Petroleum Science 22 (2025) 5258–5267

Contents lists available at ScienceDirect

Petroleum Science

journal homepage: www.keaipublishing.com/en/journals/petroleum-science

Original Paper

Electrorheological effect enhancement of waxy crude oil with graphene nanoparticles and its mechanism

Jia-Bao Kang [a], Hong-Ying Li [a,*], Chao-Yue Zhang [a,b], Yi-Wei Xie [a], Yang Su [a], Zhao-Ming Yang [a], Huai Su [a], Jin-Jun Zhang [a,**]

[a] National Engineering Research Center of Oil and Gas Pipeline Transportation Safety, MOE Key Laboratory of Petroleum Engineering, Beijing Key Laboratory of Urban Oil & Gas Distribution Technology, China University of Petroleum (Beijing), Beijing, 102249, China
[b] PipeChina Institute of Science and Technology, Tianjin, 300457, China

ARTICLE INFO

Article history:
Received 6 May 2025
Received in revised form
9 July 2025
Accepted 18 October 2025
Available online 24 October 2025

Edited by Teng Zhu

Keywords:
Waxy crude oil
Graphene nanoparticle
Electrorheological effect
Viscosity reduction
Flow assurance

ABSTRACT

Electric treatment is a promising method to improve the cold flowability of waxy crude oil by taking advantage of the electrorheological (ER) effect of the crude oil. However, the efficacy of viscosity reduction under an electric field differs significantly among various crude oils. This paper investigates the role of graphene nanoparticles (GNPs) in enhancing the ER effect of a waxy crude oil with less sensitivity to the electric field. It is found that the addition of GNPs may significantly enhance the ER effect and its durability. Quantitative results revealed that with 200 ppm GNPs, the maximum viscosity reduction reaches 78.4% (vs. 57.1% for undoped oil) at 34 °C, and the treatment time to achieve 57.1% viscosity reduction is shortened from 10 min to 2 min. Furthermore, GNPs reduce the energy density threshold for maximum viscosity reduction from 1.08 J/mL to 0.96 J/mL, weaken the structure of the gelled oil (yield stress reduction: 80.1% vs. 43.5% for undoped oil), and extend the durability of viscosity reduction from 5 to 12 h. It is further demonstrated that both the added GNPs and charged particles in crude oil accumulate on the surfaces of wax particles under an electric field, and the effect of GNPs' nano-templating and the electrostatic repulsion of charged particles work together, weakening the wax particle interactions and thereby enhancing the ER effect. The study provides an approach to the enhancement of the cold flowability improvement efficacy by electric treatment for waxy crude oil.

1. Introduction

Crude oil, as a vital energy resource and chemical feedstock, will continue to play a significant role for a considerable period in the future (Vasiljeva et al., 2022; Peng and Liang, 2023). However, the shift toward difficult-to-handle crude oils such as waxy crude oil has become an inevitable trend with the depletion of conventional light oil resources (Malozyomov et al., 2023; Hou et al., 2025). The poor cold flowability of waxy crude oil poses significant flow assurance challenges in its production and pipeline transportation (Zhang et al., 2013; Olajire, 2021; Kiyingi et al., 2022). Improving the oil's cold flowability is a fundamental measure to solve these problems (Yao et al., 2022; Ratnakar et al., 2025), and thus the industry calls for clean and efficient technology (Al-Shboul et al., 2023; Xie et al., 2025; Yang et al., 2025).

Electric treatment, first proposed by Tao's team (Tao and Xu, 2006), is a promising method to improve the cold flowability of waxy crude oils by taking advantage of the ER effect of waxy oils (Homayuni et al., 2011; Tang et al., 2011; Jalal et al., 2022; Rudyk et al., 2022). By treating with a high-voltage electric field, the oil's cold flowability may be significantly improved, with over 80% of viscosity and yield stress reduction for some crude oils (Tao and Tang, 2014; Jain et al., 2020), and this effect can last for more than 12 h after removal of the electric field (Xie et al., 2023a). It can be achieved by applying a DC electric field, whether parallel or perpendicular to the oil flow direction (Ma et al., 2017; Huang et al., 2021a), or subjecting a static crude oil to a DC or alternating current field (Zhang et al., 2023). However, the oil's wax precipitation characteristics and pour point are hardly affected by

* Corresponding author.
** Corresponding author.
E-mail addresses: lihy314@163.com (H.-Y. Li), zhangjj@cup.edu.cn (J.-J. Zhang).
Peer review under the responsibility of China University of Petroleum (Beijing).

https://doi.org/10.1016/j.petsci.2025.10.017

electric treatment (Li et al., 2019). Moreover, this flowability improvement can also achieved for gelled crude oil which was electrically treated in a liquid state and subsequently cooled to become a gel, and directly for gelled oil, with the structural behaviors weakened such as viscoelasticity, thixotropy, and yield stress (Li et al., 2019; Huang et al., 2021b).

The efficacy of electric treatment is significantly influenced by several external factors, including electric field strength, treatment time, and treatment temperature (Huang et al., 2021a). Generally speaking, higher field strength, longer treatment time, and lower treatment temperature are more likely to result in higher efficacy of electric treatment. The improved efficacy observed with a stronger electric field and extended treatment time is fundamentally attributed to the increased energy input from the electric field (Zhang et al., 2024).

However, the viscosity reduction efficacy under an electric field differs significantly among waxy crude oils with different compositions, with some exhibiting weak or even no efficacy (Xie et al., 2023a, 2023b, 2024). This fact calls for efforts to enhance the efficacy of electric treatment. To date, only a few studies have dealt with the enhancement of the electric field efficacy for an Iraqi crude oil, rather than waxy crude oil. Ibrahim et al. (2017) investigated the effect of nano-silica within a concentration range of 0–700 mg/L on the electric treatment efficacy of crude oil, and they found that the effect of the nano-silica was non-monotonic, with the optimal concentration being 100 mg/L. With an electrode spacing of 6.11 cm, by applying a voltage of 188 V to the oil for 32 s, the viscosity at 10 °C was reduced from 30.5 to 20.5 mm^2/s, marking a viscosity reduction of 32.8%. Under the same treatment conditions, the viscosity of oil added 100 mg/L of nano-silica was reduced to 12.8 mm^2/s, representing an increased reduction to 58.0%. In subsequent work, Ibrahim et al. (2022) designed a graphene supercapacitor by coating two parallel steel plates with 0, 25, and 50 wt% graphene nanoflakes to enhance the capacitance of the system. They found that the treated oil using the coated electrodes significantly increased the viscosity reduction efficacy, and the supercapacitor's optimal graphene concentration was 36.9 wt%.

The migration and accumulation of charged particles, i.e., resins and asphaltenes in crude oil, are critical mechanisms behind this viscosity-reducing effect (Chen et al., 2021). When wax molecules crystallize and precipitate, a pronounced dielectric mismatch arises between the charged particles and the relatively insulating wax particles (Charin et al., 2017; Chen et al., 2019). Subjected to an electric field, charged particles migrate toward and accumulate on the surfaces of wax particles, causing electrostatic repulsion between them, thereby weakening interparticle attractions and thus leading to a significant reduction in viscosity (Xie et al., 2023c). Furthermore, Xie et al. (2023b), by preparing waxy oils with micro-sized spherical Fe_3O_4 particles, demonstrated that the electric field caused Fe_3O_4 particles to migrate toward and collide with the wax particles, weakening the structural strength of gelled oil, though the particles could not reduce the oil's viscosity as they did not accumulate on wax surfaces. This may explain the reason why the application of an electric field can weaken the gel structure but hardly reduce viscosity for some waxy crude oils. While Jain et al. (2025) attributed the yield stress and viscosity reduction in gelled waxy crude oil to the Maxwell stress induced by the electric field.

Based on the mechanism of the ER effect of waxy crude oil, we make efforts to explore an approach to the ER effect enhancement by adding materials. Graphene nanoparticles, renowned for their excellent conductivity (James and Tour, 2013), may offer a promising solution to enhance the ER effect of waxy crude oils. Their significant dielectric mismatch with insulating wax particles under an electric field is an advantageous property. Beyond their conductivity, GNPs have been demonstrated to intrinsically improve the cold flowability of waxy crude oils even in the absence of an electric field. Crucially, GNPs' doping temperature is the primary factor influencing the GNPs' efficacy (Kang et al., 2024). Specifically, within the doping temperature range from the WAT to the WDT, the GNPs' efficacy gradually improves. Increasing the doping temperature above the WDT does not further improve the cold flowability. But unfortunately, the GNPs have no impact on the cold flowability at doping temperatures below the WAT, a behavior analogous to that of pour point depressants. The sheet-like structure of GNPs acts as a nano-template that inhibits wax particle aggregation by providing heterogeneous nucleation sites and/or altering particle morphology (Heydari and Mohammadi, 2018; Kang et al., 2024). Additionally, under an electric field, GNPs with a sheet-like structure may be more prone to accumulation on the surface of wax particles, which may generate the nano-templating effect to diminish the attraction among wax particles.

There is a research gap in the method of the ER effect enhancement of waxy crude oil by adding a certain material. Compared to nano-SiO_2, Fe_3O_4 particles, and so on, GNPs were selected for two critical reasons: their exceptional electrical conductivity and sheet-like structure. To bridge this gap, this paper investigates: (1) The influence of GNPs dosage on viscosity reduction of liquid waxy crude oil under different electric field conditions (treatment time, energy input density, temperature); (2) the effect of GNPs on the structural behaviors of gelled oil previously electrically-treated in its liquid state and then cooled; (3) the effect of GNPs on the durability of ER effect enhancement; (4) the mechanism of ER effect enhancement by adding GNPs was explored by preparing model oil and doping with GNPs. This approach aims to establish GNPs as an efficient enhancer for cold flowability improvement in waxy crude oils by an electric field.

2. Experiment

2.1. Materials

(1) Waxy crude oil

The physical properties of the waxy crude oil used in this study, along with the test methods, are presented in Table 1, and the wax precipitation curve is illustrated in Fig. 1.

Before the rheological measurements, the waxy crude oil underwent pretreatment: the oils were heated to 80 °C in sealed bottles and maintained for 2 h at this temperature, followed by naturally cooling to room temperature and standing for 48 h (Xie et al., 2025). This pretreatment aimed to eliminate the influence of thermal and shear histories on the rheological results, ensuring consistent baseline conditions across all experiments and guaranteeing the reproducibility of the data.

Table 1
Physical properties of the studied waxy crude oil.

Parameter	Value	Test method
Density at 20 °C, kg/m^3	860.0	ISO 3675-1998
Pour point, °C	33	ASTM D5853-17
WAT, °C	46.2	DSC
Wax content, wt%	19.0	DSC
Resins, wt%	9.10	ASTM D4124-09
Asphaltenes, wt%	0.70	ASTM D4124-09

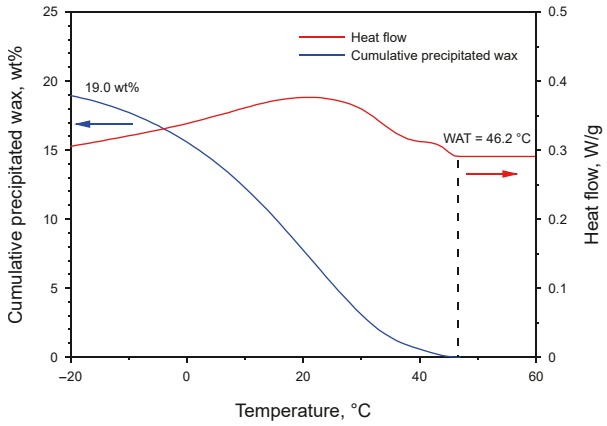

Fig. 1. Wax precipitation curve of waxy crude oil.

(2) Graphene nanoparticles

The GNPs used in this study were prepared by a physical method (Geng et al., 2009) and supplied by Shenzhen Suiheng Technology Co., Ltd. It featured an average particle size of 7–12 μm, a thickness of approximately 1 nm, and consisted of 1–3 layers with a single-layer content of ≥80%. As shown in the SEM image in Fig. 2, the GNPs exhibited a layered structure with excellent dispersion between layers, without apparent layer-wise aggregation.

(3) Preparation of the waxy crude oils doped with GNPs

The authors' previous research demonstrated that the doping temperature was a key factor influencing GNPs' efficacy in improving the cold flowability of waxy crude oil (Kang et al., 2024). When the doping temperature is below the oil's WAT, the GNPs have little effect on the cold flowability of the oil. This study focuses on the impact of GNPs on the ER effect of waxy crude oil, ensuring that the viscosity of the crude oil, undoped/doped with GNPs, before being subjected to the electric field, is kept consistent. Thus, a doping temperature of 45 °C was used, which is below the oil's WAT.

The waxy crude oil doped with various dosages of GNPs (0, 20, 50, 100, 200, 300, and 500 ppm) was put in a preheated ultrasonic water bath at 45 °C and sonicated for 30 min to ensure the GNPs were well dispersed in oil. Afterward, the oils were allowed to cool naturally to room temperature for subsequent use.

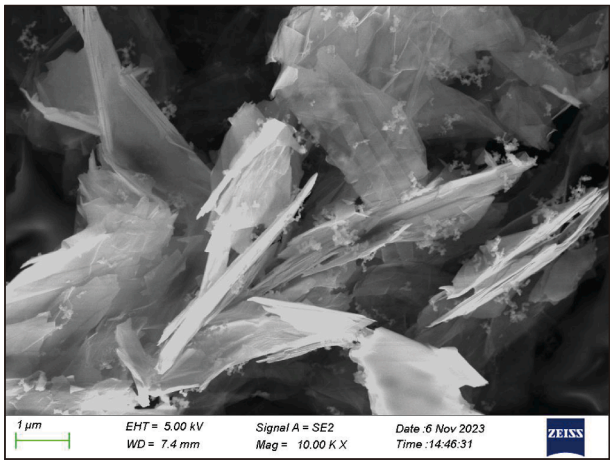

Fig. 2. Scanning electron microscopy of GNPs.

2.2. Rheological measurements

In this study, the ARES-G2 controlled-strain rheometer (TA Instruments, USA) equipped with an electrorheological module was used for energy input tests (Section 3.1.3), while the HAAKE MARS III controlled-stress rheometer (Thermo Fisher Scientific, Inc., Germany) with its corresponding electrorheological module was employed for the experiments in all other sections. The experimental workflow is illustrated in Fig. 3.

To ensure the results' reliability and account for potential variability, all rheological measurements were performed three times under identical conditions, with a relative uncertainty of less than 5%. And a fresh sample was changed after each rheological measurement. The reported values (e.g., viscosity reduction, yield stress reduction, and rheological curve) represent the median of the three measurements.

2.2.1. Viscosity measurement

The GNPs-doped oil at 45 °C was filled into a preheated rheometer and kept isothermally for 10 min, then cooled at a rate of 0.5 °C/min to the test temperature and maintained for 20 min to ensure the sample is isothermal. The equilibrium viscosity at 10 s^{-1} was then measured and recorded as η_0. Subsequently, a DC electric field was applied to the sample. After that, the viscosity at 10 s^{-1} of the treated oil was measured, and the value at 20 min was recorded as η_E. The viscosity reduction induced by the electric field was calculated as $\Delta\eta = (\eta_0 - \eta_E)/\eta_0 \times 100\%$.

2.2.2. Structural behaviors measurement

The doped oil at 45 °C was filled into a preheated rheometer and kept isothermally for 10 min, then cooled at a rate of 0.5 °C/min to 34 °C, i.e., 1 °C above the pour point. Subsequently, the high-voltage generator was activated to apply a 3 kV/mm DC electric field to the liquid oil for 10 min. Following this, the oil was further cooled at the same rate to 3 °C below its pour point and isothermally held for 60 min to ensure the full formation of the gel structure, i.e., "aging" of the structure (Huang et al., 2021b). For the rheomalaxis tests (Lesin et al., 2011), a stepwise shear rate method was employed, with six shear rates set at 1, 2, 4, 8, 16, and 32 s^{-1}. The shear rate of 1 s^{-1} was applied for 30 min, while the other shear rates were applied for 20 min to obtain the equilibrium viscosity at each shear rate. Dynamic stress sweep tests (Huang et al., 2021b) were conducted with an oscillation frequency of 1 Hz over a stress range of 1–200 Pa, taking measurements at intervals of 0.1 Pa, which can provide storage modulus, loss modulus, and yield stress simultaneously.

3. Results and discussions

3.1. Influence of GNPs dosages and electric treatment conditions on viscosity reduction of liquid oil

3.1.1. The dosage of GNPs

The influence of GNPs dosages from 0 to 500 ppm on the viscosity of the electrically treated oil was investigated under the condition of 3 kV/mm for 60 s at 34 °C. The viscosity at 10 s^{-1} was measured, and the corresponding viscosity reduction was calculated, which is shown in Fig. 4.

As shown in Fig. 4, the viscosity of the electrically treated oil observably decreased with increasing GNPs dosage from 0 to 500 ppm. Compared to the undoped oil whose viscosity at 10 s^{-1} was reduced from 779.9 to 620.8 mPa·s as a result of electric treatment, corresponding to a viscosity reduction of 20.4%, the 10 s^{-1} viscosity of the oil doped with 200 ppm GNPs was reduced to 434.4 mPa·s (a viscosity reduction of 44.3%) after the electric

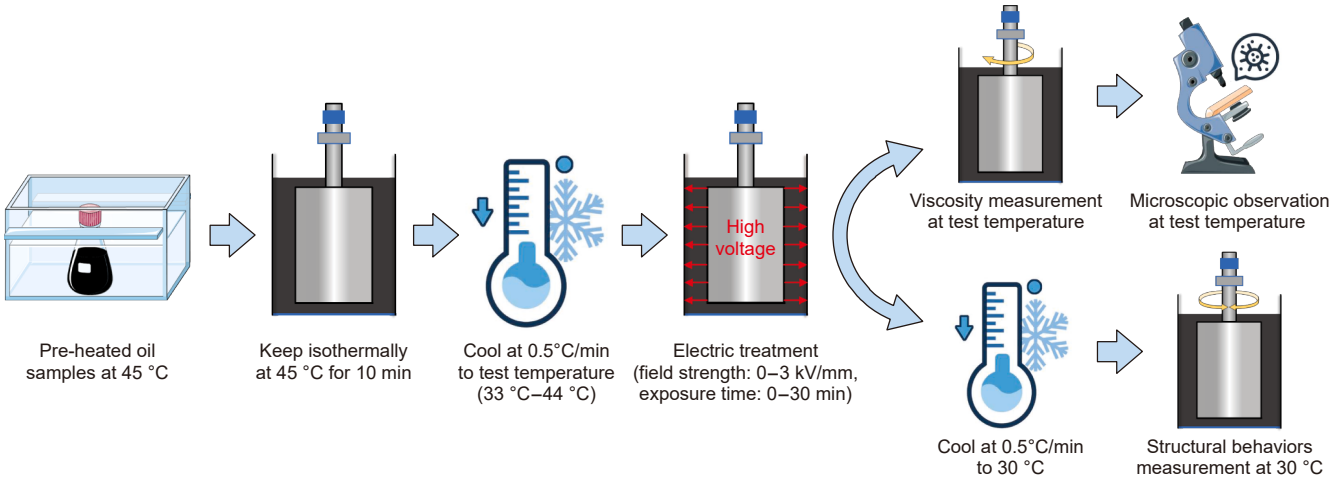

Fig. 3. Experimental flow chart in this study.

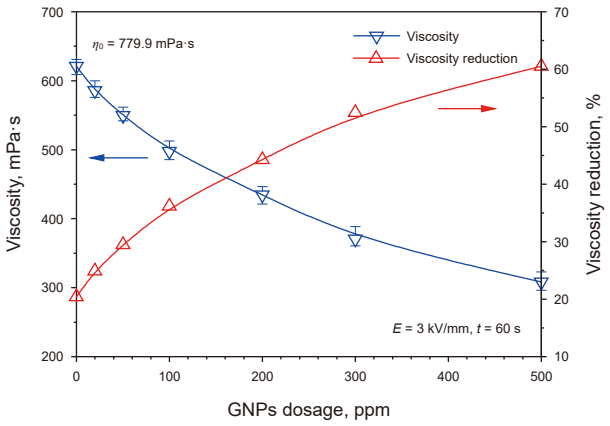

Fig. 4. The 10 s^{-1} viscosity reduction of the electrically treated oil doped with 0–500 ppm GNPs.

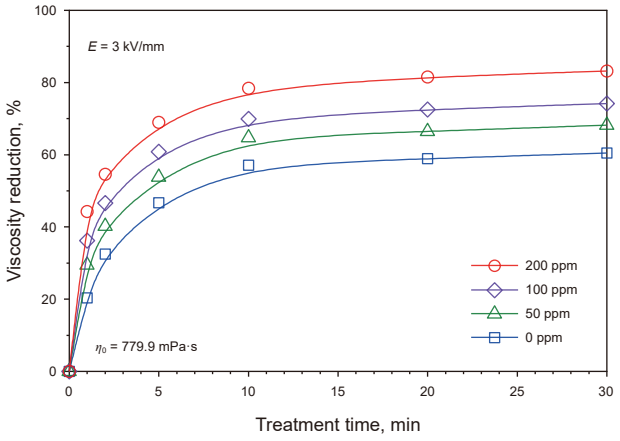

Fig. 5. The influence of electric treatment time on the viscosity reduction of the oil doped with different GNPs dosages.

treatment, indicating that the viscosity reduction contribution from GNPs was 23.9%. When the GNPs dosage was increased to 500 ppm, the viscosity further decreased to 308.1 mPa·s, achieving a viscosity reduction of 60.5%, with GNPs contributing 40.1% to this viscosity reduction. Due to the excellent conductivity of GNPs, higher dosages will lead to larger currents under an electric field. Considering factors such as economic feasibility and safety (with a current limit of 2 mA for this equipment), the maximum dosage used in the following study was limited to 200 ppm.

3.1.2. Electric treatment duration

The oils doped with GNPs were exposed to an electric field of 3 kV/mm for different time at 34 °C. The viscosity at 10 s^{-1} was measured before and after the electric treatment, and the corresponding viscosity reduction was calculated, which is shown in Fig. 5.

As can be seen in Fig. 5, the viscosity reduction gradually increases with increasing treatment time and finally reaches a maximum. After the treatment time reaches 10 min, further extension of the treatment time has a little more effect on viscosity reduction. In other words, the application of a 3 kV/mm electric field for 10 min may achieve the maximum viscosity reduction of the oil at the test temperature of 34 °C. The maximum viscosity reduction for the undoped oil and the oil doped with 50, 100, and 200 ppm GNPs is 57.1%, 64.7%, 68.5%, and 78.4%, respectively, which indicates that the GNPs significantly enhance the maximum viscosity reduction. Furthermore, the GNPs obviously shorten the time required to achieve the same viscosity reduction, and the more GNPs, the shorter the time to reach a viscosity reduction. For example, the time for the undoped oil to reach a 57.1% viscosity reduction is 10 min, while for the oil doped with 200 ppm GNPs, the same viscosity reduction is achieved in just about 2 min. In summary, the addition of GNPs may not only improve the viscosity reduction and the maximum viscosity reduction induced by the electric field but also shorten the treatment time needed to achieve the same reduction.

3.1.3. Density of electric energy input

Previous studies have revealed that energy input is a crucial factor in determining the viscosity reduction of electrically treated crude oil (Zhang et al., 2024). However, the addition of GNPs may enhance the conductivity of the oil and lead to a higher energy input under the same electric treatment conditions.

To investigate the effect of inputted energy density on the viscosity reduction before and after doping with 200 ppm GNPs, an ARES-G2 rheometer equipped with an electrorheological module was used. A parallel plate system with a diameter (D) of 50 mm was employed, and the gap (h) between the plates, ranging from

0.5 to 2.0 mm, was adjusted to change the oil volume ($V = 0.25\pi D^2 h$) from 1.0 mL to 2.5 mL. The inputted energy density ($w = UIt/V$) and viscosity reduction were calculated based on the electric field parameters (voltage U, current I, and treatment time t) and the 10 s^{-1} viscosity before and after the treatment. The results are shown in Fig. 6.

As observed in Fig. 6, in both cases the viscosity reduction gradually increases and eventually reaches a maximum at this temperature with the increase of the inputted energy density, while the oil doped with 200 ppm GNPs shows a much better effect both on the viscosity reduction and the maximum viscosity reduction than the undoped oil. Furthermore, the GNPs reduce the energy density threshold required to achieve the maximum viscosity reduction from 1.08 J/mL for the undoped oil to 0.96 J/mL for the oil doped with 200 ppm GNPs.

3.1.4. Electric treatment temperature

At temperatures below the WAT, the strong attraction between the precipitated wax particles is the primary cause of the poor cold flowability of waxy crude oil. Furthermore, it has been demonstrated that the precipitated wax amount at the electric treatment temperature is a key factor determining the viscosity reduction (Huang et al., 2021a).

This section focuses on the effect of GNPs on the viscosity reduction at different electric treatment temperatures from the pour point (33 °C) to the WAT (46.2 °C). The viscosity at 10 s^{-1} before and after electric treatment at 3 kV/mm for 10 min was measured, and the viscosity reduction was presented in Fig. 7. The relationship between viscosity reduction and the precipitated wax amount was shown in Fig. 8.

As is expected, better viscosity reduction was achieved at lower temperatures due to the existence of more wax particles that can interact with the charged particles, and again, the GNPs facilitate the achievement of better viscosity reduction at all temperatures/precipitated wax amounts. For instance, at the precipitated wax of 0.21 wt%, the viscosity reduction increases from 11.4% of the undoped oil to 20.5% of the oil doped with 200 ppm; if the precipitated wax increases to 2.32 wt%, the corresponding viscosity reduction is 57.1% and 78.4%, respectively.

3.2. Effect of GNPs on ER behaviors of gelled oil

This section investigates the impact of GNPs on the gel structure of the oil electrically treated at its liquid state and then cooled. The undoped/doped sample was exposed to an electric field of 3 kV/mm at 34 °C (1 °C above the pour point) for 10 min and then followed by cooling to 30 °C (3 °C below the pour point).

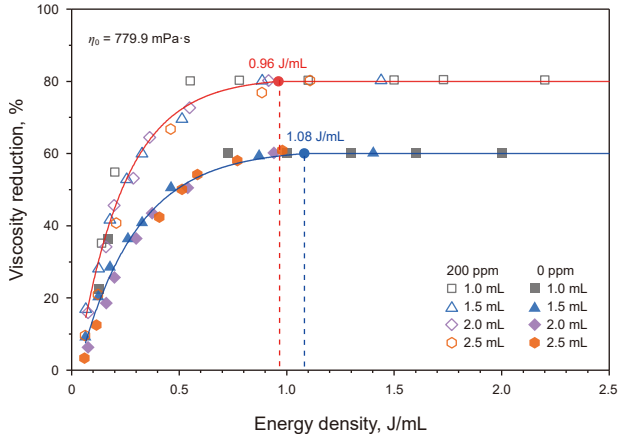

Fig. 6. Viscosity reduction vs inputted energy density of the oil undoped/doped with 200 ppm GNPs at 34 °C.

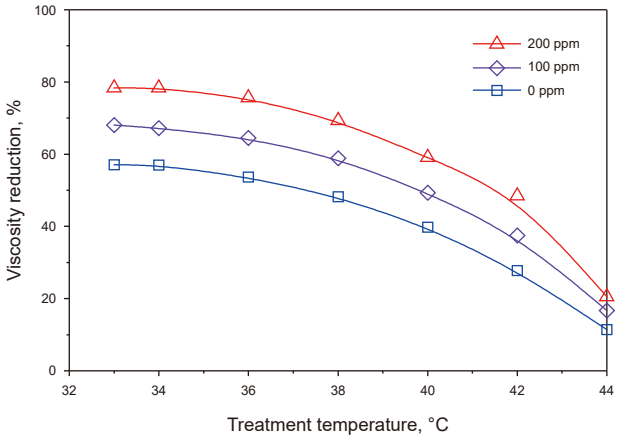

Fig. 7. The reduction of viscosity at different electric treatment temperatures.

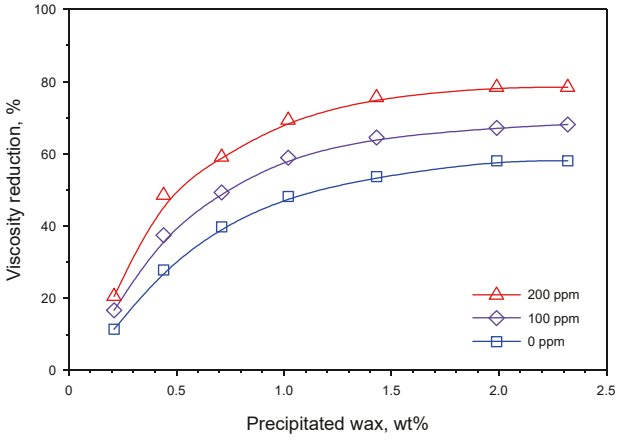

Fig. 8. The reduction of viscosity at different precipitated wax amounts.

3.2.1. Viscoelasticity and yielding behavior

Dynamic stress sweep tests were performed to investigate the impact of GNPs on the viscoelasticity and yield stress of the gelled oil described above. The results are shown in Fig. 9.

As can be seen in Fig. 9, the structure of the gelled oils, both undoped and doped, is weakened, such as decreased storage modulus, loss modulus, and yield stress. The addition of GNPs makes this weakening effect more pronounced. As shown in Table 2, the yield stress (τ_y) of the untreated oil at 30 °C is 80.9 Pa, and the τ_y of the electrically-treated oils are 45.7 Pa and 16.1 Pa, respectively, for the undoped oil and the oil doped with 200 ppm GNPs. Correspondingly, the storage modulus and loss modulus of the doped oil are also decreased significantly.

3.2.2. Rheomalaxis

The gelled waxy crude oil shows irreversible structural behavior, i.e., rheomalaxis. The stepwise shear rate increase was used to investigate the impact of GNPs on the structure breakdown of the gelled oil, as shown in Fig. 10.

As observed in Fig. 10, all samples exhibit rheomalaxis similar qualitatively, and the addition of GNPs further enhances the effect of viscosity reduction. For the untreated oil at 30 °C, the equilibrium shear stress at 1 s^{-1} is 20.4 Pa, and that of the electrically-

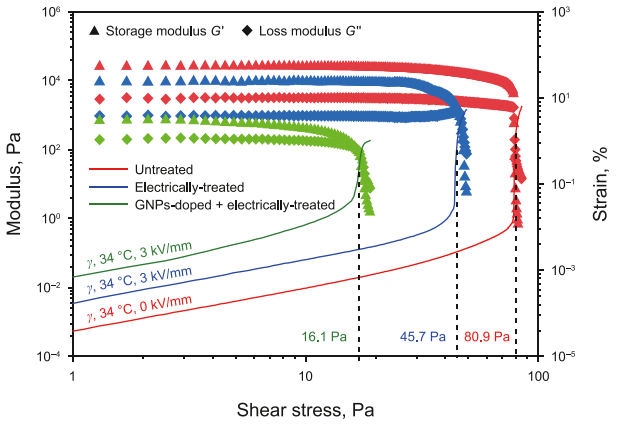

Fig. 9. Dynamic stress sweeps of the gelled oil undoped/doped with GNPs at 30 °C (Electric treatment condition: 34 °C, 3 kV/mm for 10 min).

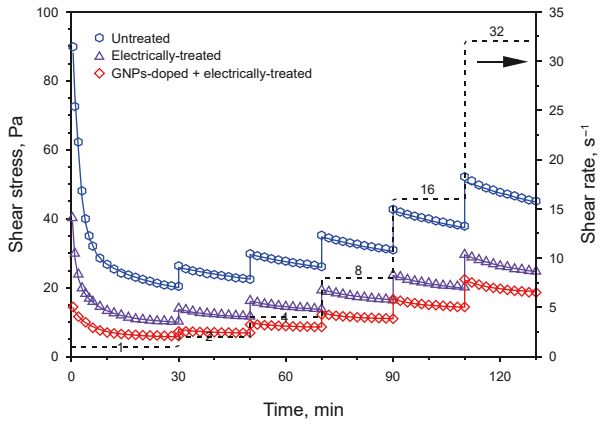

Fig. 10. Shear stress decay of the undoped/doped gelled oil at 30 °C (Electric treatment condition: 34 °C, 3 kV/mm for 10 min).

treated undoped oil is 10.2 Pa. For the oil doped with 200 ppm GNPs and electrically-treated, the value drops to 5.8 Pa, a reduction of 71.6% compared to the untreated oil. Furthermore, GNPs shorten the time required to reach the equilibrium shear stress.

To quantitatively analyze the impact of GNPs on structural breakdown, the viscoplastic thixotropic model proposed by Teng and Zhang (2013) was used (Eq. (1)), with fitting parameters shown in Table 3.

$$\begin{cases} \tau = \lambda\tau_y + (K + \lambda\Delta K)\dot{\gamma}^{n_1} \\ \dfrac{d\lambda}{dt} = \dfrac{1}{1+\gamma^{n_2}}[a(1-\lambda) - b\lambda\dot{\gamma}^m] \end{cases} \quad (1)$$

where τ is shear stress, Pa; τ_y is static yield stress, Pa; λ is the structural parameter; $\dot{\gamma}$ is shear rate, s^{-1}; γ is shear strain, %; K is completely-unstructured consistency, $Pa{\cdot}s^{n_1}$; $K + \Delta K$ is the fully structured consistency, $Pa{\cdot}s^{n_1}$; a is a rate constant for structure buildup, s^{-1}; b is a rate constant for structure breakdown, $Pa^{-m}{\cdot}s^{m-1}$; n_1 is a kinetic index; n_2 and m are positive dimensionless material parameters.

As can be seen from Table 3, the values of the structure-related parameters τ_y, ΔK, K, and n_1, n_2 all demonstrate that the gel structure weakened after electric treatment, and the addition of GNPs further enhances the efficacy.

3.3. Effect of GNPs on the durability of cold flowability enhancement

3.3.1. Durability of viscosity reduction

Regarding the durability of the viscosity reduction, i.e., the time required for the oil to return to its untreated viscosity, induced by the electric field, our previous studies have shown that the higher the electric field strength, the better the viscosity reduction efficacy, and the longer the durability of the efficacy (Xie et al., 2023a). To assess the effect of GNPs on the durability of the viscosity reduction, we applied a 3 kV/mm electric field for 60 s to the undoped/doped oil at 34 °C. Afterward, the electrically treated oils were subjected to 10 s^{-1} for 0–12 h, and the viscosity was recorded with time elapsing, as shown in Fig. 11.

As observed in Fig. 11, the durability of the viscosity reduction induced by the electric field of the oil doped with GNPs is significantly improved, and this improvement becomes more significant with increasing GNPs dosage. For example, by increasing the GNPs dosage from 0 to 200 ppm, the oil's viscosity reduction increases from 20.4% to 44.3%, and the duration of viscosity reduction extends from 5 to 12 h, indicating that the GNPs may not only significantly improve the viscosity reduction efficacy, but also makes the efficacy more durable.

3.3.2. Durability of structural strength weakening

As described in Section 3.2, weaker structural strength was observed for the oil doped with GNPs and electrically treated at its liquid state and then cooled down to become a gel. In this section, the oils doped with various GNPs dosages, electrically treated at 34 °C and 3 kV/mm for 10 min, were cooled down to 30 °C, and kept standing for 60 min to ensure the full formation of the gelled structure. The yield stress of the gelled oils was then measured after different quiescent time (0–24 h), with the results presented in Fig. 12.

As shown in Fig. 12, with increasing GNPs dosage, the yield stress decreases. The yield stress of the oil gels gradually recovers over time, but the yield stress of the doped oils remains consistently lower than that of the undoped oil, indicating the slower recovery rate induced by the GNPs. Let's look at the case of standing for 24 h, the yield stress of the undoped oil recovered from 45.7 to 60.1 Pa, with the yield stress reduction decreased from 43.5% to 25.7%, while for the oil doped with 100 ppm GNPs, the yield stress recovered from 30.1 to 40.3 Pa, and the yield stress reduction decreased from 62.8% to 50.2%. Moreover, for the oil doped with 200 ppm GNPs, the yield stress recovered from 16.1 to 23.6 Pa after 24 h, with the yield stress reduction decreasing from 80.1% to 70.8%. These results demonstrate that the GNPs may not

Table 2
The moduli and yield stress at 30 °C of the undoped/doped gelled oil.

Oil sample	G', Pa	G' reduction, %	G'', Pa	G'' reduction, %	δ, °	τ_y, Pa	τ_y reduction, %
Untreated	23860	/	2310	/	5.5	80.9	/
Electrically-treated	12325	48.3	1212	47.5	7.4	45.7	43.5
200 ppm GNPs + electrically-treated	689	97.1	198	91.4	9.2	16.1	80.1

Table 3
Fitted parameters of Eq. (1) at 30 °C.

Oil sample	τ_y, Pa	ΔK, Pa·s^{n_1}	K, Pa·s^{n_1}	n_1, –	n_2, –	a, s^{-1}	b, Pa^{-m}·s^{m-1}	m, –
Untreated	65.67	23.26	0.91	0.64	0.42	0.0656	0.0435	0.48
Electrically-treated	29.00	10.91	0.32	0.72	0.57	0.0521	0.0809	0.58
200 ppm GNPs + electrically-treated	9.22	4.98	0.18	0.82	0.68	0.0478	0.0921	0.70

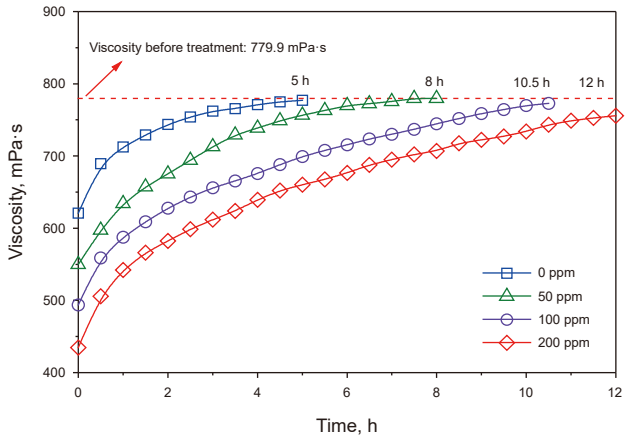

Fig. 11. Viscosity of the electrically treated oils doped with different GNPs dosages sheared at 10 s^{-1}.

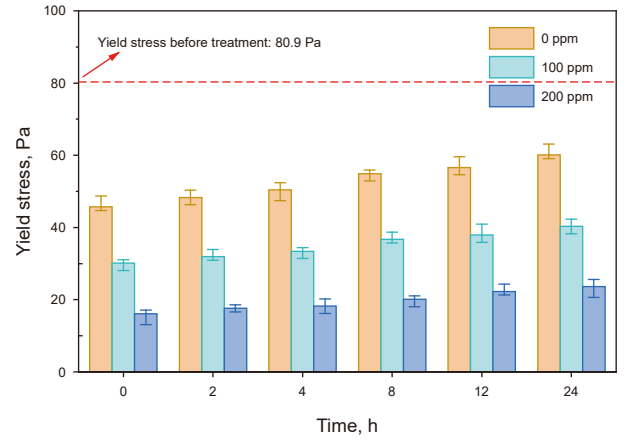

Fig. 12. Yield stress of the electrically treated oils with different GNPs dosages at different quiescent time.

only further weaken the structure of the gelled oil but also make this effect more durable.

In summary, the addition of GNPs significantly enhances the ER effect of waxy crude oil, with improved viscosity reduction for liquid oil and structural strength weakening for oil gels formed after subsequent cooling, and enhanced durability of these effects.

3.4. Mechanism exploration of GNPs' enhancement on the ER effect of waxy crude oil

Previous studies have revealed that the migration, accumulation, and diffusion of charged particles (such as resins and asphaltenes) on wax particles was the essential mechanism of the ER effect of waxy crude oil (Chen et al., 2021; Xie et al., 2023c). The charged particles accumulated on the surface of wax particles generate electrostatic repulsion and weaken the interactions between them, thus improving the flowability of the oil. The microscopic process is illustrated in Fig. 13.

The following are the two possible reasons for the GNPs' enhancement on the ER effect of waxy crude oil. First, the added GNPs and the charged particles in crude oil might interact with the wax particles under the electric field, respectively. The combined effect of GNPs and charged particles enhances the ER effect. Second, the GNPs might facilitate the interaction of charged particles with the wax particles, thereby enhancing the ER effect.

To explore the real mechanism, a waxy model oil was prepared with 200 ppm GNPs, 90% mineral oil, and 10% commercial waxes. The WAT of the model oil is 33.2 °C, and its pour point is 27 °C. A high-voltage electric field (0–5 kV/mm) was applied for 90 s at 28 °C, where the amount of precipitated wax is 2.1 wt%. The equilibrium viscosity at 10 s^{-1} before and after electric treatment was measured, as shown in Fig. 14.

As can be seen in Fig. 14, the waxy model oil containing 200 ppm GNPs shows a significant viscosity reduction induced by the electric field. The equilibrium viscosity at 10 s^{-1} and 28 °C decreases from 289.8 to 57.1 mPa·s, resulting in a viscosity reduction of 80.3%. This suggests that even in the absence of

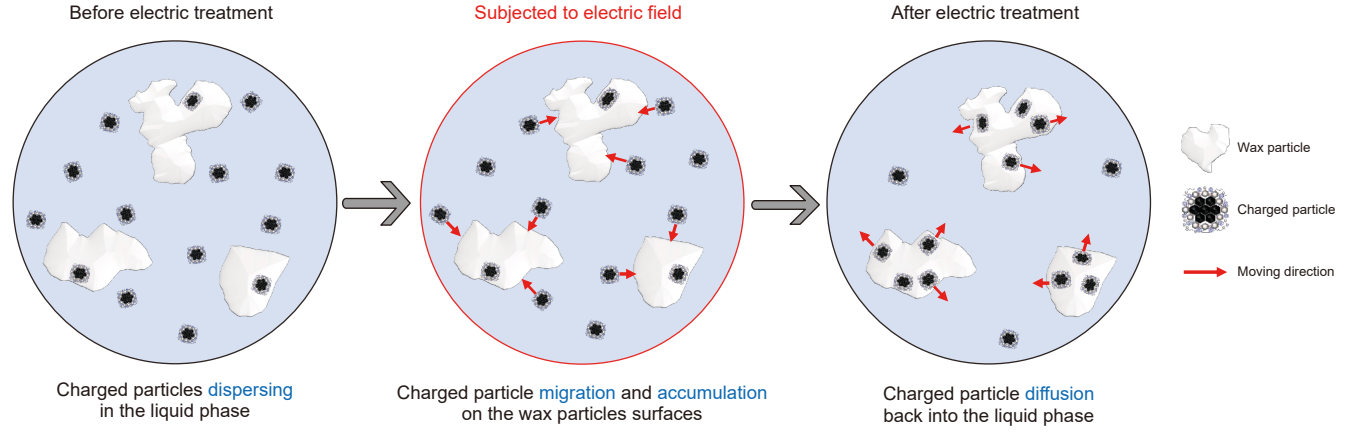

Fig. 13. Schematic diagram of the ER effect mechanism of waxy crude oil.

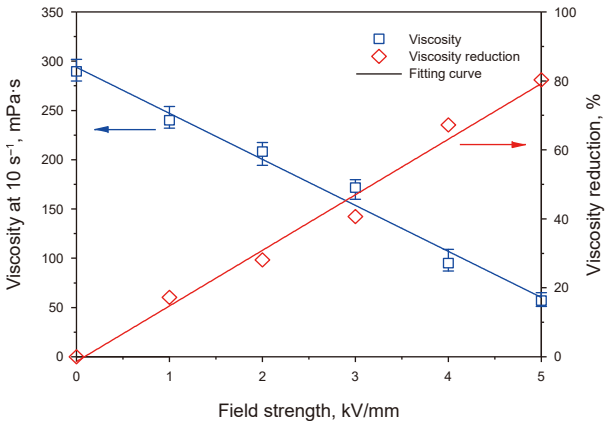

Fig. 14. Equilibrium viscosity at 10 s^{-1} and viscosity reduction of electrically-treated model oil doped with 200 ppm GNPs.

charged particles like resins or asphaltenes, the waxy oil containing GNPs can still exhibit a quite significant ER effect.

The microscopic images of GNPs and wax particles in the model oil, before and after the treatment (5 kV/mm, 90 s), were taken using a cross-polarized microscope OPTIPHOT2-POL equipped with a PE60 thermal stage by following the procedures in our previous research (Huang et al., 2021a), and the results are shown in Fig. 15, from which one may see the bright wax crystals and the black sheet-like structures of GNPs.

As can be observed in Fig. 15, GNPs and wax particles undergo extensive accumulation, and the wax particles become larger after the electric treatment. These two effects may be attributed to the improvement of the cold flowability of waxy model oil containing GNPs.

There is a significant dielectric mismatch, i.e., the high conductivity of GNPs (σ-$_{GNPs}$ > 10^3 S/cm) vs. insulating wax (σ-$_{wax}$ < 10^{-15} S/cm), between the dispersed GNPs and wax particles dispersed in the liquid phase at temperatures below the WAT of the waxy oil. Charges within the conductive GNPs migrate readily, while charges in the insulating wax and oil phases are less mobile; the differential charge mobility creates induced dipole moments at the GNPs-wax and GNPs-oil interfaces. According to the Maxwell–Wagner dynamic polarization theory (Parthasarathy and Klingenberg, 1996; Zhang et al., 2023) and the interfacial polarization mechanism (Chen et al., 2021) of the ER effect of waxy oil, GNPs accumulate on the surface of wax particles upon exposure to a high-voltage electric field. The accumulation of neutral GNPs is driven by dielectrophoretic force due to interfacial polarization.

However, unlike the charged particles (resins and asphaltenes) in crude oil, the GNPs, electrically neutral particles (Latil and Henrard, 2006; Tani et al., 2012), cannot generate electrostatic repulsion among them. Instead, the GNPs weaken the interactions

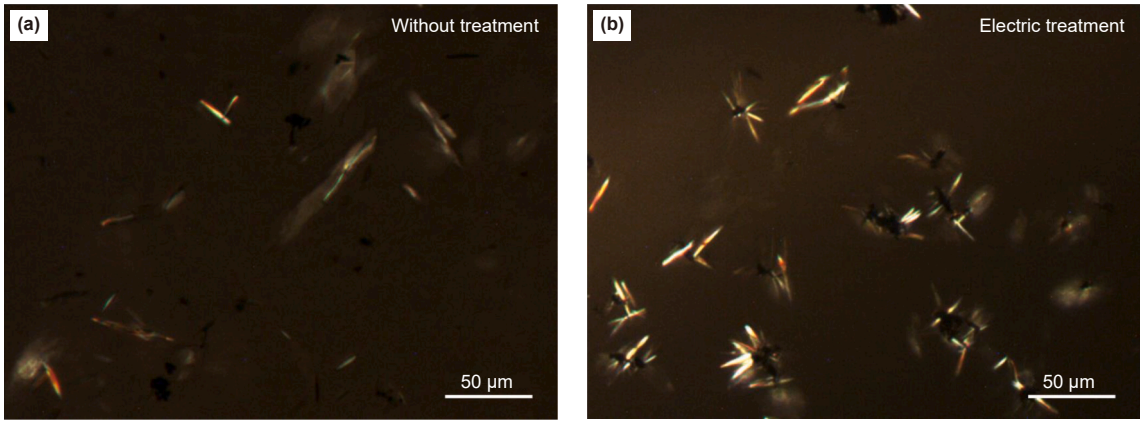

Fig. 15. Micrographs of waxy model oil containing 200 ppm GNPs at 28 °C.

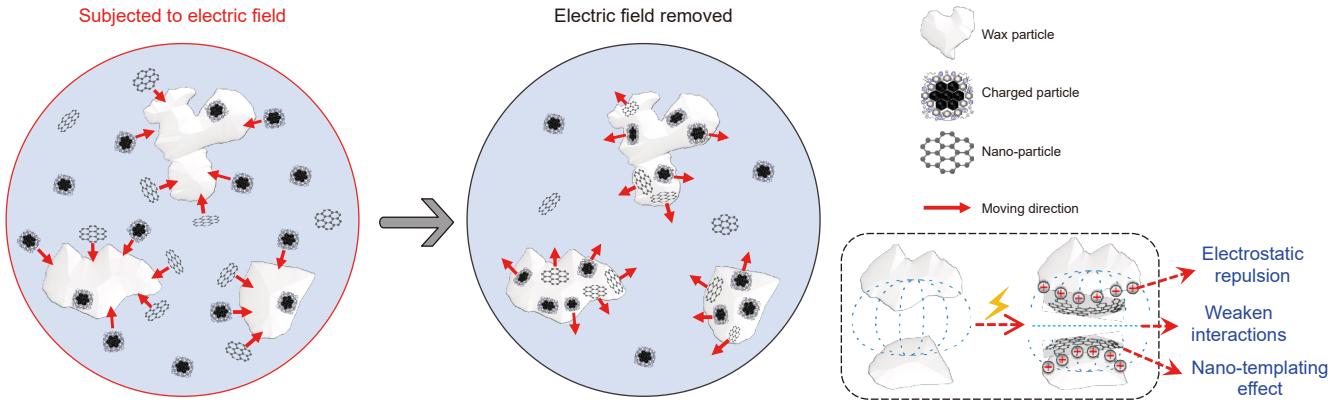

Fig. 16. Schematic diagram of the mechanism for enhanced ER effect of waxy crude oil with GNPs.

between the wax particles surrounded by them via the nano-templating effect (Liu et al., 2013; Heydari and Mohammadi, 2018; He et al., 2022), leading to a significant viscosity reduction.

In summary, for a waxy crude oil added with GNPs, both the GNPs and the charged particles in crude oil could migrate toward and accumulate on the surface of wax particles under the electric field. The combined effects of the nano-templating effect of the GNPs and the electrostatic repulsion from the charged particles work together, resulting in weakened interactions between the wax particles and thereby enhanced cold flowability improvement. The microscopic process is illustrated in Fig. 16.

4. Conclusions

This study first demonstrated that GNPs as efficient enhancers for the ER effect in waxy crude oil. We establish a dual-mechanism framework where the nano-templating effect of the GNPs together with the electrostatic repulsion from the charged particles (e.g., resins and/or asphaltenes) to weaken interactions between the wax particles, achieving unprecedented viscosity reduction (78.4%), extended durability (from 5 to 12 h), and reduced energy thresholds (0.96 J/mL). This approach overcomes the intrinsic limitations of conventional electric treatment for less sensitive crude oils. The main conclusions are as follows.

(1) For the viscosity reduction, the addition of the GNPs shows significant efficacy and extends the duration of this efficacy. Specifically, compared to the undoped oil, the oil doped with GNPs shows less time of electric field exposure required to achieve a certain viscosity reduction, higher viscosity reduction at the same energy input, increased maximum viscosity reduction, and reduced energy input to achieve the maximum viscosity reduction.
(2) For the effect of weakening the structural strength of gelled oil, which was electrically treated at its liquid state and then cooled down to become a gel, the addition of the GNPs makes the viscoelasticity, rheomalaxis, and yield stress further reduced compared to the undoped oil. And again, the GNPs significantly extend the durability of the effect.
(3) The mechanism of the GNPs' effect on the enhancement of the ER effect of waxy crude oil can be attributed to the doubled effect of GNPs and charged particles. The nano-templating effect of GNPs and the electrostatic repulsion of charged particles work together, weakening the interactions between wax particles and thus improving the oil's cold flowability.

This technology holds significant potential for flow assurance of waxy crude oil, including reducing energy consumption for pipeline transportation and mitigating restart risks after shutdowns. The ultra-low GNPs dosage (200 ppm) ensures cost-effectiveness. This strategy offers a sustainable pathway for crude transportation safety.

CRediT authorship contribution statement

Jia-Bao Kang: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Hong-Ying Li:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Chao-Yue Zhang:** Writing – review & editing, Validation, Investigation, Formal analysis. **Yi-Wei Xie:** Writing – review & editing, Validation, Methodology, Funding acquisition, Formal analysis. **Yang Su:** Validation, Methodology. **Zhao-Ming Yang:** Validation, Supervision. **Huai Su:** Validation, Supervision, Methodology. **Jin-Jun Zhang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

Acknowledgments

The authors gratefully acknowledge the National Natural Science Foundation of China (No. 52174066), the Postdoctoral Fellowship Program of CPSF (No. GZC20242006), and the Science Foundation of China University of Petroleum, Beijing (No. 2462024XKBH008) for providing financial support.

List of Acronyms

ER	Electrorheological
GNPs	Graphene nanoparticles
DSC	Differential scanning calorimetry
WAT	Wax appearance temperature
WDT	Wax disappearance temperature
DC	Direct current
SEM	Scanning electron microscopy

References

Al-Shboul, T., Sagala, F., Nassar, N.N., 2023. Role of surfactants, polymers, nanoparticles, and its combination in inhibition of wax deposition and precipitation: A review. Adv. Colloid Interface Sci. 315, 102904. https://doi.org/10.1016/j.cis.2023.102904.

Charin, R.M., Chaves, G.M.T., Kashefi, K., Alves, R.P., Tavares, F.W., Nele, M., 2017. Crude oil electrical conductivity measurements at high temperatures: Introduction of apparatus and methodology. Energy Fuel. 31 (4), 3669–3674. https://doi.org/10.1021/acs.energyfuels.6b03237.

Chen, C.H., Zhang, J.J., Ma, C.B., Liang, H.Q., Qing, M.Y., Xie, Y.W., Huang, Q., Han, S.P., Li, H.Y., 2019. Influence of wax precipitation on the impedance spectroscopy of waxy oils. Energy Fuel. 33 (10), 9767–9778. https://doi.org/10.1021/acs.energyfuels.9b02543.

Chen, C.H., Zhang, J.J., Xie, Y.W., Huang, Q., Ding, Y.F., Zhuang, Y., Xu, M.M., Han, S.P., Li, Z., Li, H.Y., 2021. An investigation to the mechanism of the electrorheological behaviors of waxy oils. Chem. Eng. Sci. 239, 116646. https://doi.org/10.1016/j.ces.2021.116646.

Geng, Y., Wang, S.J., Kim, J., 2009. Preparation of graphite nanoplatelets and graphene sheets. J. Colloid Interface Sci. 336 (2), 592–598. https://doi.org/10.1016/j.jcis.2009.04.005.

He, Z.J., Li, X.Q., Wang, H.N., Su, F.F., Wang, D.C., Yao, D.D., Zheng, Y.P., 2022. Synergistic regulation of the microstructure for multifunctional graphene aerogels by a dual template method. ACS Appl. Mater. Interfaces 14 (19), 22544–22553. https://doi.org/10.1021/acsami.2c00525.

Heydari, M., Mohammadi, N., 2018. The rheological, mechanical and templating effects of graphene oxide nanosheets in filled gel spun polyacrylonitrile. Iran. Polym. J. (Engl. Ed.) 27, 775–784. https://doi.org/10.1007/s13726-018-0649-y.

Homayuni, F., Hamidi, A., Vatani, A., Shaygani, A., Faraji Dana, R., 2011. Viscosity reduction of heavy and extra heavy crude oils by pulsed electric field. Pet. Sci. Technol. 29 (19), 2052–2060. https://doi.org/10.1080/10916461003699143.

Hou, J.K., Zhang, Z.Y., Zhu, G.Y., Han, J.F., Chi, L.X., Zhu, Z.G., Li, H.B., Li, M.Q., Wang, R.L., 2025. Genesis and quantitative evaluation of deep petroleum phase diversity in the tazhong area, tarim basin. Pet. Sci. 22 (6), 2274–2289. https://doi.org/10.1016/j.petsci.2025.03.020.

Huang, Q., Li, H.Y., Xie, Y.W., Ding, Y.F., Zhuang, Y., Chen, C.H., Han, S.P., Zhang, J.J., 2021b. Electrorheological behaviors of waxy crude oil gel. J. Rheol. 65 (2), 103–112. https://doi.org/10.1122/8.0000160.

Huang, Q., Li, H.Y., Zhuang, Y., Ding, Y.F., Ma, C.B., Chen, C.H., Xie, Y., Liang, H.Q., Han, S.P., Zhang, J.J., 2021a. Reducing viscosity of waxy crude oil with electric field perpendicular to oil's flow direction. Fuel 283, 119345. https://doi.org/10.1016/j.fuel.2020.119345.

Ibrahim, R.I., Oudah, M.K., Al-Mufti, A.M., 2022. An innovative graphene-supercapacitor for the treatment of crude oil viscosity at low temperatures. J. Pet. Sci. Eng. 209, 109829. https://doi.org/10.1016/j.petrol.2021.109829.

Ibrahim, R.I., Oudah, M.K., Hassan, A.F., 2017. Viscosity reduction for flowability enhancement in Iraqi crude oil pipelines using novel capacitor and locally

prepared nanosilica. J. Pet. Sci. Eng. 156, 356–365. https://doi.org/10.1016/j.petrol.2017.05.028.
Jain, A., Juvekar, V.A., Prakash, V., Kumar, N., Seth, J.R., 2025. Dynamics of viscosity reduction of a high-waxy crude oil under electric field: Effect of temperature and shear rate. Phys. Fluids 37 (2), 23395. https://doi.org/10.1063/5.0243962.
Jain, A., Seth, J.R., Juvekar, V.A., Verma, N., Pandey, N., 2020. Remarkable decrease in the viscosity of waxy crude oil under an electric field. Soft Matter 16 (47), 10657–10666. https://doi.org/10.1039/D0SM01404D.
Jalal, N.I., Ibrahim, R.I., Oudah, M.K., 2022. Flow improvement and viscosity reduction for crude oil pipelines transportation using dilution and electrical field. Engineering and Technology Journal 40 (1), 66–75. https://doi.org/10.30684/etj.v40i1.2192.
James, D.K., Tour, J.M., 2013. Graphene: Powder, flakes, ribbons, and sheets. Acc. Chem. Res. 46 (10), 2307–2318. https://doi.org/10.1021/ar300127r.
Kang, J.B., Li, H.Y., Zhang, C.Y., Xie, Y.W., Zhang, J.M., Su, Y., Yang, Z.M., Su, H., Zhang, J.J., 2024. Cold flowability improvement of waxy crude oil doped with graphene nanoparticles and its mechanism. J. Mol. Liq. 405, 125083. https://doi.org/10.1016/j.molliq.2024.125083.
Kiyingi, W., Guo, J.X., Xiong, R.Y., Su, L., Yang, X.H., Zhang, S.L., 2022. Crude oil wax: A review on formation, experimentation, prediction, and remediation techniques. Pet. Sci. 19 (5), 2343–2357. https://doi.org/10.1016/j.petsci.2022.08.008.
Latil, S., Henrard, L., 2006. Charge carriers in few-layer graphene films. Phys. Rev. Lett. 97 (3), 36803. https://doi.org/10.1103/PhysRevLett.97.036803.
Lesin, V.I., Koksharov, Y.A., Khomutov, G.B., 2011. Viscosity of liquid suspensions with fractal aggregates: Magnetic nanoparticles in petroleum colloidal structures. Colloid Surf. A-Physicochem. Eng. Asp. 392 (1), 88–94. https://doi.org/10.1016/j.colsurfa.2011.09.038.
Li, H.Y., Wang, X.Y., Ma, C.B., Lu, Y.D., Han, S.P., Chen, C.H., Zhang, J.J., 2019. Effect of electrical treatment on structural behaviors of gelled waxy crude oil. Fuel 253, 647–661. https://doi.org/10.1016/j.fuel.2019.05.001.
Liu, Y.D., Goebl, J., Yin, Y.D., 2013. Templated synthesis of nanostructured materials. Chem. Soc. Rev. 42 (7), 2610–2653. https://doi.org/10.1039/C2CS35369E.
Ma, C.B., Lu, Y.D., Chen, C.H., Feng, K., Li, Z.X., Wang, X.Y., Zhang, J.J., 2017. Electrical treatment of waxy crude oil to improve its cold flowability. Ind. Eng. Chem. Res. 56 (38), 10920–10928. https://doi.org/10.1021/acs.iecr.7b02140.
Malozyomov, B.V., Martyushev, N.V., Kukartsev, V.V., Tynchenko, V.S., Bukhtoyarov, V.V., Wu, X., Tyncheko, Y.A., Kukartsev, V.A., 2023. Overview of methods for enhanced oil recovery from conventional and unconventional reservoirs. Energies 16 (13), 4907. https://doi.org/10.3390/en16134907.
Olajire, A.A., 2021. Review of wax deposition in subsea oil pipeline systems and mitigation technologies in the petroleum industry. Chem. Eng. J. Adv. 6, 100104. https://doi.org/10.1016/j.ceja.2021.100104.
Parthasarathy, M., Klingenberg, D.J., 1996. Electrorheology: Mechanisms and models. Mater. Sci. Eng. R Rep. 17 (2), 57–103. https://doi.org/10.1016/0927-796X(96)00191-X.
Peng, L.J., Liang, C., 2023. Sustainable development during the post-COVID-19 period: role of crude oil. Resour. Policy. 85, 103843. https://doi.org/10.1016/j.resourpol.2023.103843.
Ratnakar, R.K., Pandian, S., Mary, H., Choksi, H., 2025. Flow assurance methods for transporting heavy and waxy crude oils via pipelines without chemical additive intervention. Petroleum Research 10 (1), 204–215. https://doi.org/10.1016/j.ptlrs.2024.07.005.
Rudyk, S., Taura, U., Al-Jahwary, M., 2022. Enhancing oil recovery by electric current impulses well treatment: A case of marginal field from Oman. Fuel 314, 123115. https://doi.org/10.1016/j.fuel.2021.123115.
Tang, H., Huang, K., Tao, R., 2011. Electrorheology improves transportation of crude oil. J. Intell. Mater. Syst. Struct. 22 (15), 1673–1676. https://doi.org/10.1177/1045389X11421816.
Tani, S., Blanchard, F., Tanaka, K., 2012. Ultrafast carrier dynamics in graphene under a high electric field. Phys. Rev. Lett. 109 (16), 166603. https://doi.org/10.1103/PhysRevLett.109.166603.
Tao, R., Tang, H., 2014. Reducing viscosity of paraffin base crude oil with electric field for oil production and transportation. Fuel 118, 69–72. https://doi.org/10.1016/j.fuel.2013.10.056.
Tao, R., Xu, X., 2006. Reducing the viscosity of crude oil by pulsed electric or magnetic field. Energy Fuel. 20 (5), 2046–2051. https://doi.org/10.1021/ef060072x.
Teng, H.X., Zhang, J.J., 2013. A new thixotropic model for waxy crude. Rheol. Acta 52, 903–911. https://doi.org/10.1007/s00397-013-0729-z.
Vasiljeva, M.V., Ponkratov, V.V., Vatutina, L.A., Volkova, M.V., Ivleva, M.I., Romanenko, E.V., Kuznetsov, N.V., Semenova, N.N., Kireeva, E.F., Goncharov, D.K., 2022. Crude oil market functioning and sustainable development goals: Case of OPEC++-participating countries. Sustainability 14 (8), 4742. https://doi.org/10.3390/su14084742.
Xie, Y.W., Li, H.Y., Huang, Q., Su, Y., Zhang, C.Y., Xu, M.M., Han, S.P., Zhang, J.J., 2023c. The mechanism of viscosity reduction of waxy oils induced by the electric field: A correlation between the viscosity reduction and the charged particle accumulation on wax particles. J. Colloid Interface Sci. 642, 373–379. https://doi.org/10.1016/j.jcis.2023.03.171.
Xie, Y.W., Li, H.Y., Liang, B., Li, Q.D., Su, Y., Zhang, C.Y., Kang, J.B., Yang, Z.M., Su, H., Ji, Z.L., Zhang, J.J., 2025. Performance and mechanism of a novel electromagnetic treatment for improving the cold flowability of waxy crude oil. Fuel 382, 133803. https://doi.org/10.1016/j.fuel.2024.133803.
Xie, Y.W., Li, H.Y., Wang, Y., Zhang, C.Y., Su, Y., Kang, J.B., Yang, Z.M., Su, H., Ji, Z.L., Zhang, J.J., 2024. Rheology and electrorheological effects of waxy oils with different carbon number distribution. Fuel 375, 132680. https://doi.org/10.1016/j.fuel.2024.132680.
Xie, Y.W., Li, H.Y., Xu, M.M., Su, Y., Zhang, C.Y., Han, S.P., Zhang, J.J., 2023a. Effect of shear on durability of viscosity reduction of electrically-treated waxy crude oils. Energy 284, 128605. https://doi.org/10.1016/j.energy.2023.128605.
Xie, Y.W., Li, H.Y., Zhang, C.Y., Su, Y., Huang, Q., Jiang, F., Chen, C.H., Han, S.P., Zhang, J.J., 2023b. A further investigation to mechanism of the electrorheological effect of waxy oils: Behaviors of charged particles under electric field. Pet. Sci. 20 (2), 1247–1254. https://doi.org/10.1016/j.petsci.2022.08.022.
Yang, Y.H., Zhang, L.N., Sun, Z.N., Bai, M.X., Jing, G.L., Liu, Y., Liu, X.Y., 2025. Preparation of EVAM-g-$NSiO_2$ nanocomposite pour point depressant and its effect on rheological properties of model waxy oil. Pet. Sci. 22 (1), 472–480. https://doi.org/10.1016/j.petsci.2024.06.012.
Yao, B., Li, C.X., Yang, F., Sun, G.Y., Xia, X., Ashmawy, A.M., Zeng, H.B., 2022. Advances in and perspectives on strategies for improving the flowability of waxy oils. Energy Fuel. 36 (15), 7987–8025. https://doi.org/10.1021/acs.energyfuels.2c01295.
Zhang, C.Y., Li, H.Y., Wang, Y., Xie, Y.W., Kang, J.B., Su, Y., Li, J.H., Han, S.P., Zhang, J.J., 2024. An energy perspective on the mechanism of crude oil electrorheological effect. Phys. Fluids 36 (4), 43101. https://doi.org/10.1063/5.0202010.
Zhang, C.Y., Zhang, J.J., Kang, J.B., Xie, Y., Han, S.P., Li, H.Y., 2023. Electrorheological effects of waxy crude oils under high-voltage AC electric field. Fuel 340, 127494. https://doi.org/10.1016/j.fuel.2023.127494.
Zhang, J.J., Yu, B., Li, H.Y., Huang, Q.Y., 2013. Advances in rheology and flow assurance studies of waxy crude. Pet. Sci. 10 (4), 538–547. https://doi.org/10.1007/s12182-013-0305-2.