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Original Paper

The relationship between heavy oil viscosity and "critical emulsification viscosity" for viscosity reduction

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ABSTRACT

This study investigates the relationship between heavy oil viscosity and emulsification performance during emulsification-based viscosity reduction. Heavy oils with different viscosities were prepared and their emulsification behavior was systematically evaluated using minimum emulsification speed (R_{min}), droplet morphology, particle size distribution, water separation rate, and oil–water interfacial tension as key indicators. The results reveal the existence of a critical emulsification viscosity of approximately 3,700 mPa·s under the experimental conditions (60 °C, oil–water ratio 3:7, surfactant concentration 1 wt%). When the viscosity decreases below this threshold, the minimum emulsification speed decreases significantly, the droplet size distribution becomes more uniform, and the emulsion stability improves markedly. Meanwhile, the oil–water interfacial tension decreases to the low interfacial tension regime (<1 mN·m^{-1}), facilitating droplet deformation and breakup during emulsification. Mechanistic analysis indicates that the observed critical viscosity originates from the synergistic effects of viscosity-controlled droplet deformation, surfactant adsorption kinetics at the oil–water interface, and the interfacial films formed by asphaltenes and resins. These findings provide theoretical guidance for optimizing emulsification viscosity-reduction systems and defining the applicable viscosity range for heavy oil emulsification technologies.

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1. Introduction

Heavy oil, as an important unconventional oil and gas resource in the world, accounts for more than 40% of the world's total oil reserves and occupies an irreplaceable position in the energy structure (Tong et al., 2018). China has extremely rich heavy oil resources, with proven reserves of more than 10 billion tons, accounting for about one-third of the country's total oil reserves. It is mainly distributed in the Bohai Oilfield, Shengli Oilfield, Liaohe Oilfield, and other production areas, and has huge development potential (Hu et al., 2025). However, heavy oil is rich in gums and asphaltenes, with their content reaching 20%–50%. Strong intermolecular forces result in extremely high viscosity at room temperature (usually greater than 1000 mPa·s) and extremely poor fluidity, which brings severe challenges to extraction, gathering, and transportation processes (Chen et al., 2013, 2021). Although traditional thermal recovery technologies (such as steam injection and steam drive) can effectively reduce the viscosity of heavy oil, they have problems such as high energy consumption, high cost, serious formation damage, and great environmental pressure, making it difficult to meet the needs of green and efficient development (Ge et al., 2009; Brandt and Unnasch, 2010; Wang et al., 2019).

Emulsification viscosity reduction technology, as an economical and efficient chemical viscosity reduction method, injects chemical agents such as surfactants into the formation to form a low-viscosity, high-flowability oil-in-water (O/W) emulsion between heavy oil and water (Jing et al., 2024; Jiang et al., 2025). This can not only significantly reduce viscosity but also improve oil displacement efficiency and increase crude oil recovery (Tan et al., 2023; Wu et al., 2025a) and has become one of the core technologies for heavy oil development (Civan et al., 2004). In recent years, this technology has achieved remarkable results in field applications in oilfields such as Bohai and Shengli. However, it has also exposed key technical bottlenecks: the compatibility of emulsification viscosity reduction systems with heavy oils of different viscosities varies greatly. Some high-viscosity heavy oils

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have low emulsification efficiency, requiring large amounts of chemical agents and external energy, while low-viscosity heavy oils face issues such as insufficient emulsion stability and difficulty in demulsification (Malkin et al., 2018; Ma et al., 2022a; Pu et al., 2026). This phenomenon indicates that the viscosity of heavy oil is the core factor affecting the performance of emulsification viscosity reduction. However, the scientific questions regarding the viscosity range in which heavy oil is most easily emulsified and the critical viscosity threshold for sudden changes in emulsification performance have not yet been clarified, resulting in the lack of specificity in the design of existing emulsification viscosity reduction systems and difficulty in achieving precise adaptation.

Existing research focuses on the synthesis and optimization of emulsion systems for heavy oils of single viscosity, or the performance comparison of different viscosity reducers. For example, Li et al. (2021a) studied the viscosity-reducing ability of polymers synthesized from two functional monomers, acrylamide and 2-acrylamido-2-methylpropanesulfonic acid. At different concentrations, the viscosity reduction ranged from 87.0% to 90.6%. Wang et al. (2022) synthesized a terpolymer of bisphenol AF, *p*-hydroxybenzenesulfonic acid, and octylphenol ethoxylate through solution polymerization. Zhang et al. (2024) synthesized a polymer that can reduce the viscosity of heavy oil by up to 98% under high temperature and high salt conditions. However, current research lacks quantitative analysis of the relationship between heavy oil viscosity, emulsification performance, and critical characteristics (Wu et al., 2025a). Therefore, systematically exploring the changes in the emulsification performance of heavy oils of different viscosities, determining the "critical emulsification viscosity", and clarifying the applicable viscosity range of emulsification viscosity reduction technology are of great theoretical and engineering significance for guiding the targeted design of efficient emulsification viscosity reduction systems, reducing development costs and improving the development benefits of heavy oils (Al-Hashmi et al., 2017; Wu et al., 2025b). The "critical emulsification viscosity" refers to the viscosity value of heavy oil corresponding to the transition (such as a sudden change in trend) of the minimum emulsification speed (i.e. the lowest speed that can achieve complete oil–water emulsification) during the process of surfactant emulsification of heavy oil. This parameter comprehensively reflects the effects of heavy oil properties, temperature, oil–water ratio, and surfactants.

By controlling the viscosity of heavy oil and using minimum emulsification speed, droplet morphology and particle size distribution of emulsion, water separation rate, half-life, and oil–water interfacial tension as evaluation indicators (Arinina et al., 2020; Liu et al., 2023; Pu et al., 2026), the evolution law of oil–water emulsification performance with the viscosity of heavy oil was systematically studied. The critical viscosity threshold at which heavy oil is easily emulsified was clarified, providing theoretical support for the optimized design and field application of heavy oil emulsification viscosity reduction system.

2. Experimental

2.1. Materials

The materials and reagents used in the experiment are shown in Table 1. All reagents were used directly without further purification.

2.2. Minimum emulsification speed test

Minimum emulsification speeds (R_{min}) for heavy oils of different viscosities were tested using a high-speed controlled cantilever stirrer. Three surfactant solutions (SDS, APG, and CTAB) with a mass fraction of 1.0 wt% were prepared and mixed with heavy oils of different viscosities at an oil-to-water ratio of 3:7 (volume ratio). The mixtures were then transferred to 30 mL colorimetric tubes. After preheating in a 60 °C water bath for 10 min, the stirrer was activated and the speed was gradually increased. If the heavy oil was not completely dispersed in the surfactant solution within 1 min, the speed was increased by 25 rpm to continue the experiment; if the heavy oil was completely dispersed within 1 min, the speed at this point was recorded as R_{min} (Dong et al., 2022; Dou et al., 2024; Liu et al., 2024b).

Table 1
Experimental materials and reagents.

Name and abbreviations	Purity	Manufacturer
Thick oil	/	Bohai Oilfield
Sodium dodecyl sulfate (SDS)	Analytical pure	Sinopharm Chemical Reagent Co., Ltd.
Alkyl glycosides (APG)	Analytical pure	Sinopharm Chemical Reagent Co., Ltd.
Hexadecyltrimethylammonium bromide (CTAB)	99.0%	Sinopharm Chemical Reagent Co., Ltd.

2.3. Emulsion stability characterization

2.3.1. Microstructure and particle size distribution

After the emulsion was prepared, a small amount of the sample was immediately transferred onto a clean glass slide and covered with coverslip. The microstructure and droplet morphology of the emulsion were observed using an XSJ-2 optical microscope. The captured micrographs were further analyzed using a Nano Measurer particle size analyzer to determine the droplet size distribution and median particle diameter (Li et al., 2020; Liu et al., 2024a).

2.3.2. Water separation rate

The stability of the emulsion can be evaluated by monitoring the time-dependent water separation behavior (Zou et al., 2023). The prepared emulsion was transferred into a graduated cylinder with a plunger stopper and kept in a constant-temperature water bath at 60 °C. The volume of the separated water was recorded at predetermined time intervals. The water separation rate was calculated according to Eq. (1):

$$\phi = \frac{V_w}{V_o} \times 100\% \quad (1)$$

where ϕ is the water separation rate, %; V_w is the volume of water separated, mL; and V_o is the total volume of the aqueous phase in the oil–water mixture, mL.

2.4. Interfacial tension test

The interfacial tension between the surfactant solution and heavy oils with different viscosities was measured using a TX-500C interfacial tensiometer based on the spinning (rotating) drop method. The experiments were conducted at 60 °C, and the rotational speed was set to 5000 rpm. The spinning drop method is widely used to determine low oil–water interfacial tension in surfactant systems due to its high accuracy and reliability for elongated droplets (Pu et al., 2026).

The interfacial tension was calculated according to Eq. (2) by measuring the major axis (L) and minor axis (D) of the oil droplet when the droplet deformation satisfies $L/D \geq 4$, which ensures the applicability of the spinning-drop model (Arinina et al., 2020).

$$\gamma = \frac{\Delta\rho\omega^2 r^3}{32} \quad (2)$$

where γ represents the interfacial tension, mN·m^{-1}; $\Delta\rho$ is the density difference between oil and water, kg·m^{-3}; ω is the angular velocity, rad·s^{-1}; r is the minor axis radius of the droplet, m; L is the axial diameter of the centrifuge tube, m; and D is the radial diameter of the centrifuge tube, m.

3. Results and discussion

Emulsification performance generally consists of two key aspects: oil–water emulsification ability and emulsion stability. Oil–water emulsification ability reflects the capability of surfactants to promote the dispersion of the oil phase into the aqueous phase and the formation of stable droplets. It is commonly characterized by parameters such as minimum emulsification speed and droplet size distribution, where smaller and more uniformly distributed droplets indicate stronger emulsification ability (Liu et al., 2024a).

Emulsion stability is closely related to the coalescence and aggregation behavior of dispersed droplets. It can be quantitatively evaluated by indicators such as water separation rate and half-life, which reflect the resistance of the emulsion to phase separation during storage or standing (Li et al., 2024).

In addition, droplet size and its distribution play a crucial role in determining emulsion stability, as smaller droplets generally reduce the probability of droplet coalescence and improve the kinetic stability of oil–water emulsions (L'Estimé et al., 2024).

3.1. Minimum emulsification speed for heavy oils of different viscosities

The minimum emulsification rotational speed (R_{min}) is an important parameter for quantitatively evaluating the ease with which a surfactant emulsifies heavy oil. A lower R_{min} value indicates a stronger emulsification ability of the surfactant toward the oil phase. Table 2 summarizes the R_{min} values obtained for three different surfactant solutions when interacting with heavy oils of various viscosities (Dong et al., 2022).

The R_{min} values of the three surfactants exhibit a similar variation trend with decreasing heavy oil viscosity. When the heavy oil remains at its original viscosity, its high density causes it to settle at the bottom of the sample bottle, while the extremely high viscosity prevents the surfactant solution from effectively dispersing the oil phase. As a result, the R_{min} value cannot be measured under these conditions.

As the viscosity of heavy oil decreases, the R_{min} value gradually decreases, indicating that the emulsification becomes easier. When the viscosity decreases to 7,400 mPa·s (approximately a 50% reduction), the R_{min} values of all three surfactants remain relatively high (above 400 rpm), suggesting that the emulsification is still difficult. However, when the viscosity decreases by more than 75% (below 3,700 mPa·s), the reduction in R_{min} becomes less pronounced and gradually stabilizes. This phenomenon indicates that heavy oil enters a viscosity range where emulsification becomes significantly easier (Ma et al., 2022a).

Table 2
Minimum emulsification speed (R_{min}) for heavy oils of different viscosities.

Heavy oil viscosity, mPa·s	R_{min}		
	SDS	APG	CTAB
14,800	/	/	/
11,100	600	550	575
7,400	525	425	475
3,700	350	225	300
1,480	325	200	275
740	300	175	200
370	275	150	175

Among the three surfactants, APG consistently shows the lowest R_{min} values, indicating the strongest emulsification ability. However, this advantage is mainly observed in low-viscosity heavy oil systems. When the viscosity of heavy oil is high, even surfactants with strong interfacial activity cannot rapidly disperse and emulsify the oil phase due to the strong internal cohesion and limited molecular mobility of the oil phase (Pu et al., 2026).

Taking the APG solution as an example, the emulsification behavior of heavy oils with different viscosities during the increase in rotational speed is shown in Fig. 1. When the heavy oil is at its original viscosity, it settles at the bottom of the sample bottle due to its high density. At low rotational speeds, the heavy oil cannot be effectively dispersed. Even when the rotational speed increases, only a small portion of the heavy oil can be entrained into the aqueous phase, making complete emulsification difficult (Fig. 1(a)).

When the viscosity decreases to 7,400 mPa·s, the heavy oil gradually detaches from the oil–water interface in a filament-like form as the rotational speed increases, and disperses into the aqueous phase, although the dispersion rate remains relatively slow (Fig. 1(b)). When the viscosity further decreases to 3,700 mPa·s, the heavy oil can be rapidly dispersed and completely emulsified at relatively low rotational speeds. The oil phase separates from the interface and diffuses into the aqueous phase in the form of fine oil droplets (Fig. 1(c)).

The oil–water interface state after ultrasonic dispersion further verifies the above trend (Fig. 2). Ultrasonic dispersion provides localized shear forces and cavitation effects that help break the bulk heavy oil into small droplets and promote contact with the surrounding surfactant solution in the oil–water interface. However, whether these oil droplets can be efficiently detached from the oil–water interface and stabilized in the aqueous phase depends strongly on the viscosity of the heavy oil and the emulsifying ability of the surfactant. For high-viscosity heavy oil, the strong internal cohesion and slow surfactant adsorption hinder droplet detachment and stabilization; consequently, the interface remains sharp and the aqueous phase stays transparent after ultrasonication. As the viscosity decreases, the oil phase becomes easier to deform and disperse under the same ultrasonic energy. The surfactant can then rapidly adsorb onto the freshly formed oil–water interfaces, reducing interfacial tension and preventing droplet coalescence. This leads to a significant increase in the number of oil droplets observed in the aqueous phase after ultrasonic treatment. Therefore, the appearance of oil droplets in the aqueous phase directly reflects successful emulsification, and the droplet population provides a semi-quantitative measure of how readily the surfactant emulsifies heavy oils of different viscosities. These observations indicate that reducing heavy-oil viscosity greatly enhances the emulsification capability of the surfactant.

3.2. Droplet morphology and particle size distribution of heavy oil emulsions with different viscosities

Droplet morphology and particle size distribution are widely recognized as key indicators for evaluating the emulsification efficiency and stability of heavy oil emulsions (Feng et al., 2019; Liu et al., 2020, 2024c). Smaller and more uniformly distributed droplets generally indicate better dispersion of the oil phase in the aqueous phase and improved emulsion stability. Therefore, analyzing droplet morphology and particle size distribution is

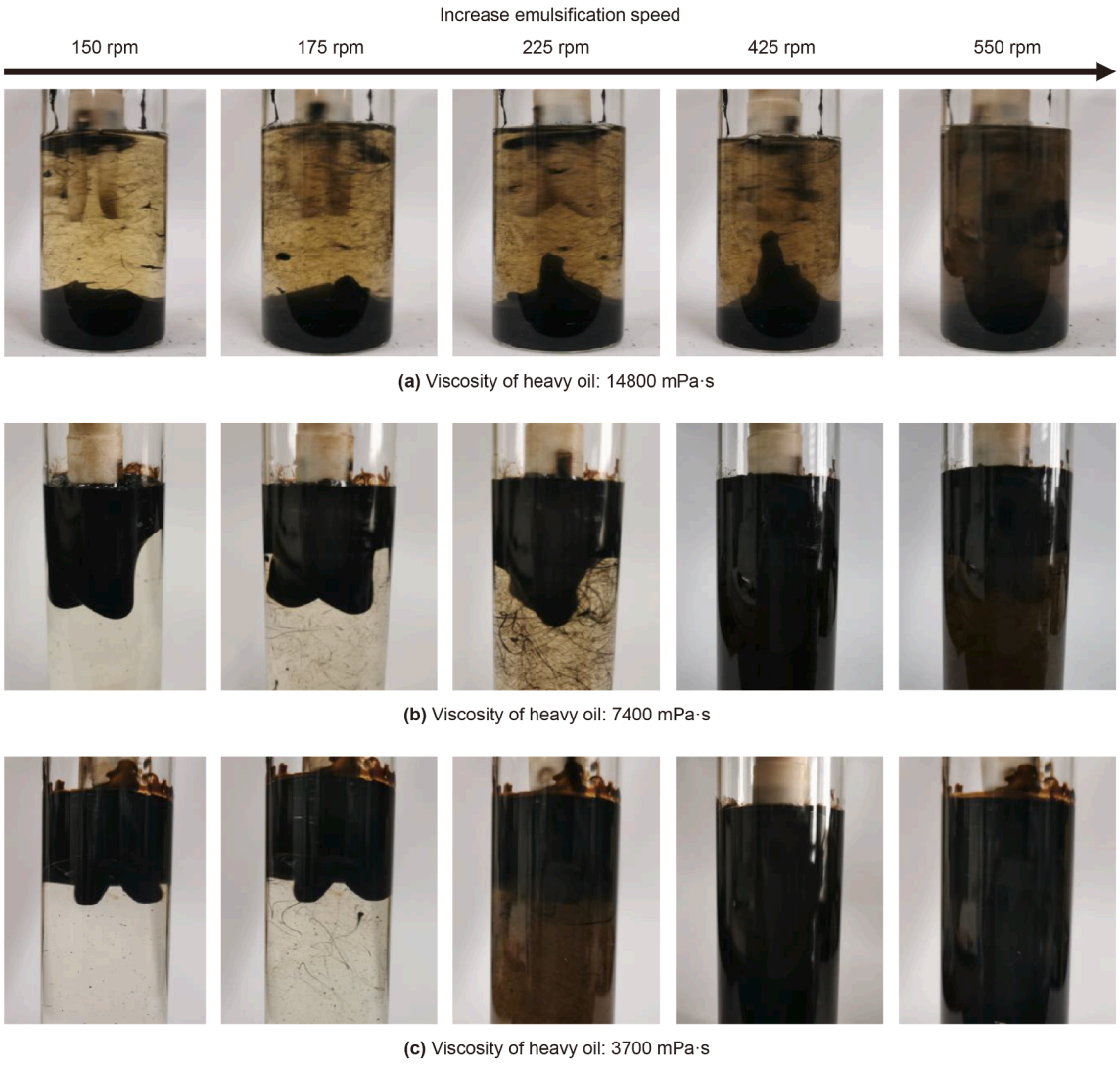


Fig. 1. Emulsification of heavy oils of different viscosities as the rotational speed increases.

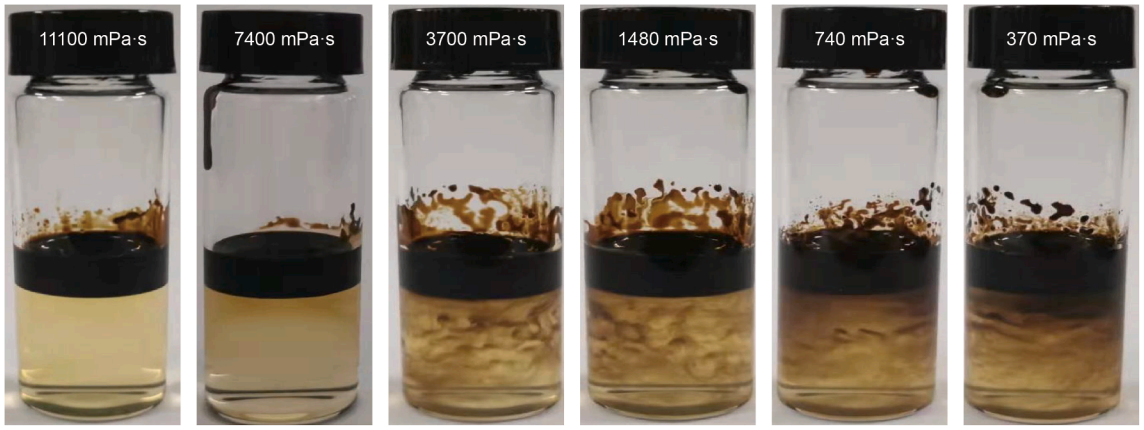


Fig. 2. Oil–water interface of heavy oils of different viscosities after ultrasonic treatment.

essential for understanding the emulsification behavior of heavy oil systems.

In this study, emulsions were prepared at a fixed rotational speed (600 rpm higher than the minimum emulsification speed) with a stirring time of 1 min. The microscopic morphology of the emulsions formed by heavy oils with different viscosities is presented in Fig. 3.

When the viscosity of heavy oil is high, the resulting emulsion exhibits relatively large droplets with uneven size distribution and a small number of droplets, indicating poor dispersion of heavy oil

in the aqueous phase (Fig. 3(a) and (b)). This phenomenon can be attributed to the strong internal resistance of the highly viscous oil phase, which inhibits droplet breakup during the emulsification process (Liu et al., 2020; Zhai et al., 2023). As the viscosity decreases, the number of droplets increases significantly, and the droplet size gradually decreases with a more uniform distribution (Fig. 3(c) and (d)). Lower oil viscosity facilitates droplet fragmentation under shear forces and enhances oil–water interfacial dispersion (Feng et al., 2019; Mettu et al., 2020).

When the viscosity further decreases to 740 mPa·s, the droplet size reaches the minimum value (Fig. 3(e)), indicating that the emulsification system achieves the most efficient dispersion state under the current experimental conditions. However, when the viscosity decreases to 370 mPa·s, the droplet size shows a slight increase again (Fig. 3(f)). This may be related to the reduced viscosity of the oil phase, which weakens the mechanical stability of the interfacial film and increases the probability of droplet coalescence (Kolotova et al., 2018; Liu et al., 2024c).

Fig. 4 presents the particle size distribution curves of heavy oil emulsions with different viscosities. When the viscosity is 11,100 mPa·s, the distribution curve shows multiple peaks located around 3 and 15 μm, indicating a highly heterogeneous droplet population. As the viscosity decreases to 7,400 mPa·s, the multi-peak distribution still exists but shifts toward smaller particle sizes. When the viscosity decreases further to 3,700 mPa·s, the distribution gradually converges to a single peak, suggesting that the droplet size distribution becomes more concentrated and uniform (Feng et al., 2019; Mettu et al., 2020).

When the viscosity decreases to 740 mPa·s, the average droplet size decreases to approximately 2 μm, reaching the minimum value. With further reduction in viscosity, the change in droplet size becomes less pronounced, indicating that the emulsification system approaches a relatively stable dispersion state. These results demonstrate that heavy oil viscosity plays a critical role in determining droplet breakup behavior and particle size distribution during emulsification (Liu et al., 2020; Zhai et al., 2023).

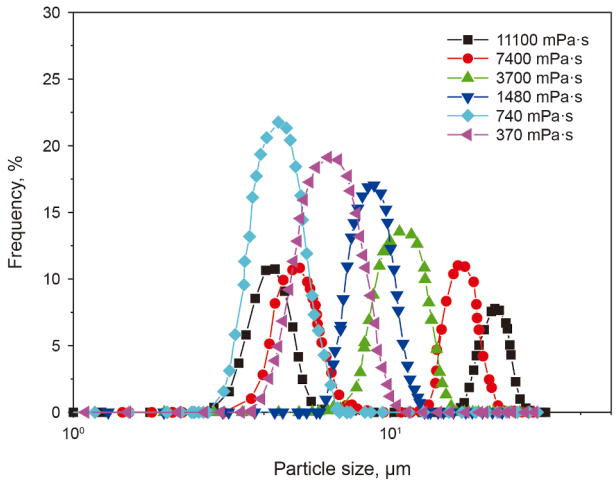


Fig. 4. Droplet size distribution curves of heavy oil emulsions with different viscosities.

3.3. Stability of heavy oil emulsions with different viscosities

The variation in water separation rate over time is widely used as a direct indicator for evaluating the stability of oil–water emulsions. A lower water separation rate and a slower increase with time generally indicate stronger emulsion stability and greater resistance to droplet coalescence. This method has been widely adopted in experimental studies of crude oil and heavy oil emulsions to characterize phase separation behavior and interfacial stability (Mahmoudi Alemi and Mohammadi, 2025). Fig. 5

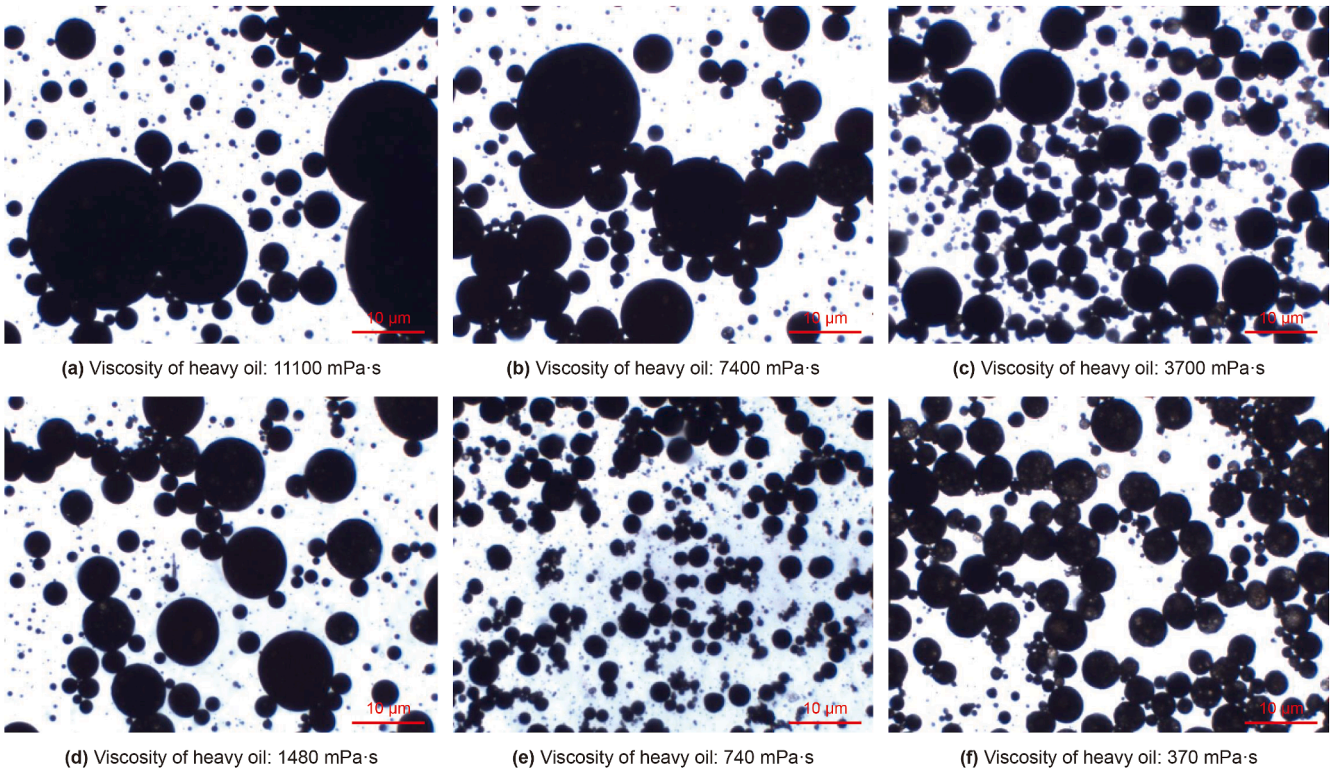


Fig. 3. Microscopic morphology of emulsion droplets formed by different viscosities of heavy oil.

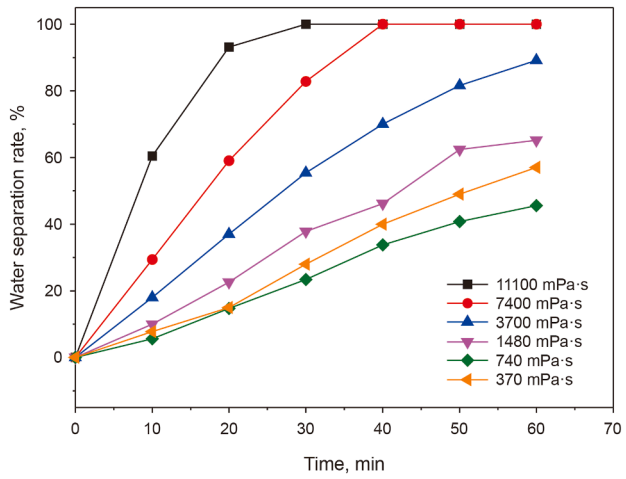


Fig. 5. Change in water separation rate of emulsions prepared with different heavy oil.

presents the variation in water separation rate for emulsions prepared using heavy oils with different viscosities. The temporal evolution of the separated water fraction provides a quantitative description of the demulsification process and reflects the kinetic stability of the emulsion system. Similar evaluation approaches based on water separation behavior have been widely applied to investigate the stability and structural evolution of heavy oil emulsions (Liu et al., 2024c).

As shown in Fig. 5, emulsions prepared from high-viscosity heavy oil (11,100 mPa·s) exhibit a rapid increase in the water separation rate and undergo nearly complete demulsification within approximately 20 min. This phenomenon indicates that emulsions formed from highly viscous crude oil generally possess poor stability (Bera et al., 2021). This behavior can be attributed to the limited dispersibility of high-viscosity crude oil, which leads to the formation of relatively large and unevenly distributed droplets during the emulsification process. The high internal resistance of viscous oil phases restricts droplet breakup and hinders the formation of fine emulsions (Ma et al., 2022a). Moreover, larger droplets are more prone to collision and coalescence, which accelerates droplet aggregation and results in rapid phase separation, ultimately leading to poor emulsion stability (Botti et al., 2022).

When the viscosity of heavy oil decreases to approximately 3,700 mPa·s, the water separation rate decreases significantly, and the stability of the emulsion improves markedly. The reduction in oil viscosity facilitates droplet deformation and breakup during mixing, resulting in the formation of smaller droplets and a more homogeneous droplet size distribution (Bonto et al., 2019; Bera et al., 2021). Smaller droplets exhibit a lower collision probability and slower coalescence kinetics, which significantly enhances the stability of the emulsion system (Dekker et al., 2020).

However, when the viscosity further decreases to 370 mPa·s, a slight increase in the water separation rate is observed. This phenomenon is closely related to the chemical composition of heavy oil, particularly the content of asphaltenes and resins (Rocha et al., 2018). The four components in the original heavy oil and two types of heavy oil diluted with kerosene were determined, and the results are shown in Table 3. These polar components can strongly adsorb at the oil–water interface and form rigid or viscoelastic interfacial films, which prevent droplet coalescence and thereby stabilize the emulsion (Yarranton and Baydak, 2022; Peng et al., 2025). In heavy oils with relatively high viscosity, the higher concentration of asphaltenes and resins contributes to the formation of stronger interfacial films, thereby improving emulsion stability (Sun et al., 2026). Conversely, in lower-viscosity heavy oils, the reduced content of these surface-active components weakens the interfacial film, which accelerates droplet coalescence and slightly decreases the stability of the emulsion system (Rocha et al., 2016).

The demulsification process of oil–water emulsions is generally considered an irreversible kinetic process. To quantitatively analyze the demulsification behavior, the experimental data were further interpreted using the Civan demulsification kinetic model, as shown in Eqs. (3)–(6) (Civan, 2023). This model has been widely applied to characterize the dehydration kinetics and stability of crude oil emulsions.

$$dX \Big/ dt = k_d \left(X_f - X\right)^n \tag{3}$$

where X is the emulsion dehydration rate, %; t is the time, min; k_d is the emulsion decomposition rate constant; X_f is the maximum emulsion dehydration rate, %; and n is the reaction order.

Because crude oil emulsions often exhibit an induction period before visible water separation begins, Eq. (3) can be transformed into Eq. (4) by introducing the delay time t_d.

$$X_f^{1-n} - \left(X_f - X\right)^{1-n} = k_d(t - t_d)(1 - n) \tag{4}$$

Plotting $X_f^{1-n} - \left(X_f - X\right)^{1-n}$ against $t - t_d$ yields a straight line passing through the zero point. Assuming the slope of the fitted line is m, the demulsification rate constant k_d can be calculated using Eq. (5).

$$k_d = \frac{m}{1 - n} \tag{5}$$

Furthermore, the half-life of the emulsion system can be determined from the limiting decomposition conditions using Eq. (6).

$$(t - t_d)_{1/2} = \frac{{X_f}^{1-n} - \left(0.5X_f\right)^{1-n}}{(1 - n)k_d} \tag{6}$$

For statically stored emulsions, previous studies have shown that the reaction order can be approximated as $n = 0.4$, with $X_f = 1$, t and the initial conditions defined as $X = 0$ and $t = t_d$.

Based on experimental dehydration data, Eq. (4) was used to process the water separation data and obtain the fitting curves of emulsion stability, as shown in Fig. 6. The slope of the linear fitting curve was subsequently used to calculate the demulsification rate constant for emulsions prepared from heavy oils with different viscosities. Finally, the emulsion half-life was determined according to Eq. (6), and the results are summarized in Table 4.

As shown in Table 4, the demulsification rate constant decreases gradually with decreasing heavy oil viscosity, while the half-life of the emulsion correspondingly increases. When the viscosity decreases from 11,100 to 3,700 mPa·s, the demulsification

Table 3
Content of components in heavy oil with different viscosities.

Viscosity of heavy oil, mPa·s	SARA components, wt%			
	Saturates	Aromatics	Resins	Asphaltenes
11,100	28.84	37.20	21.52	12.44
740	38.78	32.85	18.74	9.63
370	39.09	33.67	17.93	9.31

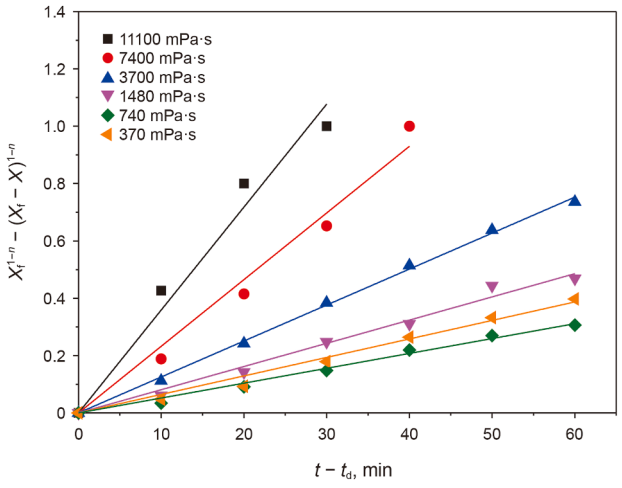


Fig. 6. Stability fitting curves of heavy oil emulsions with different viscosities.

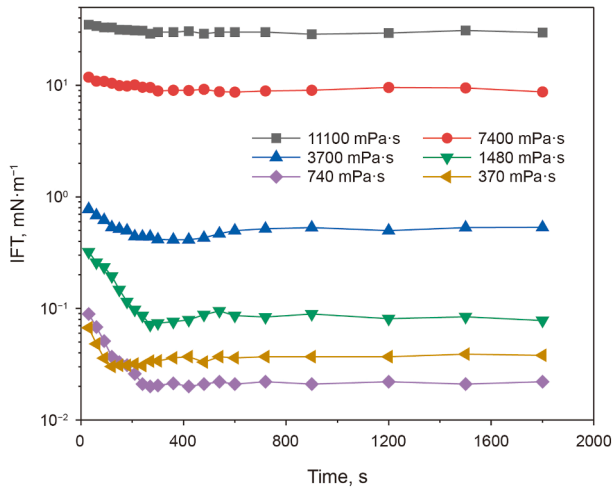


Fig. 7. Variation of oil–water interfacial tension over time under heavy oil with different viscosities.

Table 4
Dehydration rate constant and half-life of emulsions with different heavy oil viscosities.

Heavy oil viscosity, mPa·s	Demulsification rate constant k_d	Half-life $(t-t_d)_{1/2}$, min
11,100	0.066	8.6
7,400	0.054	10.5
3,700	0.015	37.8
1,480	0.012	47.2
740	0.010	56.7
370	0.010	56.7

rate constant decreases significantly from 0.066 to 0.015, while the half-life increases from 8.6 to 37.8 min, indicating a substantial improvement in emulsion stability. When the viscosity decreases further, the variation in demulsification rate constant and half-life becomes relatively small, suggesting that the emulsification behavior approaches a stable regime. These results further confirm that approximately 3,700 mPa·s represents a critical viscosity threshold for efficient emulsification in this system.

3.4. Interfacial tension between water and heavy oils of different viscosities

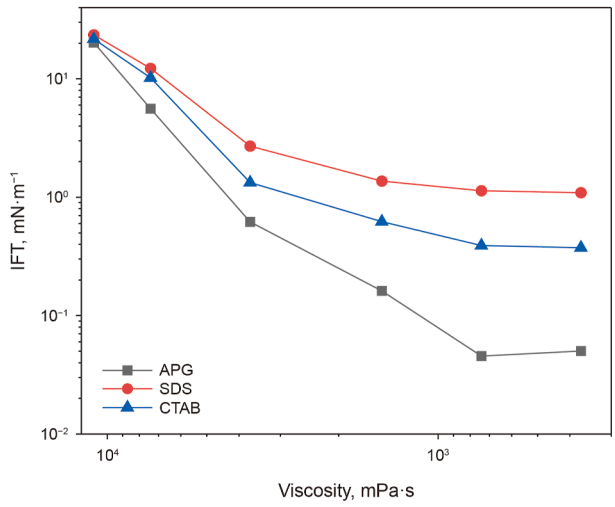
Oil–water interfacial tension is a key physicochemical parameter governing emulsification performance. Generally, a lower interfacial tension facilitates the breakup of the oil phase and promotes the formation of stable emulsions (Li et al., 2021b; Pu et al., 2026). In this study, the interfacial properties between heavy oils with different viscosities and surfactant solutions were investigated to elucidate the mechanisms responsible for the observed differences in emulsification performance.

The interfacial tension curve of the APG solution over time (Fig. 7) shows that when the viscosity of the heavy oil is high, the cohesive force is strong, and even if the surfactant can be adsorbed at the oil–water interface, it is difficult to change the shape of the heavy oil droplets (Xu et al., 2022). The lower the viscosity of the heavy oil, the faster the interfacial tension decreases, indicating that low-viscosity heavy oil is more conducive to the adsorption and spreading of surfactants at the oil–water interface, thereby reducing the interfacial tension and promoting the dispersion and emulsification of the oil phase (Tang et al., 2025). This result is consistent with the test results of minimum emulsification speed, droplet size, and stability, and together they reveal the physicochemical nature of the critical emulsification viscosity.

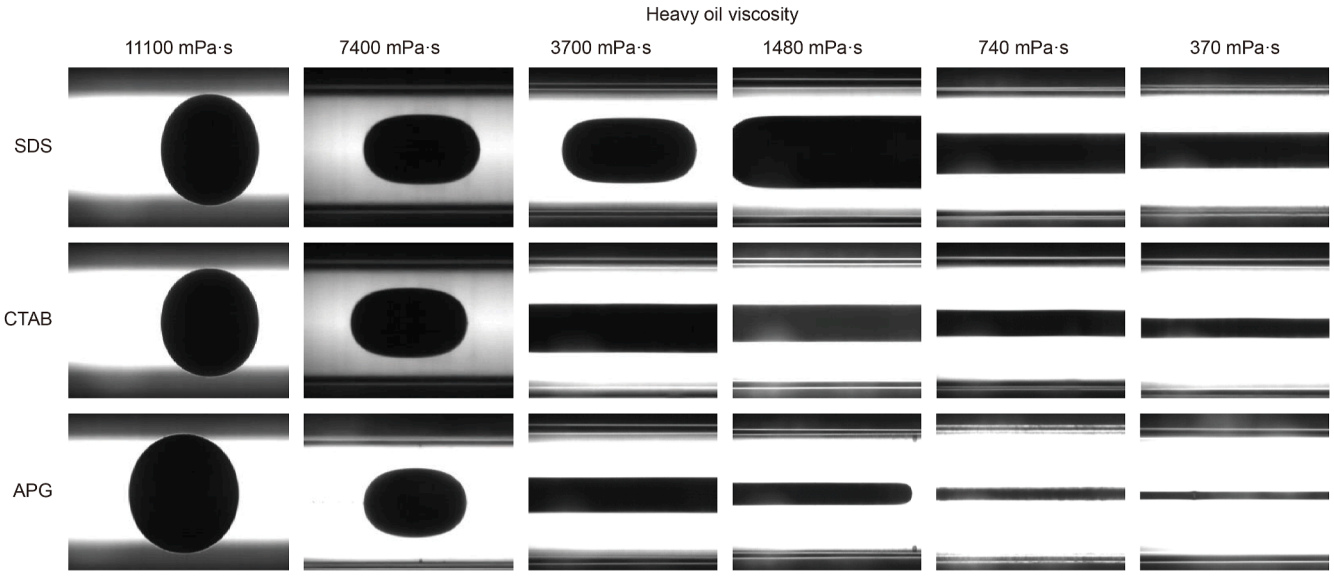
The effects of different surfactants on oil–water interfacial tension were investigated across a range of heavy oil viscosities (Fig. 8). When the viscosity of heavy oil was high (~11,000 mPa·s), all three surfactants exhibited relatively high interfacial tension values (>10 mN·m^{-1}), corresponding to spherical oil droplets that resisted deformation. As the viscosity decreased, the oil–water interfacial tension decreased significantly, and the droplet shape transitioned from spherical to ellipsoidal morphology due to enhanced surfactant adsorption and droplet deformation (Ma et al., 2022b). At intermediate viscosities (e.g., 3,700 to 740 mPa·s), oil droplets showed elongated morphology and the interfacial tension dropped markedly. The APG solution in particular reached interfacial tension values below 1.0 mN·m^{-1}, indicating enhanced interfacial activity and low-tension regimes. As the heavy oil viscosity continued to decline, the rate of interfacial tension reduction moderated, with values approaching ultra-low levels. Among the tested surfactants, the APG solution exhibited the lowest interfacial tension, demonstrating the strongest ability to reduce oil–water interfacial tension and promote oil phase dispersion (Cui et al., 2023; Tang et al., 2025). APG is a non-ionic surfactant, with a hydrophilic head group composed of multiple glucose units and a large amount of hydroxyl (–OH) present in its structure. The hydroxyl can form hydrogen bonds with polar components in heavy oil, thereby reducing the cohesion of its aggregates and making it easier to emulsify and disperse heavy oil into small droplets. In addition, APG is a non-ionic surfactant, and the long alkyl chains in its structure can also be inserted into the non-polar sites of heavy oil, thereby reducing the interfacial tension between oil and water. Unlike SDS and CTAB, APG, due to its non-ionic properties, avoids charge interference and is more suitable for complex components of heavy oil.

3.5. Mechanistic analysis

The emulsification performance of heavy oil is controlled by the combined effects of oil viscosity, surfactant adsorption behavior, and the interfacial film formed by indigenous surface-active components such as asphaltenes and resins (Ahmadi and Khormali, 2025). Based on the experimental results of



(a) Interfacial tension value



(b) Interfacial tension test images of heavy oils with different viscosities

Fig. 8. Interfacial tension of oil and water under heavy oil with different viscosities.

emulsification speed, droplet size distribution, emulsion stability, and interfacial tension measurements, the mechanism governing the critical emulsification viscosity can be interpreted from three aspects.

First, oil viscosity plays a fundamental role in determining droplet deformation and breakup behavior during emulsification. High-viscosity heavy oils possess strong internal cohesive forces and high resistance to flow, which significantly restrict droplet deformation under external shear forces. As a result, oil droplets tend to remain spherical and relatively large during mixing, leading to poor dispersion and unstable emulsions. When the viscosity decreases, the internal resistance to deformation becomes weaker, allowing oil droplets to elongate and break more easily under mechanical shear, which promotes the formation of smaller droplets and a more uniform droplet size distribution (Wu and Firoozabadi, 2021). Similar viscosity-controlled droplet deformation behavior has been widely reported in crude oil emulsification systems (Kokal, 2005; Sjöblom, 2006; Peng et al., 2025).

Second, viscosity influences the adsorption kinetics of surfactant molecules at the oil–water interface. In high-viscosity systems, the diffusion and mobility of both oil molecules and surfactant molecules are relatively slow, which limits the rate at which surfactants can migrate to the interface. As the viscosity decreases, molecular mobility increases and surfactant molecules can adsorb and spread more rapidly at the oil–water interface, resulting in a faster reduction in interfacial tension. The decrease in interfacial tension facilitates droplet breakup and promotes the dispersion of the oil phase, thereby improving emulsification efficiency (Fainerman et al., 2020; Hosseinpour et al., 2021). This phenomenon is consistent with the interfacial tension results presented in Fig. 7, where lower-viscosity heavy oils exhibit a more rapid decline in interfacial tension. This behavior is consistent with previous studies indicating that low interfacial tension is a key factor controlling crude oil emulsification and dispersion (Ma et al., 2022b; Xu et al., 2022; Cui et al., 2023).

Third, the composition of heavy oil, particularly the presence of asphaltenes and resins, plays a critical role in determining

emulsion stability. These polar components possess amphiphilic characteristics and can strongly adsorb at the oil–water interface, forming viscoelastic interfacial films around dispersed droplets. Such interfacial films act as mechanical barriers that inhibit droplet coalescence and significantly enhance emulsion stability (Alicke et al., 2020). In relatively high-viscosity heavy oils, the higher content of these natural surface-active components contributes to the formation of stronger interfacial films, which helps stabilize the emulsion system. However, when the viscosity decreases further, the relative content of asphaltenes and resins in the oil phase may become insufficient to maintain a strong interfacial film, resulting in slightly reduced emulsion stability despite the lower viscosity. This phenomenon has also been reported in previous studies on heavy oil emulsions (Spiecker and Kilpatrick, 2004; Song et al., 2024).

Therefore, the emulsification behavior of heavy oil is governed by the synergistic effects of viscosity-controlled droplet deformation, surfactant adsorption kinetics, and interfacial film stabilization by indigenous polar components. When the oil viscosity approaches a critical range, these three factors reach an optimal balance, leading to the best emulsification performance observed in this study.

4. Conclusions

The relationship between heavy oil viscosity and emulsification performance was systematically investigated to identify the viscosity range in which heavy oil can be efficiently emulsified during emulsification-based viscosity reduction processes. The results demonstrate the existence of a clear critical emulsification viscosity, which governs the transition from difficult to efficient emulsification behavior. The main conclusions are as follows.

(1) Heavy oil exhibits a distinct critical emulsification viscosity of approximately 3,700 mPa·s under the present experimental conditions (60 °C, oil–water ratio 3:7, surfactant concentration 1 wt%). When the viscosity decreases below this value, the minimum emulsification speed decreases significantly and tends to stabilize, indicating that the emulsification becomes much easier.
(2) When the viscosity of heavy oil decreases below the critical value, the oil–water interfacial tension decreases to the low interfacial tension range (<1 $mN{\cdot}m^{-1}$), the droplet size distribution becomes more uniform, and the median droplet diameter decreases to below 10 μm. Meanwhile, the emulsion stability improves significantly, as reflected by lower water separation rates and longer emulsion half-life.
(3) Among the three surfactants investigated, APG exhibits the strongest emulsification performance, showing the lowest interfacial tension and the lowest minimum emulsification speed. Its advantages are particularly pronounced in relatively low-viscosity heavy oil systems.
(4) The formation of the critical emulsification viscosity can be attributed to the combined effects of oil droplet deformation dynamics, surfactant adsorption at the oil–water interface, and interfacial films formed by heavy oil components such as asphaltenes and resins, which together control the emulsification behavior of heavy oil.

CRediT authorship contribution statement

Ning Kang: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Bauyrzhan Sarsenbekuly:** Writing – review & editing, Supervision. **Xi Li:** Investigation. **Zhen Tao:** Investigation. **Hai-Rong Wu:** Writing – review & editing, Supervision.

Declaration of interests

No conflict of interest exits in the submission of this manuscript, and manuscript is approved by all authors for publication. I would like to declare on behalf of my co-authors that the work described was original paper that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript that is enclosed.

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