculation of viscosity and shear rate**

Based on the calibrated relationship between μ and M, the fluid viscosity is calculated. The shear rate corresponding to the viscosity is calculated according to the equation for the average shear rate in the stirring tank. Then, the correspondence of $\mu - \bar{\dot{\gamma}}$ can be obtained to complete the flow characteristic measurement of the mixture.

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