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Original Paper

Impact of microwave treatment on rheological properties and structural evolution of waxy crude oil

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ABSTRACT

The transportation of waxy crude oil is severely challenged by its high viscosity and tendency to form a gel structure at low temperatures. This study comparatively investigated the effectiveness of microwave treatment versus conventional direct heating in improving the rheological properties of a representative waxy crude oil. The physicochemical alterations were characterized using differential scanning calorimetry (DSC), rotational rheometer, Fourier Transform Infrared Spectroscopy (FTIR), and SARA (saturates, aromatics, resins, asphaltenes) analysis. Experimental results demonstrated the marked superiority of microwave treatment, which reduced the crude oil's viscosity by approximately 80%, lowered the pour point by 12 °C, and increased the critical wax content for gelation from 3.59% to 6.60%. Furthermore, the yield stress and yield strain of the gelled oil were significantly reduced by 82.45% and 20.05%, respectively. Viscoelastic tests revealed a sustained viscosity reduction effect from microwave treatment, maintaining a 70% reduction rate after 10 days of aging, whereas the viscosity of directly heated samples reverted to their original level within 3 days. FTIR and SARA analyses indicated that the microwave's efficacy stems from its “non-thermal” effect, which facilitates the breakdown of large molecular aggregates, thereby reducing molecular weight and viscosity. In conclusion, microwave treatment fundamentally and persistently enhances the flowability of waxy crude oil, showing great potential for optimizing pipeline transportation.

1. Introduction

The gradual replacement of traditional fossil fuels by cleaner, low-carbon energy sources is inducing significant transformations in the global energy structure (Agrawal et al., 2024). Despite this shift, petroleum is expected to retain its critical role as a primary chemical feedstock. Meanwhile, the decline of conventional light oil resources has led to an increase in the global production of waxy and heavy crude oils, which have relatively high pour points and significantly reduced mobility at low temperatures, presenting a significant obstacle to their pipeline transportation and production (Cheng et al., 2023).

Enhancing the flow properties of crude oil through physical or chemical modification has therefore emerged as a critical research focus for ensuring safe production and pipeline transportation. The reduction of physical viscosity can be achieved through various methods, including heating (Hasan et al., 2010; Muñoz et al., 2023; Telmadarreie et al., 2022), dilution with lighter oils (Ghannam et al., 2012; Yadykova et al., 2022), electric treatment (Xie et al., 2023a, 2023b), and ultrasound treatment (Shi et al., 2017). These techniques are often favored for their operational simplicity, controllability, and in some cases, reduced environmental impact compared to chemical alternatives. However, they also have limitations, including high energy consumption, potential impacts on final oil quality, and restricted scope of application. The viscosity of oil can be significantly reduced through various chemical processes, including hydrothermal catalytic cracking (Al-Shafei et al., 2023), microbial viscosity reduction (Zhang et al., 2023), and chemical viscosity reducer application (Hashemi et al., 2014; Zhao et al., 2018). While these methods effectively reduce oil viscosity, they also lead to increased operating costs and

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environmental impacts. Consequently, developing efficient and economical flow-enhancement technologies remains a pivotal challenge for advancing crude oil transportation.

Microwave treatment has emerged as a promising physical method for crude oil viscosity reduction. The efficacy of microwave treatment stems from its synergistic thermal and non-thermal effects on the polar components of crude oil. First, it induces high-frequency oscillations in polar molecules, such as resins and asphaltenes, significantly weakening intermolecular van der Waals forces and hydrogen bonds, thereby achieving rapid viscosity reduction. Second, the synergistic interplay between thermal and non-thermal effects enhances efficacy, i.e., thermal effects preferentially heat high-polarity components, creating localized temperature gradients that fracture asphaltene macrocyclic structures into lighter compounds, while non-thermal effects alter intermolecular interactions between polar molecules and waxes, improving low-temperature fluidity. Concurrently, microwaves reconfigure wax crystal structures by increasing molecular layer spacing and reducing thixotropic behavior, forming a looser, more stable mobile phase. This structural reorganization contributes to a more sustained viscosity reduction compared to conventional thermal methods. Despite these advantages, microwave treatment still faces key limitations. The heterogeneous dielectric responses of crude oil components may lead to non-uniform heating patterns, potentially compromising treatment reproducibility across different oil sources. Additionally, the current lack of precise control over microwave parameters poses challenges for optimizing treatment efficacy across diverse crude oil compositions. Importantly, the effectiveness of the method exhibits strong dependency on specific oil compositions, particularly the asphaltene-to-wax ratio, which limits its universal applicability. However, microwave treatment viscosity reduction retains significant untapped potential as an innovative approach within the field.

Although research on microwave modification for crude oil dates back to 2004 (Jiang, 2004), studies specifically targeting viscosity reduction have remained relatively limited until recently. In recent years, this area has received renewed research attention, with significant advances in the last five years (Li et al., 2022; Tajik et al., 2024). Existing studies have demonstrated that the application of microwaves to heavy oil can achieve a viscosity reduction of up to 87% (Lei et al., 2024; Li et al., 2018, 2022), while simultaneously reducing energy consumption by up to 85% compared to conventional heating methods (Martínez-Palou et al., 2013). In residual oil treatment, Lu et al. (2018) demonstrated 82.78% decrease in viscosity following microwave treatment at 420 °C. Zhao et al. (2014) discovered that the viscosity at 100 °C decreased by 4.39%, 1.94%, and 6.04%, respectively, for three kinds of residual oils. In heavy oil treatment, Dai et al. (2013) found that when the microwave treatment temperature reached 80 °C, the viscosity of heavy oil was reduced by 43.36%, and the reduction effect could last for 30 days. Shang et al. (2018) demonstrated that the viscosity of crude oil was reduced by 46.86% at a power of 2 kW and irradiation for 3 min. Ai et al. (2016) found that the asphaltene and resin of crude oil decreased by 1.6% and 0.6%, respectively, after microwave irradiation, resulting in a decrease in viscosity. Taheri-Shakib et al. (2018) investigated the effect of microwave irradiation on waxes and asphaltenes in crude oil samples and showed that different irradiation times lead to changes in their contents. Li et al. (2014) utilized microwave radiation in conjunction with a nano carbon black and heavy crude oil mixture, which resulted in a 96% reduction in oil sample viscosity and a 60% decrease in the asphaltene mass fraction. Additionally, studies have been conducted on oil recovery processes that exhibit a certain degree of viscosity reduction (Gao et al., 2022; Shamsi Armandi et al., 2021). Despite the valuable contributions of previous studies, a significant knowledge gap remains regarding the rheological modifications induced by microwave treatment in waxy crude oils, particularly from the perspective of wax crystal structure alteration. Moreover, the predominant focus on thermal effects in many studies may overshadow the critical role of the "non-thermal" effect, which is essential for a rigorous and systematic understanding of the microwave modification mechanism.

To address these gaps, this investigation comprehensively compares the modification effects of microwave treatment versus conventional direct heating on waxy crude oil. By integrating macroscopic techniques—including wax precipitation behavior, viscosity, and yield stress measurements—with microscopic analyses such as SARA and FTIR, this study aims to decouple the intricate interplay between the "non-thermal" and "thermal" effects. The experimental data demonstrate that microwave treatment induces a distinct "non-thermal" effect, which operates through mechanisms fundamentally different from conventional thermal processing. This work therefore elucidates the macroscopic rheological consequences of the "non-thermal" effect and probes its impact on the molecular architecture of crude oil at a microscopic level. **.i 19k- xeYt ixpDCc TcP6S6S6P6SJ8k9HH8Aw6ZSJ**

2.

the pour point (18 ± 1 °C) prior to subsequent rheological and chemical analysis.

2.3. Analysis and characterization methods

2.3.1. Wax characterization

The wax precipitation behavior of the crude oil was analyzed using differential scanning calorimetry (DSC, TA Q20, USA). Each sample was first heated to 80 °C and held for 1 min to erase its thermal history, and then cooled from 80 to −20 °C at a constant rate of 5 °C/min under a nitrogen (N_2) atmosphere. The wax appearance temperature (WAT) was determined as the onset temperature of the exothermic peak. The total heat of wax precipitation was obtained by integrating the area under the entire exothermic curve from the WAT to −20 °C. Subsequently, the cumulative volume of precipitated wax at each temperature was calculated from the partial integration of the DSC exothermic curve.

2.3.2. Pour point

The pour point of the crude oil was determined in accordance with the ASTM D5853-17 (2017) standard method. The oil sample was poured into a standard test jar to the mark, and a thermometer was inserted such that its capillary bulb was positioned 3 mm below the liquid surface. The jar was then stored at ambient temperature (18–24 °C) for 24 h to allow wax crystallization to reach equilibrium. Subsequently, the sample was heated to either 45 ± 1 °C or 9 °C above the expected pour point while being gently agitated, and then immediately cooled in a cooling bath. Thereafter, the fluidity was examined at 3 °C intervals by tilting the jar horizontally for approximately 5 s. The pour point was recorded as the lowest temperature at which no movement of the sample was observed.

2.3.3. Viscosity analysis

The rheometer used for the experiments was an Anton Paar RheolabQC coaxial cylindrical rotational rheometer. According to the industry standard SY/T 7549-2000, the viscosity-temperature curve was plotted, and the relationship between the kinematic viscosity and temperature of the crude oil was depicted in a Cartesian coordinate system. For Newtonian fluids, the viscosity was independent of the shear rate. For non-Newtonian fluids, the apparent viscosity at different shear rates was obtained using the power-law fluid rheology model, as shown in Eq. (1).

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

where μ is the viscosity at the corresponding shear rate, mPa·s; $\dot{\gamma}$ is the shear rate, s^{-1}; K is the coefficient of consistency, mPa·s; n is the flow behavior index, dimensionless.

To characterize the viscosity reduction effect of crude oil before and after microwave treatment, the viscosity reduction rate (Y) was introduced, which was calculated using Eq. (2).

$$Y = \frac{\mu_0 - \mu_{\mathrm{w}}}{\mu_0} \times 100\% \tag{2}$$

where μ_0, μ_{w} (mPa·s) are the viscosities of crude oil before and after microwave treatment, respectively.

2.3.4. SARA analysis

The crude oil was fractionated into saturates, aromatics, resins, and asphaltenes (SARA) according to the petroleum industry standard SH/T 0509-92. Briefly, the oil sample was dissolved in *n*-heptane within a round-bottom flask and refluxed for 30 min to precipitate asphaltenes. After filtration, the precipitate on the filter paper was thoroughly washed with hot *n*-heptane to remove residual resins, and then dissolved with toluene. The *n*-heptane-soluble maltenes were concentrated and separated into saturates, aromatics, and resins via liquid chromatography on an alumina column using a series of solvents. Each fraction was collected, and the solvent was evaporated. The fractions were then vacuum-dried and weighed to determine their mass.

2.3.5. FTIR

FTIR was performed using the KBr pellet method. First, a background pellet was prepared by finely grinding pure KBr powder in an agate mortar and pressing it under 10–20 MPa. The background spectrum of this pure KBr pellet was recorded. Subsequently, a sample pellet for analysis was prepared by uniformly coating a new, similarly prepared KBr pellet with a thin film of the crude oil. The single-beam spectrum of the oil-coated pellet was measured and automatically ratioed against the stored background spectrum to yield the final transmittance spectrum for analysis.

3. Results and discussion

3.1. Viscosity analysis

This study investigated the changes in the apparent viscosity of crude oil following microwave and direct heating treatments. As shown in Fig. 1, the viscosity reduction reached 80.63% and 82.93% at 18 °C for the microwave and direct heating methods, respectively. In Fig. 1(a), the viscosity of the directly heated oil generally decreased with increasing treatment temperature, although a slight increase was observed at 40 °C. Meanwhile, the anomaly point remained constant at 26 °C, indicating that conventional direct heating did not alter the temperature at which the crude oil transforms into a non-Newtonian fluid. In contrast, as shown in Fig. 1(b), the viscosity of the microwave-treated crude oil decreased with increasing treatment temperature above 80 °C but increased below this temperature. After microwave treatment, this anomaly point reached a minimum of 22 °C, corresponding to a viscosity reduction of 63.90%, which signifies a change in the fluid's transition behavior. Furthermore, a sharp viscosity increase of 76.94% was observed at 60 °C for the microwave-treated sample. The underlying mechanism is attributed to microwave-induced modifications of the wax crystal structure, which in turn alter macroscopic properties such as the anomaly point. The sharp increase at 60 °C is consistent with a "non-thermal" effect (Tang et al., 2023), wherein microwaves influence the orientation and interactions of polar molecules, disrupting the nascent wax network. The subsequent viscosity recovery above 80 °C, coinciding with the shifted anomaly point, suggests that the non-thermal effect facilitated a more favorable and stable wax crystal configuration. In contrast, as shown in Fig. 1(a), the wax crystal structure was not permanently altered by direct heating. Consequently, the viscosity reduction observed with direct heating is attributed solely to the thermal dissolution of wax and the destabilization of resin and asphaltene aggregates. Conversely, the viscosity reduction after microwave treatment resulted from the synergistic action of both thermal and non-thermal processes.

Fig. 2 presents the equilibrium viscosities of the crude oil at its pour point and various shear rates, following direct heating and microwave treatments, illustrating the changes in its non-Newtonian behavior. The microwave-treated oil exhibited a lower equilibrium viscosity than the untreated oil. At a shear rate of 10 s^{-1}, the viscosity of the microwave-treated oil was reduced to 233 mPa·s, a 77.49% decrease from the untreated sample's

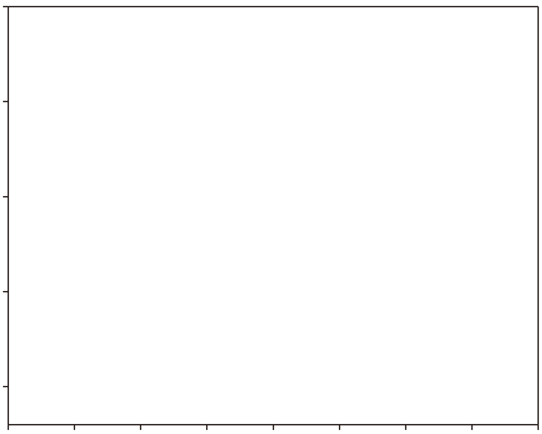

Fig. 1. Viscosity temperature curves at 10 s^{-1} using different treating methods. (**a**) Direct heating, (**b**) microwave.

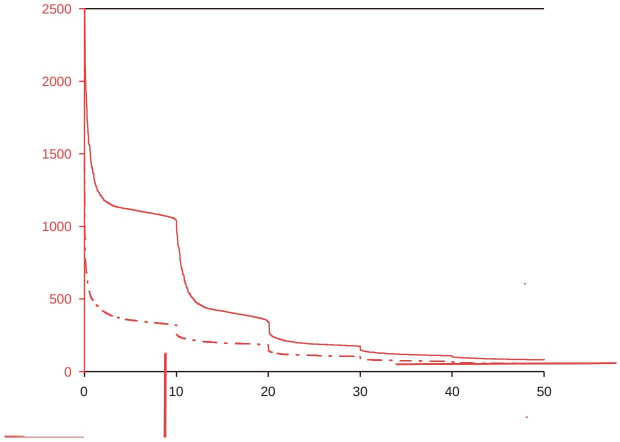

Fig. 2. The thixotropic behavior of different treating methods at pour point.

1035 mPa·s, while direct heating achieved a 69.47% reduction, lowering the viscosity to 316 mPa·s. Additionally, Fig. 2 shows that the difference in apparent viscosity between the untreated and treated oils diminishes with increasing shear rate, indicating a weakening of the structural modifications induced by the treatments.

The power-law model, as shown in Eq. (1), is employed to characterize the relationship between the apparent viscosity and shear rate for the crude oil under different treatment conditions. The fitted consistency coefficient (K) and flow behavior index (n) are summarized in Table 2. The flow behavior index (n) increased from 0.1044 for the untreated oil to 0.3490 after direct heating and to 0.6361 after microwave treatment, a trend consistent with previous studies (Su et al., 2024). Both direct heating and microwave treatment induced a substantial reduction in viscosity. More importantly, microwave treatment was more effective in suppressing the non-Newtonian characteristics of the crude oil, as evidenced by the greater shift in the anomaly point and the reduction in thixotropy. This suppression is critically for pipeline transportation, as non-Newtonian fluids require additional energy to overcome the yield stress and heterogeneous viscosity distribution inherent to their complex rheology. Their flow resistance increases nonlinearly, leading to fluctuating energy consumption and elevated pipeline blockage risks (Chala et al., 2018). Therefore, the attenuation of non-Newtonian behavior, which approximates Newtonian flow, significantly enhances pipeline transport efficiency. This underscores the critical importance of the microwave-specific effect, namely the non-thermal effect, achieved in this study, which went beyond mere thermal dissolution to fundamentally modify the oil's rheology.

Table 2
Values of the power-law model parameters at pour point.

Oil sample	K, mPa·s^n	n
Crude oil	6458.8	0.1044
Direct heating	1349.5	0.3490
Microwave treatment	528.7	0.6361

3.2. Pour point and DSC analysis

Fig. 3 compares the pour point and wax precipitation behavior of the crude oil before and after different treatments. Microwave treatment reduced the pour point from 18 to 6 °C. This 12 °C reduction is attributed to the disruption of the “card house” structure—a network of wax crystals responsible for gelation in waxy crude oil (Kiyingi et al., 2022; Li et al., 2024). The results suggest that the microwave's “non-thermal” effect altered the

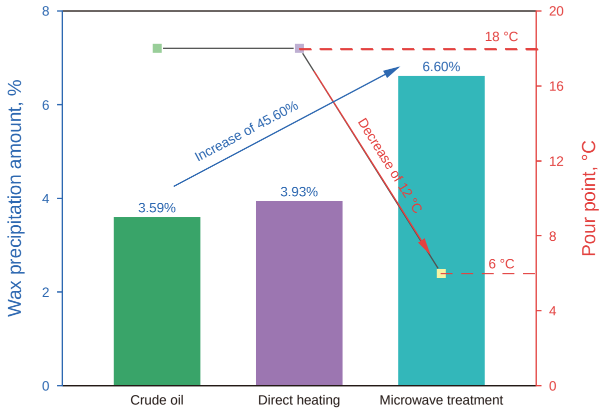

Fig. 3. Comparison of pour point and wax precipitation using different heating methods.

molecular orientation of the crude oil, thereby modifying the interactions between polar substances (e.g., asphaltenes) and wax crystals during their precipitation, a mechanism consistent with prior research (Liu et al., 2021).

Consequently, the precipitation of 6.60% of the waxes was required to form a “card house” structure capable of gelling the crude oil by immobilizing the liquid oil. In contrast, only 3.59% of precipitated waxes were sufficient to form a robust “card house” structure that gelled the untreated and directly heated oils at 18 °C. Following microwave treatment, the wax content required to form a continuous gel network increased from 3.59% to 6.60%. To accumulate this greater amount of wax crystals for gelation, a lower temperature was required, which is directly reflected in the observed decrease in the pour point. This further indicates that microwave treatment exerted a distinct “non-thermal” effect, which altered the orientation and interactions of internal molecules. This change in macroscopic properties is driven by an alteration in the wax crystallization pathway, wherein waxes tend to form localized aggregates—either by associating with limited resins and asphaltenes or through independent crystallization—rather than a cohesive, sample-spanning network.

Fig. 4 presents the DSC heat flow curves for the crude oil before and after microwave treatment, alongside the corresponding wax precipitation curves. Microwave treatment significantly reduced the wax appearance temperature (WAT) of the crude oil from 31.1 to 26.7 °C. The “non-thermal” effect of microwave treatment altered the orientation and interaction of asphaltenes and resins with wax molecules, reducing the number of wax crystal nucleation sites. Wax crystal precipitation during the cooling process of crude oil is a non-homogeneous phase nucleation process. It is generally believed that resins and asphaltenes in crude oil serve as crystallization points for wax crystallization (Mansoori, 2010). As a result, even though the wax molecules reached a supersaturated state at 31.1 °C, precipitation was inhibited by the scarcity of available crystallization points. As the temperature decreased to 26.7 °C, the wax molecules accumulated higher supersaturation. At this point, wax crystals began to form at a limited number of crystallization points. Upon further cooling to 24 °C, the wax molecules achieved even greater supersaturation, leading to an increased crystallization driving force and a higher wax precipitation rate. Notably, below 24 °C, the amount of precipitated wax following microwave treatment was consistently lower than that after direct heating. As the temperature continued to decrease, the influence of asphaltenes and resins on wax crystallization gradually diminished. At sufficiently low temperatures, extensive wax precipitation occurred, and the precipitation rate became governed by the diffusion of supersaturated wax molecules to the surfaces of existing crystals. Therefore, the “non-thermal” effect of microwaves influenced the wax precipitation properties of the crude oil.

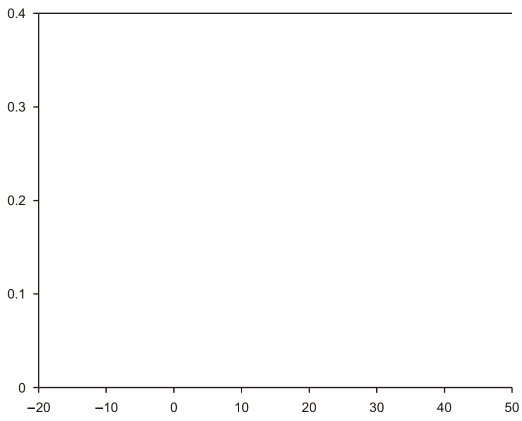

Fig. 4. Comparison of wax separation characteristic curves for different treatments.

The particle size distribution of wax crystals in the crude oil was characterized using polarized light microscopy coupled with image analysis (ImageJ), leveraging the birefringent properties of wax crystals under polarized light. Fig. 5 compares representative micrographs of the crude oil samples at their respective pour points before and after treatment. As corroborated by the wax precipitation curves in Fig. 4, the total amount of wax precipitated at the pour point was identical both before and after treatment. However, the spatial distribution and size of the wax crystals differed markedly. In both the untreated and directly heated oils (shown in Fig. 5(a) and (b)), the wax crystals were homogeneously distributed and exhibited small, uniform sizes. In contrast, microwave treatment (shown in Fig. 5(c)) resulted in a heterogeneous microstructure featuring localized clusters of numerous crystals. The corresponding particle size distributions are quantified in Fig. 6, confirming the formation of larger crystal aggregates after microwave treatment. This microstructural evolution is attributed to the “non-thermal” effect of microwave radiation, which disrupted the initial three-dimensional wax crystal network, thereby weakening the overall gel strength.

The experimental findings demonstrate that microwave treatment fundamentally alters the assembly and morphology of wax crystals. This “non-thermal” effect operates through a dual mechanism: It simultaneously weakens the intermolecular interactions between wax crystals and disrupts the functionality of the natural crystallization points, e.g., resins and asphaltenes. This dual action promotes pronounced wax supersaturation upon cooling below the WAT. This high supersaturation drives excessive crystal nucleation at the limited remaining sites and is sufficient to induce homogeneous nucleation in the bulk oil. Consequently, the crystallization process yields localized, bulky aggregates rather than a uniform gel network, ultimately leading to the fundamental alteration of the crude oil's non-Newtonian characteristics, as detailed in Section 3.1.

In summary, the “non-thermal” effect of microwave treatment altered the gelling properties of the crude oil. To evaluate these changes, yield stress tests were conducted on the three forms of crude oil, and the results are presented in Fig. 7. Following microwave treatment, the yield stress decreased to 62.30 Pa, representing an 82.45% reduction, while the yield strain was reduced to 5.66%, corresponding to a 20.05% decrease. This phenomenon is attributed to microwave-induced reorientation of wax molecules, which attenuates intermolecular forces. Concurrently, microwaves alter the crystalline alignment of wax, reducing inter-crystalline contact points and thereby diminishing gel strength (Zhu et al., 2024). The marked reduction in yield stress directly indicates a weakening of the wax crystal network. This demonstrates that the “non-thermal” effect modified the crystallization habit of the wax, disrupting the continuous network by reducing the interparticle forces between crystals. Consequently, the macroscopic rheological properties of the crude oil were fundamentally modified, as exemplified by the substantial reductions in both yield stress and strain.

3.3. Viscoelastic analysis

To evaluate the practical implications of the microwave “non-thermal” effect, this study focused on crude oil transportation, a process in which viscosity is a determining factor. The temporal stability of viscosity under both dynamic and static conditions was

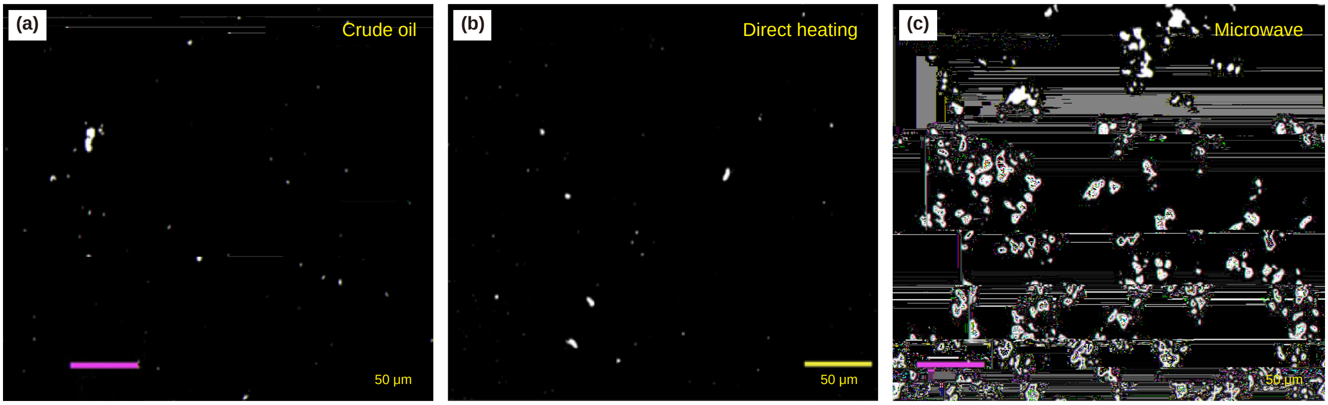

Fig. 5. Micrographs for oil samples using different heating methods. **(a)** Crude oil, **(b)** direct heating, **(c)** microwave.

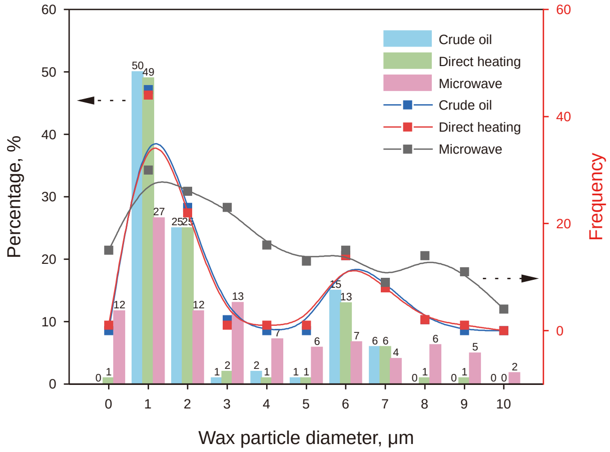

Fig. 6. Wax particle size distribution of the model oil samples at pour point using different heating methods.

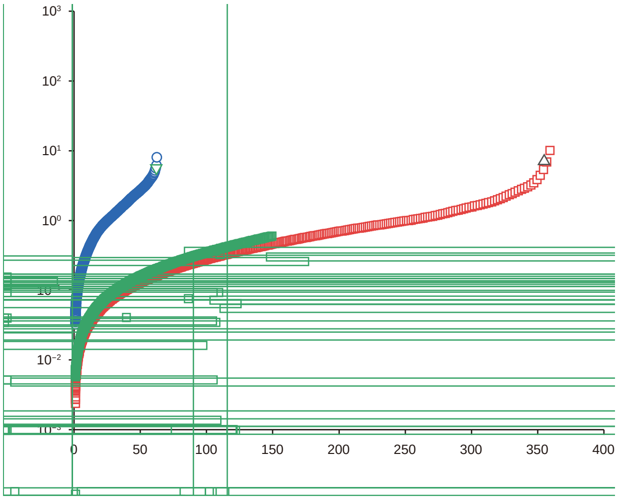

Fig. 7. Yield characteristics of different treatments at 5 °C.

Table 3
Static and dynamic stability after microwave treatment.

Static stability			Dynamic stability		
Oil sample	Viscosity, mPa·s		Oil sample	Viscosity, mPa·s	
	10 s^{-1}	50 s^{-1}		10 s^{-1}	50 s^{-1}
Crude oil	448.50	137.52	Crude oil	448.50	137.52
Microwave100	44.90	44.23	Microwave100	44.90	44.23
Microwave100-1d	45.85	48.99	Microwave100-1h	47.24	33.56
Microwave100-3d	70.52	72.69	Microwave100-2h	43.74	29.37
Microwave100-10d	100.25	83.56	Microwave100-5h	44.16	43.75
Microwave100-20d	437.25	135.47	Microwave100-24h	51.28	39.82

Microwave100-1d: Microwave treatment at 100 °C and 1 day of static aging. Microwave100-1h: Microwave treatment at 100 °C and 1 hour of shearing.

assessed for the treated oils, following established methods (Xia et al., 2022; Jalili Darbandi Sofla et al., 2020). As shown in Table 3, the microwave-treated oil maintained stable viscosity at shear rates of 10 s^{-1} and 50 s^{-1} for 10 days before beginning a gradual transition back to non-Newtonian behavior, fully reverting to its original state only after approximately 20 days. In stark contrast, the directly heated oil reverted to its original non-Newtonian state within just 2 days. These findings confirm that the “non-thermal” effect of microwave treatment confers superior stability to the crude oil compared to conventional heating. The sustained viscosity reduction underscores the potential of microwave treatment as a highly effective technology for enhancing pipeline flow.

Microwave treatment altered the polar molecules in the waxy crude oil, which lowered the wax crystallization temperature and

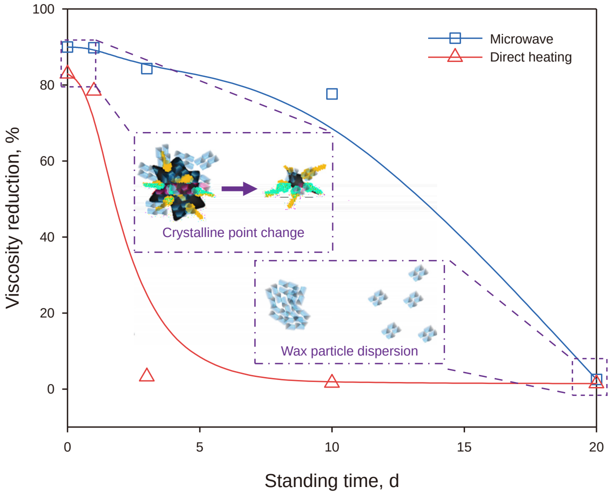

Fig. 8. Trends of viscosity reduction of oil samples heated in different ways during 20 days of standing time.

Table 4
SARA fractions of crude oil before and after microwave treatment.

Oil sample	Saturates, wt%	Aromatics, wt%	Resins, wt%	Asphaltenes, wt%
Crude oil	71.30	15.51	7.17	5.69
Microwave treatment	74.64	18.80	2.57	4.00

modified its crystallization habit. Consequently, the microwave “non-thermal” effect significantly reduced both the viscosity and the pour point of the waxy crude oil. To isolate the non-thermal effect, the long-term viscosity rebound was investigated after excluding the contribution of mere heating. To this end, oil samples were subjected to both direct heating and microwave treatment at the established optimum conditions (100 °C, 800 W, 3 min) and then monitored over a 20-day period. The apparent viscosities of both samples were measured periodically over the 20-day aging period to track the viscosity reduction rates, as shown in Fig. 8. The microwave-treated oil maintained a 70% viscosity reduction for 10 days, after which the reduction rate began to decrease rapidly. By the 20th day, the viscosity had rebounded to 97.49% of its original value. In contrast, the viscosity of the direct heating sample reverted to its original level within just 3 days. This rapid reversion indicates that the viscosity reduction from direct heating was primarily thermal and did not induce lasting molecular-level changes. The experimental results demonstrate that microwave treatment not only reduced the viscosity but also sustained this reduction over an extended period, as reported in previous studies (Taheri-Shakib et al., 2017). Therefore, the microwave “non-thermal” effect is critical for pre-transportation conditioning and subsequent processing of crude oil.

3.4. SARA and FTIR test analysis

SARA analysis revealed significant changes in the composition of the microwave-treated oil compared to the untreated crude oil, as presented in Table 4. Specifically, the proportions of the saturates (S) and aromatics (A) increased, whereas those of resins (R) and asphaltenes (A) decreased. This suggests that the microwave “non-thermal” effect disrupted the molecular structure of polar resins and asphaltenes, leading to their partial conversion into lighter fractions. The reduction in these network-forming components weakened the overall gel structure, thereby enhancing the oil's fluidity.

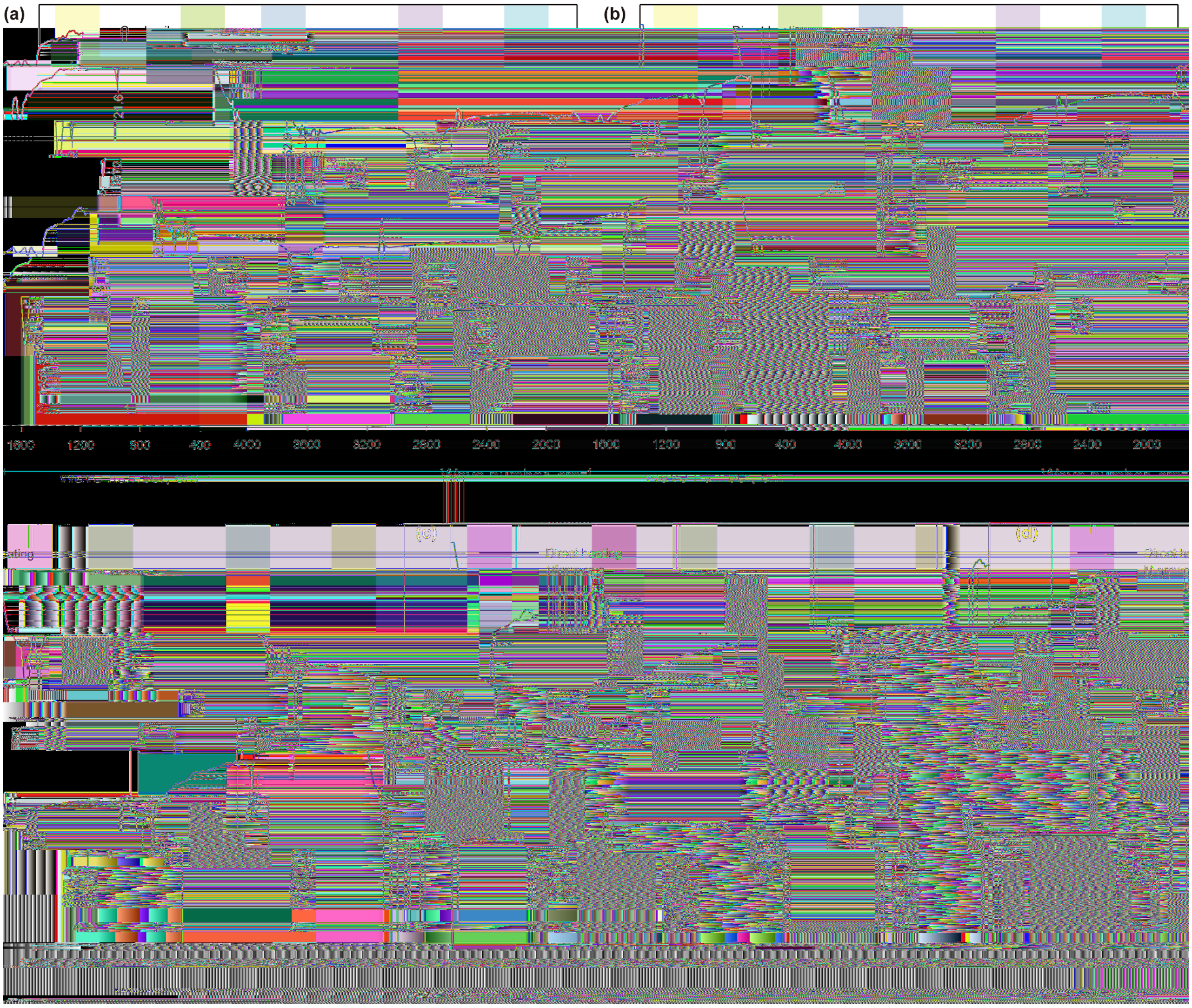

Fig. 9. Infrared spectra of oil samples using different heating methods. Treatment temperature at **(a)** 100 °C, **(b)** 80 °C, **(c)** 60 °C, and **(d)** 40 °C.

Table 5
Ratio of infrared peak area and peak intensity of oil samples using different treating methods.

Temperature	N	I_1	I_2	I_3	R	I'	I
Crude oil	0.0054	20.70	0.61	0.20	12.29	0.23	0.0005
DH40	0.0330	1.55	0.34	0.49	4.26	6.23	0.0061
MW40	0.0044	2.18	0.44	0.41	6.01	0.30	0.1100
DH60	0.0100	0.68	0.39	0.28	27.07	0.35	0.0100
MW60	0.0034	1.71	0.53	0.35	12.88	0.28	0.0300
DH80	0.0034	1.12	0.53	0.34	12.77	0.28	0.0022
MW80	0.0017	1.68	0.49	0.33	19.55	0.13	0.0005
DH100	0.0025	1.53	0.28	0.46	8.60	0.19	0.0500
MW100	0.0004	1.61	0.24	0.34	12.23	0.18	0.0002

DH40: Direct heating at 40 °C. MW40: Microwave treatment at 40 °C, same for other content.

FTIR spectroscopy is widely used to analyze molecular structures and identify chemical functional groups. The spectrum reveals characteristic absorption bands in several regions: the 2500–3700 cm^{-1} region for X–H stretching, the 2000–2300 cm^{-1} range for triple bonds, and the 1600–2000 cm^{-1} zone for double-bond vibrations, while the fingerprint region (1000–1600 cm^{-1}) contains signals from bending vibrations and polycyclic aromatics, before finally spanning the 400–1000 cm^{-1} range for aromatic C–H bending (Jain et al., 2023).

FTIR analysis was conducted to compare the chemical structures of crude oil samples subjected to direct heating and microwave treatment at different temperatures. The results are summarized in Fig. 9. The characteristic peaks were assigned as follows: Peak 1 to aromatic C–H bending; Peak 2 to aliphatic C–H bending vibrations of $–CH_3$ and $–CH_2$ groups; Peak 3 to stretching vibrations of triple bonds (e.g., $C\equiv C$); Peak 4 to C–H stretching vibrations of aliphatic $–CH_3$; and Peak 5 to aromatic C–H and O–H stretching vibrations. Comparative analysis of the spectra indicates that microwave treatment significantly altered the crude oil's chemistry. These alterations include enhanced hydrogen bonding, modifications to triple-bond moieties, structural rearrangements of double bonds, and changes in the composition or conformation of functional groups and aromatic systems.

After processing Fig. 9, the area and intensity of each peak were calculated, and the ratio relationship between the area and intensity of each peak was analyzed (Borda et al., 2024), as shown in Table 5.

As shown in Table 5, the N value of crude oil decreased after microwave treatment, indicating a reduction in the number of carbon atoms in the alkyl side chains of the crude oil. This suggested a significant increase in the dispersion of macromolecules within the crude oil. While the R value increased after microwave treatment, the aromaticity of the crude oil increased, and more ring structures were formed from the broken alkyl side chains in the crude oil, resulting in a higher number of planar molecules. The increase in asphaltene indices I_1 and I_2 after microwave treatment indicated shorter aliphatic substituent chains and an increased abundance of aliphatic and aromatic groups. The higher pre-treatment asphaltene I_3 ratio suggested a greater propensity for asphaltene molecules to aggregate via hydrogen bonding prior to microwave treatment. $I' = I_{2838}/I_{2971}$ and $I'' = I_{1460}/I_{1374}$ significantly decreased after microwave treatment, indicating that the alkane long chains were converted to shorter-chain structures during the reaction process. In summary, the shortening of alkane chains in crude oil and the formation of coplanar ring structures following chain breakage, a process where coplanar aromatic configurations facilitate π–π stacking interactions, collectively altered the wax crystallization process, ultimately weakening the gelling structure.

The integrated analysis of SARA and FTIR data demonstrates that microwave treatment significantly reduced the viscosity and pour point of the crude oil by altering molecular chemical structures and polarity, as shown in Fig. 10. This transformation was driven by the synergistic interaction between the microwave's "non-thermal" and thermal effects. Firstly, microwave irradiation modified intermolecular interactions, which reduced the wax crystallization points, altered the crystal morphology, and disrupted the cohesive wax network. These changes collectively suppressed the crude oil's non-Newtonian behavior, resulting in a substantially reduced pour point. Secondly, microwaves facilitated

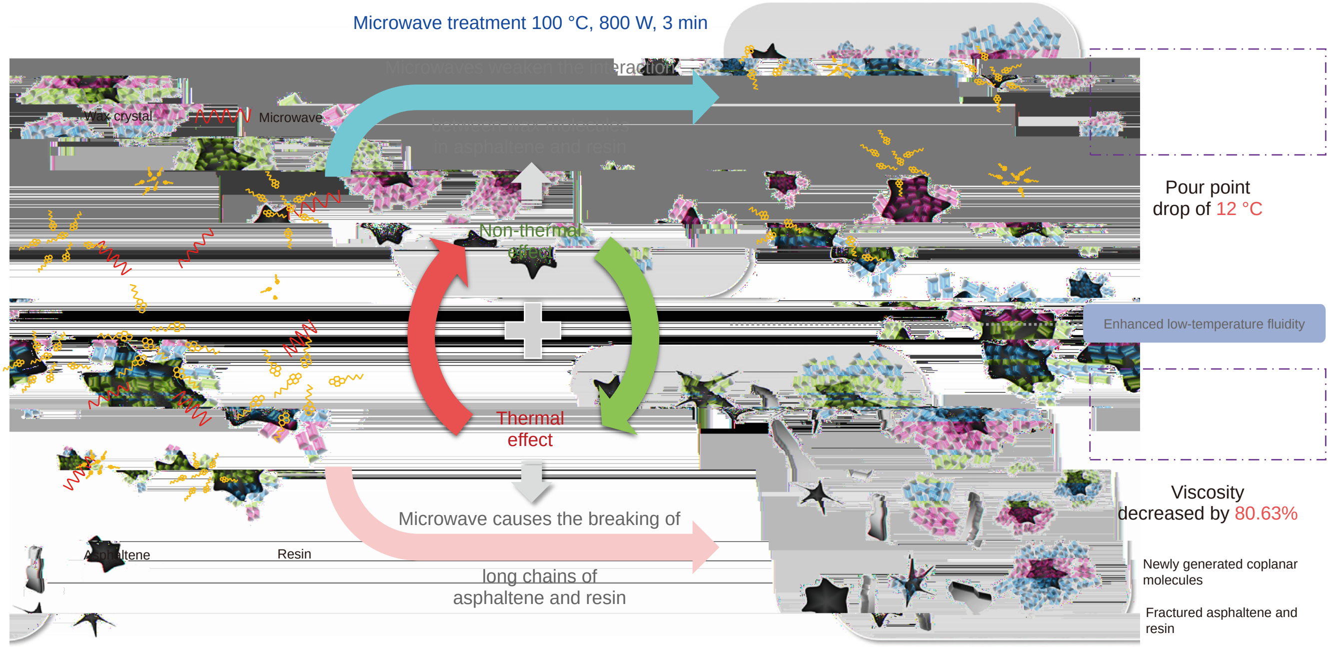

Fig. 10. Mechanism diagram for changing the rheological properties of waxy crude oil under microwave treatment.

the cleavage of large polar molecules (resins and asphaltenes), thereby disrupting the wax flocculation networks. This structural modification of the heavy fractions directly improved the crude oil's rheology. The microwave effects further orchestrated an orderly alignment of these molecules, facilitating their recombination into aromatic cyclic structures and thereby reducing the viscosity of the crude oil. In conclusion, microwave treatment is a highly effective method for enhancing the rheological properties of waxy crude oils. Its efficacy surpasses that of conventional thermal treatment by fundamentally altering both the wax crystallization process and the chemical composition of the governing heavy fractions.

4. Conclusions

This study employed a comparative approach, subjecting waxy crude oil to both microwave and conventional direct heating, to decouple the distinctive “non-thermal” effects of microwave irradiation from general thermal effects. The “non-thermal” effect was found to reorient polar molecules, modify wax crystal morphology, lower the pour point, and significantly reduce viscosity. These improvements provide a novel strategy for enhancing crude oil transportation efficiency.

(1) The microwave “non-thermal” effect modified the interactions between asphaltenes, resins, and waxes, thereby inhibiting crystallization and altering wax crystal morphology. These changes reduced the wax appearance temperature by 6 °C and increased the critical wax content required for gelation from 3.59% to 6.60%. Consequently, the yield stress and yield strain decreased by 82.45% and 20.05%, respectively, and the pour point was lowered by 12 °C due to the higher wax content needed to form a stable network.
(2) The synergy between thermal and non-thermal effects reduced the apparent viscosity by 63.90%–80.63% within the temperature range of 18–22 °C. This viscosity reduction persisted for up to 20 days, demonstrating the treatment's sustained effectiveness and its potential for optimizing pipeline transport.
(3) At the molecular level, the “non-thermal” effect increased the proportions of saturates and aromatics while reducing resin and asphaltene contents. Furthermore, microwave treatment induced the cleavage of macromolecules, as evidenced by SARA analysis, resulting in a lower average molecular weight. FTIR spectroscopy confirmed modifications in hydrogen bonding and aromatic structures, promoting the formation of more planar molecules. These compositional and structural changes collectively contributed to the sustained viscosity reduction and improved fluidity.

CRediT authorship contribution statement

Ming-Yue Lv: Visualization, Resources, Data curation, Writing – review & editing, Methodology, Formal analysis, Investigation, Writing – original draft, Validation, Conceptualization. **Yu-Ming Zhang:** Investigation, Validation, Conceptualization, Writing – review & editing, Supervision, Methodology, Data curation, Resources. **Jia-Zhou Li:** Formal analysis, Validation, Methodology, Supervision, Writing – review & editing, Investigation, Data curation. **Duo Cai:** Conceptualization, Software, Data curation, Validation, Resources. **Shan-Peng Han:** Conceptualization, Supervision, Methodology, Software, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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