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Abstract: The study focuses on the flow patterns and pressure drop characteristics of three crude oils and water in a horizontal pipe. The experimental results showed that the transformation boundary of the flow pattern and phase inversion water fraction were related to the flow parameters. Comparing the three oils, it was found that the viscosity and composition of the oil also significantly influence the flow performance, which can be explained by the adsorption properties of the asphaltenes at the oil-water interface. In particular, the droplet size in water-in-oil dispersion flow was observed and measured. It showed that the water droplet size decreased with the increase of oil viscosity, the decrease of water content, the drop of temperature, and the growth of mixing velocity, probably due to higher shear stress and lower frequency of collision and coalescence between droplets. The apparent viscosity of water-in-oil emulsions was calculated by the rheological model, and the qualitative relation between flow parameters and interfacial area concentration on apparent viscosity was obtained. Taking the influence of interfacial area concentration into consideration, a simple and accurate viscosity model was established based on dimensional analysis, which is of great significance for process design in gathering and transportation systems.

**Keywords:** oil-water flow; pressure gradient; droplet size; interfacial area concentration; viscosity model

# 1. Introduction

With oilfield exploitation entering the stage of high water cut, oil-water two-phase flow has become one of the main forms of pipeline transportation in the petroleum and chemical industry [1,2]. The study of oil-water flow is of great significance for improving the theory of multiphase flow and transportation efficiency. Flow pattern [3–5] and its transformation characteristics [6–8], pressure drop [9–11], and reverse phase characteristics [12–14] are the focus of current research for oil-water two-phase flow.

Some experiments of oil-water flow with non-crude oil, such as white oil and kerosene, indicate that oil-water flow patterns can be divided into stratified flow, dispersed flow, and mixed flow [3,6,15,16]. In particular, the flow pattern can be further subdivided according to the change in the oil-water interface [7,15]. Compared to mineral oil, the composition of crude oil is complex, and stable emulsions in pipelines and separation equipment caused by the asphaltenes lead to the higher cost of crude oil transportation and lower separation efficiency [17,18]. That is, the two-phase flow patterns of crude oil-water are more diverse. For example, the intermittent flow and annular flow mostly appeared in the highly viscous two-phase flow found by Bannwart et al. [19]. The semi-annular flow [11] and multi-mixed flow pattern [20] have also been discovered in experiments.

It is found that the droplet size is an important factor in determining the rheology and stability of dispersed flow [12,21]. In recent years, several methods have been applied to



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**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). measure droplet size in tubes, such as the conductance probe method [22,23], the dynamic light scattering technique [24–26], the focused beam reflection measurement (FBRM) [27], and particle video microscopy (PVM) [28], and Brown and Pitt [29] and Chatzi and Kiparisside [30] pointed out that the droplet size distribution was affected by the dispersed phase fraction. The experimental results of Vankova et al. [31] showed that the size of oil droplets in o/w emulsions changed with the oil volume fraction when the water volume content was less than 50%. Boxall et al. [32] measured the size of droplets with water content ranging from 10 to 20 vol% and found that the size distribution was independent of the volume fraction of the dispersed phase but had a well-behaved distribution with the log-normal distribution. Wahaibi et al. [33] studied the effect of mixture velocity on droplet size in oilwater dual continuous flow and reported that there was no significant difference between the size of the oil droplet and the water droplet. What's more, the droplet size was not observed to decrease with the mixture velocity increasing. The result was consistent with the findings of Yi et al. [34]. However, Gonzalez et al. [12] found that in a water-dominated dispersed flow, the oil droplet size decreased as the mixture velocity increased, but the mixture velocity had little influence on the size in oil continuous flow. In addition, the authors demonstrated that the impact of oil viscosity on droplet size in the water-dominated flow was smaller than that in the oil-dominated. And in the oil-dominated flow, the larger the oil viscosity, the smaller the droplet size. The results suggested that the variation of droplet size and flow velocity was influenced by dispersion state and oil properties.

The research on the viscosity of oil-water dispersion flow mainly focuses on the influence of temperature, velocity, oil properties, water content, etc., and most of the models are suitable for specific experimental conditions and working fluids [35,36]. These models can be classified into three categories: linear, power, and exponential function models. Table 1 shows some representative viscosity models. The development of these models indicates that the factors affecting viscosity are taken into account as more microcosmic, but the factors considered in a single model are still relatively simple and have poor universality. The droplet size in dispersed oil-water flow is one of the key microscopic parameters that affect the effective viscosity [28]. Pal and Rhodes [37] fully considered the interaction between dispersed droplets and proposed a semi-empirical model of oil-water mixture viscosity that was applicable to Newtonian and non-Newtonian fluids. Moreover, it was found in the subsequent experiments that the effective viscosity of the concentrated emulsion increased significantly with decreasing the droplet size for both kinds of emulsions [38]. Zhang and Xu [39] proposed the apparent viscosity model considering the particle size distribution of droplets and found that the viscosity increased with the decrease of the mean diameter. However, the experiment was carried out using the rheometer, which is different from the actual pipeline flow.

Table 1. Mixture viscosity models of oil-water two-phase flow.

Researchers	Viscosity Model	Application Condition	Remarks
Camy [40]	$\mu_{\rm m} = \mu_{\rm o} exp(k\phi_d)$	w/o&o/w	w/o: <i>k</i> = 3.8; o/w: <i>k</i> = 6.6.
Chen [41]	$\mu_{\rm m} = rac{\mu_{\rm o}}{1-\phi_{\rm w}}(1+rac{1.5\mu_{\rm w}\phi_{\rm w}}{\mu_{\rm o}+\mu_{\rm w}})$	w/o	Take into account the effect of viscosity of oil and water phase and the volume fraction of dispersed phase.
Pal and Rhodes [42]	$\mu_{\rm m} = \mu_{\rm c} (1 - 0.8415 \frac{\phi}{\phi_{100}})^{-2.5}$	w/o&o/w	$\phi_{100}$ is the volume fraction of dispersed phase which give 100 times the single-phase viscosity.
Wang [43]	$\eta_{\rm r}^{2/5} \left(\frac{\eta_{\rm r}+2.5K}{1+2.5K}\right)^{3/5} = (1 - K_{\rm f}(\phi) \cdot K_{\rm f}(N_{Re,\rm p}) \cdot \phi_{\rm d})^{-1}$	w/o&o/w	$K_{\rm f}(N_{Re,p})$ is the droplet Reynolds number factor relate to the shear action and size of droplet.
Pal [44])	$\eta_{\rm r} \left[ \frac{2\eta_{\rm r} + 5\varepsilon_{\rm m}/(1-\varepsilon_{\rm m})}{2+5\varepsilon_{\rm m}/(1-\varepsilon_{\rm m})} \right]^{3/2} = f(\phi_{\rm d})$	o/w	Considered the influence of shear rate and interfacial rheology, $\phi_d$ is the volume fraction of dispersed phase, $\varepsilon_m$ is the interfacial mobility parameter.

	Table 1. Cont.			
Researchers	Viscosity Model	Application Condition	Remarks	
Zhang and Xu [39]	$\eta_{\rm r} = \exp(rac{2.5arepsilon_{ m d}}{1-k_{ m c}arepsilon_{ m d}}) (rac{\mu_{ m d}}{\mu_{ m c}})^h$	w/o&o/w	<i>h</i> is determined by the dispersed phase distribution and the ratio of the viscosity between dispersed phase and continuous phase.	

In this work, the experiments were carried out in horizontal oil-water flow with three crude oils. Different flow structures and flow pattern transition boundaries were studied under the condition of a large flow velocity range and complete water content. Besides, we emphatically analyze the pressure drop characteristics and droplet characteristics of water-in-oil dispersion flow. Based on the analysis of flow parameters, the interfacial area concentration was introduced, and the relationship between interfacial area concentration and viscosity was investigated. A simple viscosity prediction model for water-in-oil emulsions was developed considering oil physical properties, flow parameters, and dispersed phase distribution characteristics. This work is beneficial for the in-depth understanding of oil-water two-phase flow in real oilfield production, and more accurate flow models can be established.

## 2. Experimental Section

# 2.1. Materials

The main parameters of the crude oils and water are shown in Table 2. The SARA analysis (including resins, asphaltenes, saturates, and aromatics) for three oils is illustrated in Table 3.

Fluids	Density (kg/m <sup>3</sup> )	Viscosity (mPa·s)	Interfacial Tension (mN/m)
crude oil A	792	1.01	41.72
crude oil B	850	7.16	47.68
crude oil C	893	65	54.98
water	990	0.546	

**Table 2.** Physical properties of the fluids at 50 °C.

#### Table 3. SARA of crude oil.

Fluids	Resins (wt%)	Asphaltenes (wt%)	Saturates (wt%)	Aromatics (wt%)
crude oil A	4.29	0.60	34.1	61.01
crude oil B	11.61	1.58	53.42	33.39
crude oil C	16.62	2.91	48.74	31.73

The range of experimental parameters, such as mixture velocity ( $v_m$ ), temperature (T), and water fraction (*WF*), were determined below: crude oil A:  $0.55 \le v_m \le 1.2 \text{ m/s}$ ,  $30 \le T \le 40 \text{ °C}$ ,  $0 \le WF \le 100\%$ ; crude oil B:  $0.3 \le v_m \le 2.0 \text{ m/s}$ ,  $40 \le T \le 60 \text{ °C}$ ,  $0 \le WF \le 100\%$ ; crude oil C:  $0.3 \le v_m \le 2.0 \text{ m/s}$ ,  $55 \le T \le 70 \text{ °C}$ ,  $0 \le WF \le 100\%$ .

#### 2.2. Experimental Apparatus

As shown in Figure 1, the experimental apparatus was mainly composed of a pipeline section, a mixture preparation section, and other temperature and pressure measurement sensors. The pipe loop section consisted of two parallel horizontal stainless-steel pipelines (25.8 mm inner diameter and 12 m length) and a return U-bend with a radius of 0.4 m. The

pipe is a double-layer casing structure. Dimethyl silicone oil was used as the temperature control medium in the casing, and the temperature was controlled by a water bath. In addition, the entire experimental system was coated with polyurethane material to reduce heat dissipation. Four temperature transmitters were used to measure the change in temperature along the pipe. Two differential pressure transducers installed over the main test section were used to observe the pressure development together with five pressure transmitters. At the 26 m long test section, there was a 0.5 m -long Perspex pipe section at an axial location of L/D = 600 from the inlet to ensure that the two-phase flow was well developed [45]. A self-made local sampling device was installed along the silica window to collect samples for observation.



Figure 1. Schematic of the temperature-controlled flow loop.

Firstly, the oil and water were added into the tank in a certain experimental ratio and heated to the experimental temperature with the water bath. Then, the propeller stirrer mixed the mixture at a constant speed of 150 r/min for 2 h. After that, the oil sample was kept at a constant temperature for 20 min to eliminate the shear history. The prepared mixture was transferred to the test loop by the screw pump and then returned to the tank through the pipeline flow. When the flow parameters were stable for a certain period of time, the process was switched (V5 was opened, V2 and V3 were closed), and the mixture was circulated in the pipeline. The data acquisition system along the loop monitored and recorded the flow parameters as the flow became stable. Besides, the industrial CCD camera (Work Power, China) and Canon EOS 90D camera (Canon, Japan) set up in the observation section recorded the flow structure, and the fluid samples obtained by the sampling valve were analyzed in detail.

## 2.3. Measurement of the Droplet Size

The parameters of water droplets in the microscopic images were measured and processed using the Image Pro Plus 6.0. In order to obtain accurate size, the number of droplets in each condition was more than 500.

The Sauter Mean Diameter (SMD) is introduced to characterize the variation of water droplet diameter.

$$d_{32} = \sum_{j=1}^{N} d_j^3 / \sum_{j=1}^{N} d_j^2 \tag{1}$$

where *N* is the number of droplets in the unit volume of the oil-water mixture and  $d_j$  is the diameter of droplet *j*.

## 3. Results

### 3.1. Flow Patterns

Visual photography, local sampling, microphotography and differential pressure analysis were used to identified and confirmed the two fluids flow patterns in horizontal tube. The examples of discriminating flow structures are shown in Appendix A. The crude oil-water flow can be mainly divided into water continuous flow and oil continuous flow, which contains five flow patterns, as shown in Figure 2.



**Figure 2.** Diagram of each flow pattern: (a) w/o dispersed flow; (b) w/o&w intermittent flow; (c) o/w dispersed flow; (d) w/o&w core-annular flow; (e) (w/o)/w flow.

(1) Oil continuous flow

**w/o dispersed flow**: In this flow regime, water is dispersed in the form of droplets into the oil.

**w/o&w intermittent flow**: The separated water phase appears at the bottom of the pipeline as the flow rate further increases, while a large amount of water-in-oil emulsion droplets are in the tube.

(2) Water continuous flow

Water droplets coalesce and collide to form a continuous water phase when the content of water is greater than the reverse point.

**o/w dispersed flow**: Oil droplets are shear broken by continuous water phase, forming a stable oil-in-water dispersion flow.

**w/o&w core-annular flow**: The water-in-oil emulsion is in the middle of the pipe, and the water is distributed around the pipe to form a water ring.

(w/o)/w flow: The oil blocks are continuously cut by the water flow and dispersed into different sizes and shapes.

As shown in Figures 3–5, three oils have different flow patterns under various temperatures, mixing flow rates, and water cut, especially for crude oil C, which forms a w/o&w core-annular and (w/o)/w flow in the water-dominated region besides o/w flow. This may be due to the high viscosity of oil C, which makes it difficult for water to break the oil block directly at the experimental flow velocity. In addition, the high concentration of asphaltenes and resins in oil are adsorbed at the oil-water interface, resulting in the great stability of water-in-oil droplets.



Figure 3. Flow regime maps under different experimental conditions for crude oil A.



Figure 4. Flow regime maps under different experimental conditions for crude oil B.

Furthermore, it is found that the flow pattern boundary moves towards the lower water fraction with the temperature decreasing. This is because the physical properties of oil are influenced by the temperature. On the one hand, the oil viscosity rises to a large value with decreasing temperature, causing the shear force on the liquid-liquid interface to increase. On the other hand, it has an adverse impact on the stability of the oil-water interface as surface tension increases induced by the decrease in temperature [17]. Therefore,



the collision and coalescence between water droplets in the oil are intensified, and the reverse phase is more likely to occur.

Figure 5. Flow regime maps under different experimental conditions for crude oil C.

### 3.2. Pressure Drop

Figure 6 shows the pressure drop change of three oils with water content at different flow rates. For oil A, with the increase of water content, the pressure drop first increases and then decreases. The difference in pressure drop between w/o and o/w flow is relatively small, but the resistance in the reversed-phase region is significantly increased. Comparing Figure 6a,b, it is found that the pressure drop of oil B with w/o dispersed flow is significantly greater than that of o/w flow because the viscosity of oil B is about seven times that of oil A and the flow resistance increases in the oil continuous flow. Similarly, the flow velocity has little effect on the pressure drop in the o/w flow. For crude oil C, the pressure gradient is largely affected by the mixture velocity in w/o flow. The intermittent flow occurs at higher flow velocity, and the water is in contact with the bottom of the pipe by which the wall fraction is reduced. In this inversion region, a new phenomenon appears: the pressure drop of a high flow rate is less than that of a low flow rate. In the water-dominated area, the resistance of w/o&w core-annular and (w/o)/w flow depend on the internal structure of the flow, and some drag reduction is observed.

The phase inversion water content of crude oil A, B, and C are approximately 0.45 (40 °C), 0.63 (40 °C) and 0.65 (55 °C), respectively. At the same temperature, we can observe the inversion water content of oil A lower compared to crude oil B, while the viscosity of crude oil A is much lower, which contradicts the conclusion of conclusion that the greater the viscosity, the smaller the inversion water content [46]. This shows that viscosity is not the only factor determining the inversion point. We analyze the inversion water content from the composition of crude oil. The content of asphaltenes and resins in oil A is smaller than that in oil B, but the ratio of (asphaltenes + resins)/(saturates + aromatics) is 0.15 and 0.05, respectively, indicating that the aggregation state of asphaltenes in oil B is more conducive to rapidly adsorb at the liquid-liquid interface and stabilize water droplets in the oil [18]. Therefore, it cannot easily form a continuous water flow.



**Figure 6.** Pressure gradient at different fluid velocities: (**a**) crude oil A at 40 °C; (**b**) crude oil B at 40 °C; (**c**) crude oil C at 55 °C (the dashed line indicates the inversion point).

The influence of temperature on the pressure drop of w/o flow is shown in Figure 7 and Table 4. The pressure drop for three oils is found to decrease with the growth of temperature. Besides, the pressure drop shows an increased tendency variation with the growing mixture velocity.



**Figure 7.** Influence of temperature on pressure gradient at different fluid velocities: (**a**) crude oil B with 47% water cut; (**b**) crude oil C with 50% water cut.

Table 4. Pressure gradient for crude oil A at different temperatures (50% water cut).

Temperature	Pressure Gradient (kPa/m)						
(°C)	0.55 m/s	0.65 m/s	0.76 m/s	0.88 m/s	0.99 m/s	1.1 m/s	1.21 m/s
30	1.09	1.40	1.80	2.19	2.77	3.28	3.79
40	0.99	1.26	1.61	1.99	2.57	3.09	3.57

The objective of this paper is to analyze the flow characteristics of water-in-oil dispersion flow, and other flow patterns will be studied in subsequent studies. Generally, oil viscosity, water fraction, mixture velocity, and temperature are analyzed to characterize the size of the water droplet.

# 3.3.1. Effect of Oil Viscosity

The influence of the oil viscosity on the droplet size is illustrated in Figure 8. It can be seen that the SMD of water droplets in crude oil B is obviously larger than that in crude oil C when the temperature and mixing velocity are constant, and the concentration of the dispersed phase is approximately equal. This is because the viscosity of crude oil C is nine times that of crude oil B. The higher the viscosity of the continuous phase, the greater the resistance of water droplets to collision and coalescence, making it difficult to form larger water droplets. Furthermore, the shear effect of the pump on the dispersed flow formed by crude oil C is greater than that of oil B, resulting in the difference in droplet size increases with the growth of fluid flow velocity.



**Figure 8.** Comparison of SMD of crude oil B with crude oil C ( $T = 60 \degree C$ ).

#### 3.3.2. Effect of Water Fraction

Water fraction significantly affects water droplet diameter. The relationship between the droplet size and the water fraction is shown in Figure 9. There are similar changing trends in droplet size for the three oils. Consistent with the finding by Ward and Knudsen [47], as the water fraction rises near the inverting point, the SMD of water droplets increases. The increase of SMD becomes larger when the water content is relatively high. The SMD curve of crude oil C at the velocity of 0.6 m/s is analyzed. The SMD of water droplets changes from 56.89 µm to 82.68 µm when the water content increases from 20% to 39%. In stark contrast, the SMD of water droplets increases obviously from 129.52  $\mu$ m with 50% water content to 188.56  $\mu$ m with 67% water content at the same velocity. It can be considered that the increase in SMD is due to the effect of water volume fraction and the concentration of asphaltenes and resins in oil. On the one hand, the greater the water content, the larger the surface area of water, and the greater the probability of collision and coalescence between water droplets. On the other hand, the resins and asphaltenes in the oil can adsorbed at the oil-water interface to stabilize water droplets in the oil [18]. At low water content, the content of asphaltenes decreases as the volume fraction of continuous phase decreases, while there is still enough to adsorb at the surface of the increased water droplets and reduce the collision and coalescence of water droplets, leading to little difference in the SMD. As the water content exceeds 40%, the amount of water droplets increases

rapidly while the content of asphaltenes decreases significantly, which contributes to the higher collision frequency and coalescence probability of "bare" water droplets. Thus, the SMD is rapidly increased.



**Figure 9.** Effect of the water fraction on SMD at different flow velocities: (**a**) crude oil A ( $T = 40 \degree$ C); (**b**) crude oil B ( $T = 60 \degree$ C); (**c**) crude oil C ( $T = 60 \degree$ C).

### 3.3.3. Effect of Temperature

Figure 10 displays the effect of temperature on SMD for crude oils B and C. Increasing the temperature improves the SMD on the condition of different velocities for crude oils B and C. In this case, on the one hand, the oil-water viscosity ratio decreases with the increment of temperature, and the shear and disturbance effects on water droplets are reduced, resulting in the collision between water droplets is more likely to occur. On the other hand, the interfacial tension decreases with the temperature increasing, but the asphaltene aggregates will disassociate at high temperatures, resulting in the transformation of the interfacial film structure, weakening the rigidity of the interfacial film and causing the water droplets in the oil to become unstable [48]. Therefore, the water droplets are more likely to collide and coalesce into bigger droplets at a higher temperature.



**Figure 10.** Effect of the temperature on SMD at different flow velocities: (**a**) crude oil B (WF = 0.47); (**b**) crude oil C (WF = 0.5).

### 3.3.4. Effect of Mixture Velocity

It is clear from Figure 11a that the SMD of water droplet generally decreases gradually with the increase of mixture velocity. However, with a constant water fraction of 10% and 30%, the SMD increases slightly as the flow velocity increases when the flow rate is greater than 1 m/s, and the size tends to be stable. This is due to the unstable flow disturbance with higher mixture velocity.



**Figure 11.** Effect of the mixture velocity on SMD: (**a**) crude oil A ( $T = 40 \degree$ C); (**b**) crude oil B (*WF* = 0.47); (**c**) crude oil C (*WF* = 0.5).

As shown in Figure 11b,c, increasing the flow rate leads to the decline in the water droplet diameter at a constant temperature, which is attributed to the shear effect of turbulence disturbance and the increase of pump speed on water droplets. In the case of a temperature of 60 °C, the curvature change occurs at the flow rate of 1.2 m/s, as shown in Figure 10b. When the flow rate is 1.6 m/s, the decline rate of the SMD increases first and then decreases again with the increase of mixture velocity. This indicates that there is a maximum difference between the breakup velocity and the convergence velocity of water droplets at the mixture velocity of 1.6 m/s. Thus, the particle size changes greatly. As the flow rate continues to increase, the shear breakage and collision coalescence of water droplets gradually reach an equilibrium state, and the increase in disturbance makes it difficult to further reduce the size. At temperatures of 50 °C and 40 °C, it is found that the breakpoint appears at a larger mixing flow rate, which is mainly due to the large viscosity and larger external shear required.

#### 3.4. Apparent Viscosity Model

According to the rheological model theory [49], the experimental apparent viscosity is obtained:

$$\mu = K \dot{\gamma}^{n-1} \tag{2}$$

where  $\mu$  is the apparent viscosity, *K* is the consistency coefficient, *n* is the rheological index, and  $\dot{\gamma}$  is the shear rate. The calculation of viscosity is shown in Appendix B.

### 3.4.1. Effect of Flow Parameters on the Apparent Viscosity

Figures 12–14 show the influence of flow velocity, water content and temperature on the apparent viscosity of the three oils. The relationship between the viscosity of oils and flow velocity as shown in Figure 12. The viscosity of the three oils is changed with the increase of mixture flow rate, which indicates that the mixture belongs to non-Newtonian fluids.



**Figure 12.** Effect of the mixture velocity on apparent viscosity: (**a**) crude oil A ( $T = 40 \degree$ C); (**b**) crude oil B (*WF* = 0.47); (**c**) crude oil C (*WF* = 0.5).



**Figure 13.** Effect of the water fraction on apparent viscosity: (**a**) crude oil A ( $T = 40 \degree C$ ); (**b**) crude oil B ( $T = 60 \degree C$ ); (**c**) crude oil C ( $T = 70 \degree C$ ).

(a)

Viscosity (mPa·s)





Temperature (°C)

**Figure 14.** Effect of the temperature on apparent viscosity: (a) crude oil B (WF = 0.47); (b) crude oil C (WF = 0.5).

Temperature (°C)

The apparent viscosity at different water fraction are compared in Figure 13. The apparent viscosity of oil-water mixture increases with the growing of water content in w/o flow. The increasing water content lead to the larger SMD of water droplets (see Figure 9), which is benefit to the collision between water droplets, water droplets and continuous oil phase. The higher interphase friction result in the increasing of viscosity. For oil B and C, the viscosity is the exponential growth with the amount of water fraction, which demonstrates that the water content has a greater effect on the viscosity when the water content is high.

As seen in Figure 14, the viscosity decreases as the temperature increases. Taking crude oil B and flow rate of 2 m/s as an example, when the temperature increases from 40 °C to 60 °C, the apparent viscosity of the oil B decreases from 388 mPa·s to 160 mPa·s. This is because that viscosity of the continuous oil phase is greatly affected by the temperature. The higher the temperature, the longer intermolecular spacing within the oil, the weaker the interaction, thus the viscosity is decreased.

### 3.4.2. Effect of Interfacial Area Concentration on the Apparent Viscosity

The interfacial characteristics were used to understand the interfacial transfer of mass, momentum, and energy and further provide the necessary parameters for the two-fluid model [50,51]. Several experimental results showed that the interfacial area concentration of bubbles was related to the gas-liquid flow rate [52,53] and was affected by the coalescence and rupture between bubbles and turbulent eddies [54]. However, the study of interfacial area concentration for oil-water two-phase was relatively less. Moreover, the impact of interfacial area concentration on the viscosity was not studied. The above experimental results show that different flow parameters will form different droplet sizes, resulting in various interfacial areas of oil-water two-phase and viscosity. In this paper, we attempt to study the relationship between the interfacial area concentration and viscosity.

The interfacial area concentration,  $a_i$ , is defined as:

$$a_{i} = \sum_{j=1}^{N} S_{j} / V_{mix} = \pi \sum_{j=1}^{N} d_{j}^{2} / V_{mix}$$
(3)

where  $S_j$  is the surface area of droplets,  $m^2$ ;  $d_j$  is the diameter of the droplets, m;  $V_{mix}$  is the volume of oil-water two phase dispersed flow mixture,  $m^3$ ; and N is the total number of droplets.

It should be noted that the interfacial area concentration in this paper is the average interfacial area concentration on the cross-section of the sampling position. As shown in Figure 15, the apparent viscosity increases with increasing interfacial area concentration at various mixture velocities. The reason for this is that the contact area between the two

phases becomes larger with the increase of interfacial area concentration, which enhances the friction resistance. Besides, there is a growth trend for the interfacial area concentration as mixture velocity rises. The reason is considered to be directly related to the size of the droplet. The larger the mixture velocity, the bigger the shear action, the smaller the size, and the larger the number of the water droplets, which increases the interfacial area concentration.



**Figure 15.** Viscosity at different mixture velocities: (**a**) crude oil B at 60 °C; (**b**) crude oil C at 70 °C; (**c**) crude oil D at 40 °C.

### 3.4.3. The new Apparent Viscosity Model

The existing viscosity models do not fully consider the influencing factors, and the undetermined parameters contained in the model closely relate to the physical properties of oil and experimental conditions, which weakens the applicability of the models. Therefore, it is of great significance to establish a quantitative viscosity model which can be applied to different oil-water systems.

Based on the analysis of influencing factors, the viscosity of oil-water two-phase  $\mu_m$  can be derived using the following equation:

$$\mu_{\rm m} = f(\mu, \rho, v, WF, D, a_i) \tag{4}$$

where  $\mu_{\rm m}$  is the viscosity of mixture,  $\mu$  is the viscosity of single-phase fluid,  $\rho$  is the density of single-phase fluid, v is the flow velocity of fluid, *WF* is the water fraction, *D* is the inner diameter of tube, and  $a_i$  is the interfacial area concentration.

The parameters are dimensionless and are defined as:

$$N_{\rm m} = f(Re_{\rm so}, Re_{\rm sw}, WF, Fr_{\rm m}, A_{\rm c})$$
(5)

where the  $N_{\rm m}$ ,  $Re_{\rm so}$ ,  $Re_{\rm sw}$ ,  $Fr_{\rm m}$ , and  $A_{\rm c}$  can be described as  $N_{\rm m} = \sqrt{\rho_{\rm m}^2 g D^3}/\mu_{\rm m}$ ,  $Re_{\rm so} = \rho_{\rm o} v_{\rm so} D/\mu_{\rm o}$ ,  $Re_{\rm sw} = \rho_{\rm w} v_{\rm sw} D/\mu_{\rm w}$ ,  $Fr_{\rm m} = v_{\rm m}^2/gL$ , and  $A_{\rm c} = a_i D$ , respectively.

Therefore, the viscosity model of water-in-oil emulsion can be expressed as follows:

$$N_{\rm m} = a R e_{\rm so}{}^{b_1} R e_{\rm sw}{}^{b_2} W F^{b_3} F r_{\rm m}{}^{b_4} A_{\rm c}{}^{b_5} \tag{6}$$

The model constants a,  $b_1$ ,  $b_2$ ,  $b_3$ ,  $b_4$ , and  $b_5$  in the equation can be obtained by solving linear equations.

The viscosity model for crude oils A, B, and C can be expressed as:

$$\mu_{\rm m} = 442 \sqrt{\rho_{\rm m}^2 g D^3} / \left( R e_{\rm so}^{0.3758} R e_{\rm sw}^{0.1697} W F^{-1.0844} F r_{\rm m}^{-0.0319} A_{\rm c}^{-1.4185} \right)$$
(7)

$$\mu_{\rm m} = 9300 \sqrt{\rho_{\rm m}^2 g D^3} / \left( R e_{\rm so}^{3.5552} R e_{\rm sw}^{-1.8155} W F^{2.4175} F r_{\rm m}^{-0.8477} A_{\rm c}^{-0.2093} \right)$$
(8)

$$\mu_{\rm m} = 3.4 \sqrt{\rho_{\rm m}^2 g D^3} / \left( R e_{\rm so}^{1.8721} R e_{\rm sw}^{-1.2648} W F^{0.5656} F r_{\rm m}^{-0.3339} A_{\rm c}^{0.5387} \right) \tag{9}$$

The comparison of the experimental results with the predicted viscosity of water-in-oil emulsion is shown in Figure 16. As we can see, the calculation results of the model fit the viscosity data for different oils, among which the average relative errors are 10.1%, 4.8%, and 9.1% for oils A, B, and C, respectively. The maximum relative error remains within 18%, 15%, and 21% for oils A, B, and C, respectively, which is within the acceptable range. The reason for the difference is that there are statistical errors in droplet size when calculating the interfacial area concentration. The interfacial area concentration in this paper is just an average value over the sampling position. Actually, the interfacial area concentration varies with radial and axial positions [50]. In addition, the experimental apparent viscosity calculated according to the rheological model is one of the reasons for the error between the values of the model and the experiment.



**Figure 16.** Comparison of the predicted viscosity with experimental viscosity: (**a**) crude oil A; (**b**) crude oil B; (**c**) crude oil C.

## 4. Conclusions

In this study, with the help of visualization photographic image, real-time sampling, micro-photographing, and differential pressure fluctuation analysis, five main flow regimes were identified for three crude oils, namely w/o dispersed flow, w/o&w intermittent flow, w/o&w core-annular flow, (w/o)/w flow and o/w dispersed flow. The flow pattern and the boundary of flow were extremely affected by the water fraction, mixture velocity, and physical properties of oil. With the increase in temperature, the transition occurred at a higher water fraction. The high viscosity caused difficulty in forming the o/w dispersed

flow. The water fraction had a great effect on the pressure gradient, which implied the significant difference between the oil continuous flow and water continuous flow. The peak of pressure drop was observed at the inversion area. The phase inversion water fraction was related to the oil viscosity and composition, especially for the asphaltenes and resins. The high temperature contributed to the w/o dispersed flow.

The Influence of oil properties, water cut, temperature, and flow velocity on the Sauter Mean Diameter of water droplets in oil-dominant flow was analyzed. Its essence was that the flow parameters played an important role in breakup and collision coalescence of water droplets. Physical properties of crude oil also influenced the droplet size. Much smaller water droplets were observed in the oil phase when the asphaltenes and resins in crude oil had better adsorption at the oil-water interface.

Moreover, we explore the relationship between the interfacial area concentration and apparent viscosity, which shows that the apparent viscosity increases with the interfacial area concentration increasing. The quantitative relationship between oil-water interfacial concentration and mixture viscosity is proposed, which shows the predicted values are in good agreement with the experimental results. The difference is the error of the experimental apparent viscosity calculation method and the calculation error of interfacial area concentration caused by the inaccuracy of droplet data. The influence of oil-water interfacial characteristics on flow characteristics is clearly given, which has certain guiding significance for the research on oil-water two-phase flow characteristics and actual production work.

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### Appendix A

The flow pattern is determined by a combination of visual photography, local sampling, microphotography, and differential pressure analysis. Five different flow patterns are distinguished as follows. For continuous oil flow, the pipe wall is obscured by black crude oil, which makes it hard to observe the flow structure with the help of a photographic image. For w/o dispersed flow, the pressure drop is larger when the water content is high, but the amplitude changes with time, and the water droplets are dispersed in the oil from the microscopic image, as shown in Figure A1. For w/o&w intermittent flow, the pressure drop fluctuates greatly with a certain periodicity, and the compound droplets appear on the microscopic image, as shown in Figure A2. For water continuous flow, the fluctuation of pressure is small for three flow patterns, and the flow pattern can be easily distinguished by visual images and micrographs, as shown in Figures A3–A5.

(1) w/o dispersed flow





**Figure A1.** Visual photography, microphotography, and the change of differential pressure for oil C with w/o dispersed flow.

(2) w/o&w intermittent flow



Microphotography

**Figure A2.** Visual photography, microphotography and the change of differential pressure for oil C with w/o&w intermittent flow.

(3) w/o&w core-annular flow



**Figure A3.** Visual photography, microphotography and the change of differential pressure for oil C with w/o&w core-annular flow.

# (4) (w/o)/w flow



**Figure A4.** Visual photography, microphotography, and the change of differential pressure for oil C with (w/o)/w flow.

# (5) o/w dispersed flow





**Figure A5.** Visual photography, microphotography, and the change of differential pressure for oil B with o/w dispersed flow.

#### Appendix B

In this paper, a Power law model is used to study the rheological properties of fluids. The oil-water emulsion is regarded as an incompressible homogeneous fluid with no obvious slip on the tube wall. The shear rate of a non-Newtonian fluid in a pipe can be calculated by Equation (A1):

$$\left(-\frac{du}{dr}\right)_{b} = \frac{8V}{D}\left(\frac{3n'+1}{4n'}\right) \tag{A1}$$

where u is the flow velocity at a point on the cross-section of the pipe flow, m/s; r is the distance from a point on the cross-section of the pipe flow to the center of the pipe, m; D is the inner diameter of the pipeline, m; and V is the average flow rate of the fluid, m/s.

The shear stress on the pipe wall is expressed as:

$$\tau_{\rm b} = \frac{\Delta PD}{4L} \tag{A2}$$

where  $\tau_b$  is shear stress, N/m<sup>2</sup>;  $\Delta P$  is the pressure difference, Pa; *L* is the pipe length corresponding to the measurement of pressure difference, m.

Therefore, for the power-law fluid, it can be obtained:

$$\frac{\Delta PD}{4L} = K \left(\frac{8V}{D} \frac{3n'+1}{4n'}\right)^n \tag{A3}$$

Taking the logarithm of both sides simultaneously:

$$\ln\left(\frac{\Delta PD}{4L}\right) = n\ln\left(\frac{8V}{D}\right) + \ln\left[K\left(\frac{3n'+1}{4n'}\right)^n\right]$$
(A4)

Plot on double logarithmic coordinates with  $\frac{8V}{D}$  as the horizontal coordinate and  $\frac{\Delta PD}{4L}$  as the vertical coordinate, and obtain the fitting curve. *n* is the tangent slope of the corresponding point on the curve and  $K\left(\frac{3n'+1}{4n'}\right)^n$  is the corresponding intercept. For the power-law fluid, n' = n.

The experimental apparent viscosity is obtained by Equation (2). Taking the data of crude oil B at 60 °C as an example to calculate the viscosity, the results are shown in Table A1.

Table A1. The apparent viscosity of w/o emulsion formed by crude oil B at 40 °C.

WF	v <sub>m</sub> (m/s)	n	K	$\dot{\gamma}$	µ (mPa⋅s)
	0.3			94.67	107.52
	0.4			126.22	105.50
	0.6			189.33	102.72
	0.8			252.44	100.79
	0.9			283.99	100.01
0.2	1	0.9341	0.1452	315.55	99.31
	1.2			378.66	98.13
	1.4			441.77	97.13
	1.6			504.88	96.28
	1.8			567.99	95.54
	2			631.10	94.88
	0.3			91.08	168.62
	0.4			125.45	166.51
	0.6			188.17	163.59
	0.8			250.89	161.55
	0.9			282.25	160.72
0.3	1	0.9563	0.2056	313.62	159.98
	1.2			376.34	158.71
	1.4			439.06	157.65
	1.6			501.79	156.73
	1.8			564.51	155.93
	2			627.23	155.21
	0.3			94.67	458.86
	0.4			126.23	450.19
	0.6			189.35	438.26
	0.8			252.46	429.98
	0.9			284.02	426.64
0.52	1	0.9337	0.6204	315.58	423.67
	1.2			378.70	418.58
	1.4			441.81	414.33
	1.6			504.93	410.68
	1.8			568.04	407.49
	2			631.16	404.65

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