Scientific Research Publishing

Advances in Chemical Engineering and Science, 2019, 9, 299-316
https://www.scirp.org/journal/aces
ISSN Online: 2160-0406
ISSN Print: 2160-0392

The Influence of the Microstructure of W/O Emulsion of Waxy Crude Oil on Its Rheology

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How to cite this paper: Wei, L.X., Bi, H.M., Zhao, J., Dong, H., Wang, D.W. and Zhang, X. (2019) The Influence of the Microstructure of W/O Emulsion of Waxy Crude Oil on Its Rheology. *Advances in Chemical Engineering and Science*, **9**, 299-316.
https://doi.org/10.4236/aces.2019.94022

Received: August 13, 2019
Accepted: September 22, 2019
Published: September 25, 2019

Abstract

In this article, the viscosity-temperature characteristics of W/O waxy crude oil emulsion under different microstructures were studied, and the characteristics of the microstructure were described by the analysis of the dispersed phase parameters including the average particle size, the degree of dispersion, and the nonuniformity of average particle size. On this basis, we discuss the effects of temperature, shear rate and the microstructure on the apparent viscosity of Daqing crude oil emulsion. The results showed that with the increasing of stirring speed, the number of droplets and the degree of dispersion phase dispersion increased, average droplet size and nonuniformity of average particle size reduced; the average particle size of the dispersed phase decreased by 0.5 μm, and the abnormal point increased by about 1˚C. For emulsions with the same microstructure, as the temperature or shear rate rising, the rate and percentage of the reduction in apparent viscosity decreased. At the same temperature or shear rate, the reduction rate in apparent viscosity increases with the average particle size of dispersed phase decreases, in contrast to the percentage of reduction in apparent viscosity, which revealed a definitive correlation between average particle size of dispersed phase and the apparent viscosity in the non-Newtonian fluid that from 34˚C to 48˚C; the absolute value of Pearson's correlation coefficient was above 0.8, which was highly negatively correlated; as the temperature rose, the absolute value of Pearson's correlation coefficient decreased from 0.839 to 0.216.

Keywords

Microstructure, Crude Oil Emulsion, Rheological Test, Apparent Viscosity

1. Introduction

Crude oil emulsions are inevitably associated to the production and transportation of crude oil [1] [2], which are formed through the role of natural emulsifiers such as gums, asphaltenes, waxes and solid particles in crude oil [2] [3] [4] while the oil-water mixture is agitated through the oil nozzles, pipelines, centrifugal pumps, elbows, valves, etc., during the entire gathering and transportation process of oil production. Compared to crude oil, the nature of the emulsion is more complex and exhibits Newtonian or non-Newtonian fluids at different temperatures, which means a diversity of rheological properties. Especially in the state of the non-Newtonian fluid, the apparent viscosity of the emulsion exhibits different laws at the same temperature depending on the shear rate [5]. For example, mixing equipment design for emulsion production depends on the rheological properties of emulsions. The viscosity of fluid is an important parameter in determining the pressure drop along pipeline and its size. Therefore, the exploration of crude oil emulsion rheology is beneficial to the improvement of efficiency in production. Furthermore, the apparent viscosity of the crude oil emulsion is one of the key characteristics to have an insight into the rheological properties of the W/O emulsion, and it is necessary to conduct in-depth studies by the application of the transient multiphase flow simulator. Meanwhile, the apparent viscosity data of oil-water mixtures in transportation must be indispensable [6].

At present, there have been numerous studies on the rheological properties of crude oil emulsions which mostly focused on dispersed phase concentration, temperature and shear rate effects for developing an equation in order to predict emulsion viscosity [7]-[17]. However, for wax-containing crude oil emulsions with the same water content, there are relatively few studies about the regularity of the abnormal point and apparent viscosity changes under different microstructures, and the microstructure of the emulsion is considered to be one of the keys to determine the rheological properties of the emulsion [1]. Therefore, using Daqing crude oil as a sample, it is significant to study the rheological behavior of the high waxy crude oil emulsion and its microstructure and to analyze the internal mechanism between the two.

2. Experiment Process

2.1. Experimental Apparatus

Experimental apparatus and materials are listed in **Table 1**.

2.2. Experimental Procedure

2.2.1. Crude Oil Pretreatment

The Daqing crude oil as an experimental sample was pretreated, which was in a solid-state at room temperature. The sample which had been placed in a water bath thermostat was heated to 80˚C, stirred for 2 h at a constant speed of 1000 rpm by using IKA RW20 Digital Stirrer and then kept for 2 h at a constant temperature. It naturally got cooling to room temperature and was stored for 48 h in a dark place [18].

Table 1. Experimental apparatus and materials list.

Apparatus	Quantity/Accuracy
Rheolab QC Rotary Rheometer (Anton Paar, Austria)	0.01 mPa·s
SC/AC-S Water Bath Thermostat (Thermo Scientific)	0.01˚C
IKA RW20 Digital Stirrer	0.01 rpm
LV100NPOL Nikon Microscope	0.001 μm
Electronic scale	0.1 g
Electric blast drying box	0.1˚C
Beakers	Several
Daqing crude oil	Several
Distilled water	Several
Iron stand	1

2.2.2. Emulsion Preparation

The formation of an emulsion with two immiscible liquid phases is a process in which the interfacial area increased, and this process is non-spontaneously performed without non-volumetric work. Therefore, it is necessary to make the two immiscible liquid phases to form an emulsion by working or dispersing means such as shaking or shearing. According to Ronningsen [19], in the process of preparing crude oil emulsion, prolonging the stirring time and increasing the stirring rate will lead to the decrease of the average particle size of the droplets of the dispersed phase, which will increase the apparent viscosity. In order to further investigate the influence of the microstructure of the crude oil emulsion on the rheology of the emulsion, crude oil emulsions were prepared at different stirring speeds.

The pretreated oil sample and the beaker containing distilled water were placed in SC/AC-S Water Bath Thermostat and heated to 50˚C which should be kept for 30 min. The quality of crude oil and water needed to prepare an emulsion with a water cut of 10% were calculated. After being loaded in beakers, they were weighted on the scale and fixed in a water bath incubator. According to the spontaneous downward trend of the Gibbs function, that is, the tendency of the droplets of the dispersed phase to spontaneously agglomerate and increase their size, which cause the emulsion to be destroyed, an appropriate stirring rate and stirring time must be selected to ensure that the crude oil emulsion will not break during the experiment: The oil-water mixture was stirred for 10 min by using an IKA stirrer and then three kinds of W/O emulsions were prepared at a stirring rate of 950 rpm, 1150 rpm, and 1450 rpm, respectively.

2.2.3. Viscosity and Temperature Characteristics Test

The experimental oil sample was Daqing crude oil, which has the characteristics of high wax content, high freezing point, and complex rheology at low temperature. To prepare crude oil emulsion with a water cut of 10%, the set temperature was 50˚C, the stirring time was 10 min, and the stirring rates were 950 rpm, 1150 rpm, and 1450 rpm, respectively. For different crude oil emulsions, the rheometer was used to measure the tendency of the apparent viscosity of crude oil emulsion prepared at different shear rates and different temperature points and the results were compared and analyzed with those of crude oil.

The specific experimental scheme was as follows: with the rotational viscometer method [20], crude oil emulsions or crude oils which were prepared at different stirring rates and stood at a constant temperature of 50˚C, were cut at six shear rates from low to high, *i.e.* at constant shear rates of 10 s^{-1}, 20 s^{-1}, 50 s^{-1}, 80 s^{-1}, 100 s^{-1} and 150 s^{-1}. When crude oil emulsions or crude oils were cut at the lower temperature, the apparent viscosity did not basically change with time in order to make the fluid reach the dynamic balance state. When they were cut at a higher temperature, the shearing time required for each shear rate was only 10 minutes which was shorter than the set required shearing time—30 min, due to the Newtonian fluid characteristics of the emulsion. From the experimental data, the viscosity-temperature curve could be derived, which reflected the regularity between the apparent viscosity and temperature of crude oil and its emulsion. The above processes were repeated at temperatures of 34˚C, 36˚C, 38˚C, 40˚C, 42˚C, 44˚C, 46˚C, 48˚C, and 50˚C, respectively, and the viscosity-temperature test of the crude oil emulsion and the crude oil were prepared at the stirring speed of 950 rpm, 1150 rpm and 1450 rpm with the above method. The results were compared and analyzed.

2.3. Uncertainty Analysis and Solution

1) In the previous process, the Daqing crude oil emulsion prepared by 800 rpm will demulsify within about 2 hours which means the stability of the emulsion is poor, and affects the precision of the experiment. In order to avoid the above situation, the stirring speed used in this study was 950 rpm, 1150 rpm, and 1450 rpm, and the stirring time was 10 min.

2) In the process of moving the prepared emulsion, there is a dissipation of temperature, which causes the apparent viscosity to increase.

3) Due to a small amount of heat history and shear history during the viscosity-temperature test, the crude oil or its emulsion needed to stand still for 30 minutes before each shearing motion in the experiment, so that the effect on the experimental test data was reduced to being negligible.

3. Experimental Results and Analysis

3.1. Microstructure

In the process of preparing crude oil emulsion, the different configuration conditions will affect the distribution of the dispersed phase particle size, which will affect the apparent viscosity. The description of waxy crude oils with different microstructures was based on the characteristic parameters of the disperse phase average particle size, the degree of dispersion and the nonuniformity of average particle size [21]. The specific calculation method is as follows:

1) The average particle size of the dispersed phase

The average particle size of the dispersed phase of the crude oil emulsion is calculated using the following formula:

$$d_{1,0} = \frac{\sum n_i d_i}{\sum n_i} \tag{1}$$

where d_i is the diameter of dispersed droplets, the unit is μm; n_i is the number of droplets with the diameter of d_i.

2) Dispersion of disperse phase

For a dispersed system, the specific surface area refers to the surface area (or interfacial area) of a unit volume (or unit mass) of the dispersed phase. The specific surface area can be used to indicate the degree of dispersion. A larger specific surface area indicates a greater degree of dispersion of the dispersed phase.

$$SA = \frac{6\sum n_i d_i^2}{\sum n_i d_i^3} \tag{2}$$

where SA is the specific surface area in units of μm^{-1}.

3) Nonuniformity of the average particle size of the dispersed phase.

The polydispersity PDI is used to describe the nonuniformity of the dispersion. The polydispersity of the nonuniform dispersion is larger than 1, and the larger of the value, the wider of the particle size distribution. Polydispersity is calculated using the following formula:

$$PDI = \frac{d_{2,1}}{d_{1,0}} \tag{3}$$

where $d_{2,1}$ is the average particle size of the system and is calculated using the following formula:

$$d_{2,1} = \frac{\sum n_i d_i^2}{\sum n_i d_i} \tag{4}$$

The parameters that determine the characteristics of the microstructure of the three kinds of emulsions were calculated according to the above method, as shown in **Table 2**, while the micrographs of the three emulsions taken by the LV100NPOL Nikon microscope are shown in **Figures 1-3**.

Table 2. Distribution data of particle size of crude oil emulsion with different stirring speed.

Stirring speed/rpm	Average particle size of dispersed phase/μm	Dispersion of disperse phase (specific surface area)/μm^{-1}	Nonuniformity of the average particle size of the dispersed phase (polydispersity)
950	8.624	0.546	1.14
1150	7.943	0.596	1.134
1450	7.467	0.606	1.082

As shown in **Figures 1-3** and **Table 2**, for crude emulsions, with the same water cut, the average particle size of droplets decreases with the increase of stirring rate; at the same time, the specific surface area will increase, which means the degree of dispersion of the dispersed phase will increase; increasing the stirring speed will decrease the polydispersity of the system and reduce the range of particle size distribution.

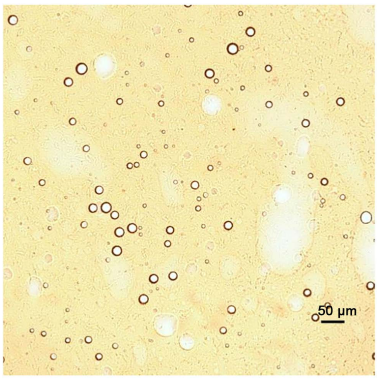

Figure 1. The micrograph of crude oil emulsion was prepared by 10% water cut and at the stirring speed of 950 rpm.

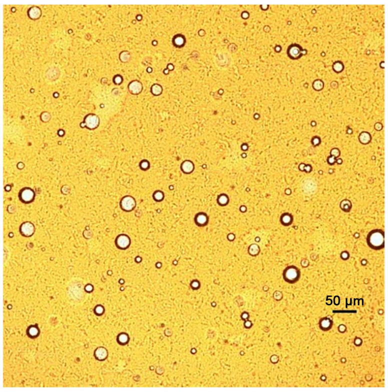

Figure 2. The micrograph of crude oil emulsion was prepared by 10% water cut and at the stirring speed of 1150 rpm.

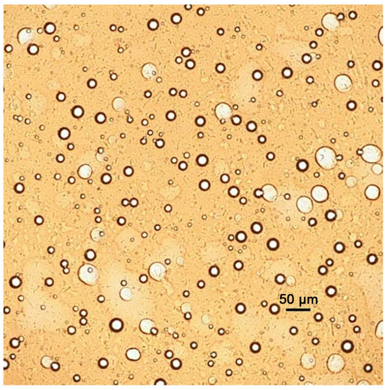

Figure 3. The micrograph of crude oil emulsion was prepared by 10% water cut and at the stirring speed of 1450 rpm.

The reasons for the above results are as follows: 1) The rotation of the impeller drives the tangential fluid moving in a tangent circle, to break the liquid into a larger liquid group and bring to everywhere, under the action of the high-velocity jet formed at the blade edge and the strong shear or high turbulence due to a large velocity gradient at the boundary of the surrounding fluid, vortices generate and disperse liquid globules into smaller scales that promote microscopic mixing. 2) The temperature for the preparation of the emulsion was 50˚C, the viscosity of the oil-water mixture was low, and a lot of vortices were generated during stirring. The vortexes of different sizes and intensities have different effects of crushing on the liquid mass. The smaller or stronger of the vortex size, the larger of the crushing effect, and the smaller of the liquid mass formed. 3) For the oil-water mixture system with the same water cut, the increase of the stirring speed of the preparation increases the turbulence intensity of the total fluid, and the ability to disperse the aqueous phase into smaller droplets is stronger. As a result, the number of droplets in the dispersed phase of the system increases, the average particle size decreases, and the degree of dispersion increases. At the same time, the stronger stirring results in more uniform distribution of the dispersed phase in the system, and the degree of polydispersity decreases.

3.2. Abnormal Point and Wax Precipitation Point

Analyzing the experimental data of crude oil and its three kinds of emulsions with different microstructures and comparing the four groups of viscosity-temperature test curves, it can be observed that there are significant differences.

As shown in **Figures 4-7**, for crude oils and emulsions at the same shear rate, the apparent viscosity decreases more and more slowly as the temperature rises, and the time required to achieve dynamic equilibrium becomes shorter and shorter. At the same temperature, with the increase of shear rate, the apparent viscosity of crude oil and its emulsion became smaller, and the decreasing speed was slower and slower. When the temperature rises to an abnormal point, the crude oil and its emulsion exhibit Newtonian fluid characteristics, and the apparent viscosity change is almost no longer affected by the shear rate and shearing time.

As the stirring speed increases, the average particle size of the dispersed phase of the crude oil emulsion decreases, the abnormal point (the lowest temperature point exhibiting Newtonian fluid characteristics) increases, and the wax precipitation point (the temperature point at which the fluid precipitates the wax crystal) do not change substantially. In order to improve the accuracy of the value of abnormal points, three apparent viscosity values corresponding to three continuous temperature points in the vicinity of the abnormal point are taken to draw a curve and then six curves are obtained by analogy. Find out the intersection of multiple curves, and calculate their average value which is the abnormal point. The resulting error is not more than 5%. As shown in **Table 3**, the crude oil

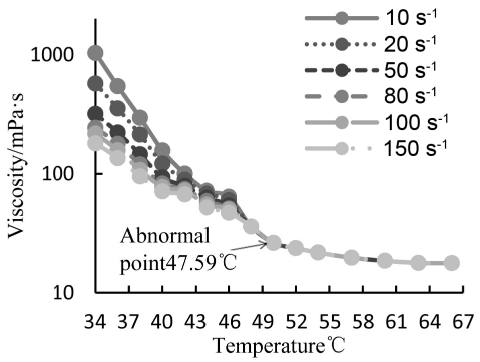

Figure 4. The viscosity-temperature curve of emulsion was prepared at 1150 rpm.

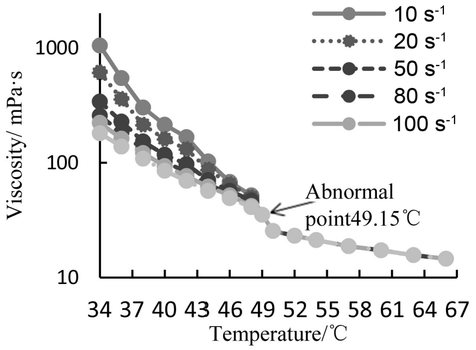

Figure 5. The viscosity-temperature curve of emulsion was prepared at 1450 rpm.

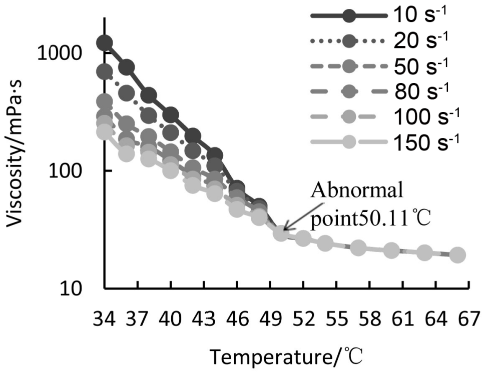

Figure 6. The viscosity-temperature curve of emulsion was prepared at 950 rpm.

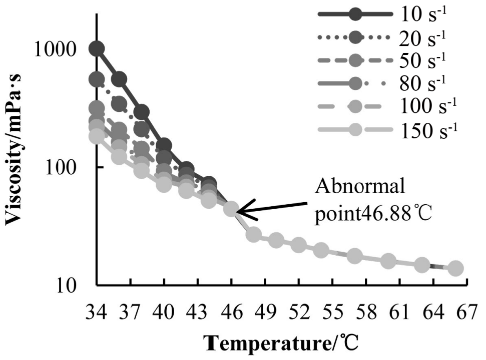

Figure 7. The viscosity-temperature curve of crude oil.

Table 3. Comparison between abnormal point and wax precipitation point of crude oil and emulsion.

Average particle size of dispersed phase/μm	7.467	7.943	8.624	Crude oil
Stirring speed/rpm	1450	1150	950	Crude oil
Abnormal point/˚C	50.11	49.15	47.59	46.88
Wax precipitation point/˚C	54	54	54	54

emulsion with the stirring speed of 1450 rpm has the highest abnormality point, the crude oil emulsion with the stirring rate of 1150 rpm has an abnormal point, the crude oil emulsion with the stirring rate of 950 rpm has an abnormal point again, and the crude oil abnormal point is the lowest. The discrepancy of abnormal points between the two crude oil emulsions with the average particle size of 7.467 μm and 7.943 μm is 0.96˚C. While the discrepancy of abnormal points between the two crude oil emulsions with the average particle size of 7.943 μm and 8.624 μm is 1.56˚C. According to the data, it can be calculated that when the average particle size of the dispersed phase decreases by 0.5 μm, the abnormal point increases by about 1˚C roughly.

Under the microstructure, the wax component in the crude oil and its emulsion is easy to form the three-dimensional network structure of wax crystals at a lower temperature [14], and impedes fluid flow and increases its apparent viscosity. With the increase of temperature and the increase of shear rate, the three-dimensional network structure of wax crystals has less and less influence on the apparent viscosity of crude oil and its emulsion. As shown in **Figure 8**, it can be seen that when the temperature is near the wax precipitation point, the crude oil and its emulsion exhibit Newtonian fluid characteristics, and the apparent viscosity drops faster when the temperature is before the wax precipitation point. That is to say, before the precipitation of the wax crystal, the wax component still has an influence on the apparent viscosity of the crude oil and its emulsion at a higher temperature.

3.3. Apparent Viscosity

3.3.1. Comparison of Apparent Viscosity at Different Temperatures

By comparing the viscosity and temperature test data of crude oil emulsions, the effect of different average particle size of dispersed phase on the rheology of crude oil emulsion can be revealed.

At the same temperature, the apparent viscosity of the crude oil emulsion at the six shear rates, respectively, was averaged for comparison. As shown in **Table 4**, the apparent viscosities of crude oil emulsions decrease with increasing temperature. With the other experimental conditions unchanged, the apparent viscosity of the crude oil emulsion with the smaller average particle size of the dispersed phase is higher than the apparent viscosity of the crude oil emulsion with the larger average particle size of the dispersed phase. It means the apparent viscosity of the crude oil emulsion increases with the decrease of the average

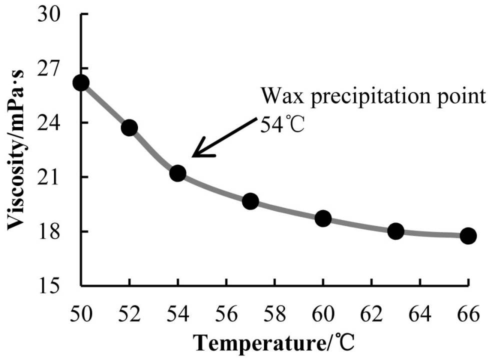

Figure 8. Wax precipitation point of crude oil emulsion was prepared at the stirring speed.

Table 4. Average apparent viscosity of crude oil and three kinds of emulsions at the same temperature.

Temperature/˚C	34	36	38	40	42
Average particle size of dispersed phase/μm	Viscosity/mPa·s	Viscosity/mPa·s	Viscosity/mPa·s	Viscosity/mPa·s	Viscosity/mPa·s
8.624	426.67	264.48	162.55	100.43	80.17
7.943	443.12	269.11	171.44	128.79	103.99
7.467	478.83	325.17	226	164.67	117
Crude oil	420.33	256.17	160.17	99.167	76.33
Temperature/˚C	44	46	48	50	52
Average particle size of dispersed phase/μm	Viscosity/mPa·s	Viscosity/mPa·s	Viscosity/mPa·s	Viscosity/mPa·s	Viscosity/mPa·s
8.624	61.5	54.33	36	25.43	21.71
7.943	73.94	57.5	46.17	27.19	23.11
7.467	89.67	58.17	50.5	31.35	26.61
Crude oil	60.83	34.25	26.88	24.02	21.89
Temperature/˚C	54	57	60	63	66
Average particle size of dispersed phase/μm	Viscosity/mPa·s	Viscosity/mPa·s	Viscosity/mPa·s	Viscosity/mPa·s	Viscosity/mPa·s
8.624	19.02	17.86	16.77	15.66	14.56
7.943	21.74	19.65	18.56	17.45	16.34
7.467	24.2	22.11	21.02	20.13	19.45
Crude oil	19.79	17.65	16.02	14.80	13.88

particle size of the dispersed phase at the same temperature. Moreover, due to the apparent viscosities of the three kinds of emulsion are all higher than the apparent viscosity measured by the crude oil, the apparent viscosity increases with the increase of the water cut of the crude oil. In other words, for W/O emulsions, an increase in the internal phase leads to an increment of the apparent viscosity.

According to the data in **Table 5**, for crude oil emulsions with the same average particle size of the dispersed phase, as the temperature rises, the reduction rate and reduction percentage of the apparent viscosity decreases, and the apparent viscosity of emulsions is decreasing more and more slowly. In the whole temperature range, the reduction rate and reduction percentage of the apparent viscosity of the crude oil emulsion is smaller with the larger average particle size of the dispersed phase.

As shown in **Table 6**, at the same temperature, the reduction rate and reduction percentage of the apparent viscosity of three kinds of emulsions with different microstructures increased with decreasing the average particle size of the dispersed phase. For different microstructures of crude oil emulsions, the reduction rate of apparent viscosity decreases with increasing temperature; conversely, the reduction percentage increases with increasing temperature.

Table 5. The reduction rate and reduction percentage of the apparent viscosity of crude oil emulsions with the same average particle size of dispersed phase at the different temperatures.

Average particle size of dispersed phase/μm	34˚C - 36˚C Viscosity reduction rate mPa·s/˚C	46˚C - 48˚C Viscosity reduction rate mPa·s/˚C	63˚C - 66˚C Viscosity reduction rate mPa·s/˚C	34˚C - 66˚C Viscosity reduction rate mPa·s/˚C
8.624	81.09	9.165	0.37	12.87
7.943	87	5.67	0.31	13.32
7.464	76.83	3.835	0.23	14.36
Average particle size of dispersed phase/μm	34˚C - 36˚C Viscosity reduction percentage %/˚C	46˚C - 48˚C Viscosity reduction percentage %/˚C	63˚C - 66˚C Viscosity reduction percentage %/˚C	34˚C - 66˚C Viscosity reduction percentage %/˚C
8.624	19	16.87	0.07	12.88
7.943	19.64	9.85	2.34	13.34
7.464	16.05	11.53	1.46	14.36

Table 6. The reduction rate and reduction percentage of the apparent viscosity of crude oil emulsions with a different average particle size of dispersed phase at the same temperature.

Temperature/˚C	8.624 - 7.943 μm Viscosity reduction rate mPa·s/μm	7.943 - 7.464 μm Viscosity reduction rate mPa·s/μm	8.624 - 7.464 μm Viscosity reduction rate mPa·s/μm
34	24.16	75.02	45.08
50	2.58	8.74	5.12
66	2.61	6.53	4.23
Temperature/˚C	8.624 - 7.943 μm Viscosity reduction percentage %/μm	7.943 - 7.464 μm Viscosity reduction percentage %/μm	8.624 - 7.464 μm Viscosity reduction percentage %/μm
34	5.43	15.57	9.38
50	10.26	27.7	16.28
66	15.99	33.38	21.67

3.3.2. Comparison of Apparent Viscosity at Different Shear Rates

At the same shear rate, the average values among the apparent viscosities of the crude oil emulsion are calculated in the whole temperature range. As shown in **Table 7**, the apparent viscosity of the crude oil and emulsions decreases with the growth of the shear rate.

As shown in **Table 8**, for crude oil emulsions with the same average particle size of the dispersed phase, as the shear rate increases, the reduction rate and reduction percentage of the apparent viscosity decreases. Within the same range of shear rate, the average particle size of the dispersed phase has less influence on the reduction rate and reduction percentage of apparent viscosities of crude oil emulsions.

As shown in **Table 9**, at the same shear rate, the reduction rate and reduction percentage of the apparent viscosity of three kinds of emulsions with different microstructures increase with decreasing the average particle size of the dispersed phase. For different microstructures of crude oil emulsions, the apparent viscosity reduction rate decreases with the increase of shear rate; otherwise, the reduction percentage increases with the increase of shear rate.

Table 7. Average apparent viscosity of crude oil and three kinds of emulsions at the same shear.

Shear rate/s^{-1}	10	20	50	80	100	150
Average particle size of dispersed phase/μm	Viscosity /mPa·s	Viscosity /mPa·s	Viscosity /mPa·s	Viscosity /mPa·s	Viscosity /mPa·s	Viscosity /mPa·s
8.624	162.82	110.46	77.1	64.90	60.21	54.28
7.943	167.72	116.63	80.05	69.16	62.71	56.21
7.467	219.79	145.98	93.65	76.78	70.18	66.45
Crude oil	158.35	105.21	72.82	62.28	58.08	52.15

Table 8. The reduction rate and reduction percentage of the apparent viscosity of crude oil emulsions with the same average particle size of dispersed phase at the different shear rates.

Average particle size of dispersed phase/μm	10 - 20 s^{-1} Viscosity reduction rate mPa·s/10s^{-1}	50 - 80 s^{-1} Viscosity reduction rate mPa·s/10s^{-1}	100 - 150 s^{-1} Viscosity reduction rate mPa·s/10s^{-1}	10 - 150 s^{-1} Viscosity reduction rate mPa·s/10s^{-1}
8.624	52.36	4.07	1.18	7.75
7.943	51.09	3.63	1.3	7.96
7.464	73.81	5.62	0.75	10.95
Average particle size of dispersed phase/μm	10 - 20 s^{-1} Viscosity reduction percentage %/10s^{-1}	50 - 80 s^{-1} Viscosity reduction percentage %/10s^{-1}	100 - 150 s^{-1} Viscosity reduction percentage %/10s^{-1}	10 - 150 s^{-1} Viscosity reduction percentage %/10s^{-1}
8.624	32.15	4.49	1.97	4.76
7.943	30.46	4.53	2.07	4.75
7.464	33.58	6.01	1.06	4.98

Table 9. The reduction rate and reduction percentage of the apparent viscosity of crude oil emulsions with a different average particle size of dispersed phase at the same shear rate.

Shear rate/s^{-1}	8.624 - 7.943 μm Viscosity reduction rate mPa·s/10s^{-1}	7.943 - 7.464 μm Viscosity reduction rate mPa·s/10s^{-1}	8.624 - 7.464 μm Viscosity reduction rate mPa·s/10s^{-1}
10	14.54	18.76	16.28
50	4.33	32.77	16.03
150	4.36	17.31	9.69
Shear rate/s^{-1}	8.624 - 7.943 μm Viscosity reduction percentage %/10s^{-1}	7.943 - 7.464 μm Viscosity reduction percentage %/10s^{-1}	8.624 - 7.464 μm Viscosity reduction percentage %/10s^{-1}
10	3.44	17.16	8.94
50	5.42	25.49	16.72
150	7.75	26.7	14.99

3.4. Correlation Analysis

As mentioned above, the apparent viscosity varies under the same experimental conditions by changing the microstructure of the crude oil emulsion. To investigate the influence of the microstructure of the crude oil emulsion on its apparent viscosity, a correlation analysis was needed. Correlation analysis refers to the analysis of two or more relevant variable elements to measure the degree of relatedness. The Pearson correlation coefficient between the apparent viscosity of the crude oil emulsion and the characterization parameters which could characterize its microstructure at different temperatures are compared using SPSS software [22]. Conclusions are as follows.

3.4.1. Average Particle Size of the Dispersed Phase

As shown in **Table 10** and **Figure 9**, between 34˚C and 48˚C, there is a highly negative correlation between the average particle size of the dispersed phase of the crude oil emulsion and its apparent viscosity. Between 48˚C and 60˚C, there is a moderate negative correlation between the average particle size of the crude oil emulsion dispersed phase and its apparent viscosity. Between 60˚C and 63˚C, there is a low negative correlation between the average particle size of the crude oil emulsion dispersed phase and its apparent viscosity. Between 63˚C and 66˚C, there is essentially no correlation between the average particle size of the dispersed phase of the crude oil emulsion and its apparent viscosity.

3.4.2. Dispersion of Disperse Phase

As shown in **Table 11** and **Figure 10**, from 40˚C to 48˚C, there is a highly positive correlation between the degree of dispersion of the crude oil emulsion and its apparent viscosity. From 34˚C to 40˚C, there is a moderate positive correlation between the degree of dispersion of the crude oil emulsion and its apparent viscosity. From 48˚C to 60˚C, there is a low positive correlation between the

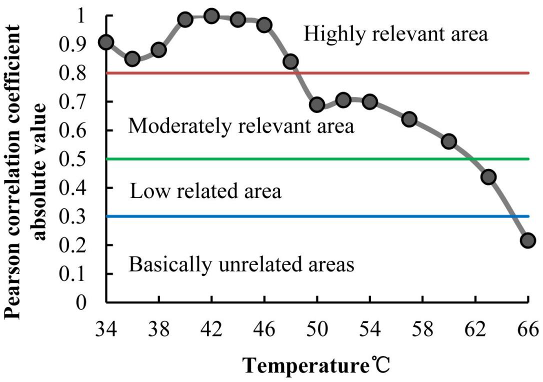

Figure 9. The trend chart of Pearson correlation coefficient absolute value between the apparent viscosity and the average particle size of the dispersed phase.

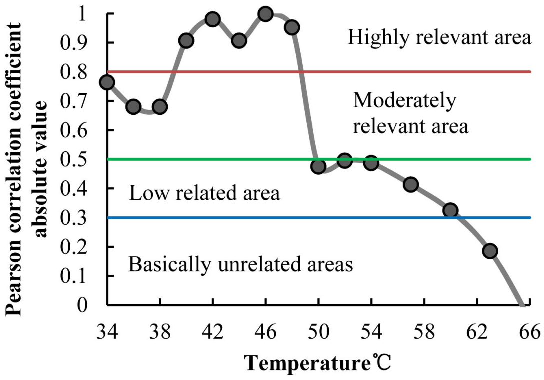

Figure 10. The trend chart of Pearson correlation coefficient absolute value between the apparent viscosity and the degree of dispersion of the dispersed phase.

Table 10. The correlation coefficient between the apparent viscosity and the average particle size of the dispersed phase.

Temperature/˚C	34	36	38	40	42
Pearson correlation coefficient	−0.907	−0.849	−0.880	−0.986	−0.998*
Temperature/˚C	44	46	48	50	52
Pearson correlation coefficient	−0.986	−0.967	−0.839	−0.689	−0.705
Temperature/˚C	54	57	60	63	66
Pearson correlation coefficient	−0.699	−0.638	−0.561	−0.437	−0.216

Table 11. The correlation coefficient between the apparent viscosity and the degree of dispersion of the dispersed phase.

Temperature/˚C	34	36	38	40	42
Pearson correlation coefficient	0.764	0.68	0.680	0.907	0.980
Temperature/˚C	44	46	48	50	52
Pearson correlation coefficient	0.907	0.998*	0.952	0.475	0.495
Temperature/˚C	54	57	60	63	66
Pearson correlation coefficient	0.487	0.413	0.324	0.185	−0.048

degreed of dispersion of the crude oil emulsion and its apparent viscosity. From 60˚C to 66˚C, there is almost no correlation between the average particle size of the dispersed phase of the crude oil emulsion and its apparent viscosity.

3.4.3. Nonuniformity of the Average Particle Size of the Dispersed Phase

As shown in Table 12 and Figure 11, between 34˚C and 44˚C and between 50˚C and 63˚C, there is a highly negative correlation between the polydispersity of the crude oil emulsion and its apparent viscosity. Between 44˚C and 46˚C and between 48˚C and 50˚C and between 63˚C and 66˚C, there is a moderate negative correlation between the polydispersity of the crude oil emulsion and its apparent viscosity. Between 46˚C and 48˚C, there is a low negative correlation between the polydispersity of the crude oil emulsion and its apparent viscosity.

4. Conclusions

1) In the process of preparing the Daqing crude oil emulsion with the same water cut, the microstructure of the Daqing crude oil emulsion varies with the stirring speed. As the stirring speed increased from 950 rpm to 1450 rpm, the average particle size of the dispersed phase of the crude oil emulsion decreased from 8.624 μm to 7.467 μm, the degree of dispersion (specific surface area) increased from 0.546 μm^{-1} to 0.606 μm^{-1} and nonuniformity of the average particle size (polydispersity) decreased from 1.14 to 1.082.

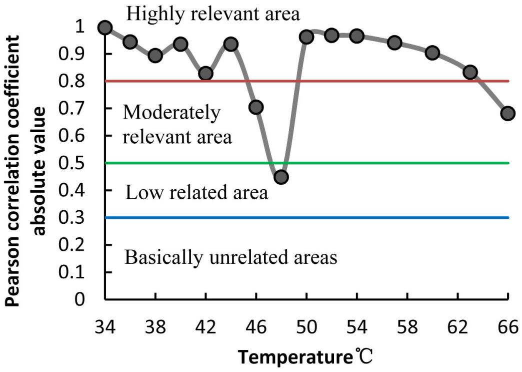

Figure 11. The trend chart of Pearson correlation coefficient absolute value between the apparent viscosity and the nonuniformity of the average particle size of the dispersed phase.

Table 12. The correlation coefficient between the apparent viscosity and the nonuniformity of the average particle size of the dispersed phase.

Temperature/˚C	34	36	38	40	42
Pearson correlation coefficient	−0.995	−0.943	−0.893	−0.935	−0.827
Temperature/˚C	44	46	48	50	52
Pearson correlation coefficient	−0.935	−0.704	−0.448	−0.961	−0.967
Temperature/˚C	54	57	60	63	66
Pearson correlation coefficient	−0.965	−0.940	−0.903	−0.832	−0.681

2) As the average particle size of the dispersed phase of the crude oil emulsion decreases, the abnormal point increases; the average particle size of the dispersed phase decreases by 0.5 μm, and the abnormal point increases by about 1˚C. The apparent viscosity of the crude oil and emulsions near the wax precipitation point drops faster before the wax precipitation point. Therefore, the wax component in the crude oil and its emulsion still has an effect on its apparent viscosity at the higher temperature.

3) Under the same experimental condition, for the crude oil emulsions with the same average particle size of the dispersed phase, as the temperature or shear rate rose, the reduction rate and reduction percentage of the apparent viscosity decreased and the apparent viscosity of emulsions was decreasing more and more slowly. In the whole temperature range, the reduction rate and percentage of the apparent viscosity are smaller with a larger average particle size of the dispersed phase. In the same shear rate range, the average particle size of the dispersed phase has less effect on the reduction rate and percentage of apparent viscosity. At the same temperature or shear rate, the reduction rate and percentage of the apparent viscosity of different emulsions increased with decreasing the average particle size of the dispersed phase. For different microstructures of emulsions, the reduction rate of apparent viscosity decreases with increasing temperature; conversely, the reduction percentage increases with increasing temperature.

4) From 34˚C to 48˚C, there is a highly negative correlation between the average particle size of the dispersed phase of the emulsion and its apparent viscosity. From 40˚C to 48˚C, there is a highly positive correlation between the degree of dispersion of the emulsion and its apparent viscosity. From 34˚C to 44˚C and from 50˚C to 63˚C, there is a highly negative correlation between the polydispersity of the emulsion and its apparent viscosity.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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