https://doi.org/10.3311/PPch.43801

Periodica Polytechnica Chemical Engineering, 70(2), pp. 357–369, 2026

Synergistic Composite Additives for Rheological Optimization of High-paraffin Crude Oil

Aysel Gasimzade[1*], Vali Nurullayev[2]

[1] Azerbaijan State Oil and Industry University (ASOIU), Faculty of Oil and Gas Engineering, AZ1010 Baku, Azerbaijan
[2] State Oil Company of the Azerbaijan Republic (SOCAR), Quality Control Department, AZ1010 Baku, Azerbaijan
[*] Corresponding author, e-mail: aysel.qasimzade@asoiu.edu.az

Received: 24 February 2026, Accepted: 20 April 2026, Published online: 28 May 2026

Abstract

This study investigates the rheological behavior and wax-deposition tendency of a model high-paraffin crude oil prepared by blending samples from the Palchig–Pilpilasi field. The oil is characterized by a density of 901.0 kg/m^3, resin content of 4.3 wt%, asphaltenes of 0.18 wt%, and paraffins of 15.2 wt%, forming a stable paraffin–resin–asphaltene system suitable for laboratory evaluation.

The performance of individual depressor additives, Difron-3971 and HY-154, was first assessed and resulted in a moderate viscosity reduction of 15–25% at low temperatures while preserving non-Newtonian behavior. To enhance treatment efficiency, a composite formulation was developed and tested at a dosage of 600 g/t. Rheological measurements showed that the composite reduced the viscosity by 3.5–4.0 times and decreased the yield stress from 0.1625 Pa to 0.0325 Pa, indicating a pronounced weakening of the internal structure and a transition toward near-Newtonian flow.

Cold-finger experiments confirmed a strong suppression of wax deposition, with inhibition efficiency reaching approximately 95% at low temperatures. The results highlight the synergistic effect of the composite formulation and its potential as an effective flow-assurance solution for high-paraffin crude oils.

Keywords

rheology, yield stress, wax deposition, flow behavior index, chemical additives

1 Introduction

Crude oils with high paraffinic content are complex colloidal systems whose structural and rheological behavior is strongly governed by temperature and applied mechanical stress. At elevated temperatures such oils behave as homogeneous liquids, whereas cooling reduces the solubility of high-molecular-weight *n*-paraffins, leading to the formation of a dispersed solid phase. Linear paraffinic hydrocarbons crystallize to form primary nuclei that grow and interact, generating extended crystalline structures within the liquid phase [1–4].

The initiation and evolution of paraffin crystallization critically control the rheological behavior and transportability of high-paraffin crude oils. When straight-chain alkanes in the C_{16}–C_{30} range exceed approximately 10–15 wt%, crystallization can occur even under moderate cooling. As wax crystals interact through van der Waals forces and resin–asphaltene associations, a three-dimensional network develops, resulting in increased viscosity and the emergence of yield stress. This structural evolution restricts flow and significantly complicates crude oil transportation and processing [5–9].

Conventional thermal and mechanical methods provide only temporary mitigation and do not eliminate crystallization mechanisms. Consequently, recent studies have emphasized chemical treatment strategies that modify wax nucleation, crystal growth, and aggregation. Pour-point depressants, dispersants, and composite formulations can suppress network formation by maintaining wax crystals in a dispersed state, thereby improving low-temperature flow properties [10–14].

The use of chemical wax inhibitors and depressor additives represents one of the most widely applied approaches for improving the flowability of high-paraffin crude oils. Numerous studies have demonstrated that polymeric depressants, surfactant-based additives, and aromatic solvents are capable of modifying wax crystallization behavior by influencing nucleation and crystal growth processes. In particular, ethylene–vinyl acetate copolymers,

Cite this article as: Gasimzade, A., Nurullayev, V. "Synergistic Composite Additives for Rheological Optimization of High-paraffin Crude Oil", Periodica Polytechnica Chemical Engineering, 70(2), pp. 357–369, 2026. https://doi.org/10.3311/PPch.43801

comb-like polymers, and alkylated aromatic compounds have been shown to reduce pour point and apparent viscosity by altering the morphology and size distribution of paraffin crystals. These additives interact with *n*-paraffin molecules through adsorption and co-crystallization mechanisms, resulting in the formation of smaller and less interconnected crystal structures, which reduces the formation of a rigid three-dimensional paraffin network [15–18].

Previous investigations have reported viscosity reduction in the range of 20–60% and wax-deposition inhibition efficiencies typically between 50–85%, depending on crude oil composition and additive structure. However, the effectiveness of individual depressor additives is often limited due to the complex composition of crude oils containing paraffins, resins, and asphaltenes, which may interact competitively with inhibitor molecules. In addition, single-component additives may exhibit insufficient compatibility with high-molecular-weight paraffin fractions, resulting in incomplete suppression of crystal growth and aggregation [19–22].

Recent studies suggest that composite formulations containing polymeric depressants combined with aromatic solvents or dispersing agents may provide enhanced inhibition efficiency due to synergistic effects between components. Aromatic solvents such as xylene improve the solubility of heavy hydrocarbon fractions, while surfactant-type molecules enhance the dispersion of asphaltene–resin structures and prevent agglomeration of wax crystals. As a result, composite systems are capable of simultaneously influencing crystal nucleation, growth kinetics, and structural organization of paraffin networks.

Despite the significant progress achieved in the development of wax inhibitors, further research is required to optimize the composition of multifunctional additives capable of providing stable rheological behavior under low-temperature conditions typical for transportation of high-paraffin crude oils. In this context, the development of composite depressor systems remains a promising direction for improving flow assurance and reducing wax deposition in petroleum production and transportation systems [23].

Chemical depressor additives influence the crystallization behavior of paraffin waxes by modifying both nucleation and crystal-growth processes. Many polymer-based inhibitors contain long alkyl side chains capable of co-crystallizing with n-paraffin molecules, thereby disturbing the regular packing of wax crystals and leading to the formation of smaller and less ordered crystalline structures. As a result, the formation of an extended three-dimensional network of interlocking paraffin crystals is suppressed. This structural modification reduces the rigidity of the oil matrix and delays the onset of gelation at low temperatures [24, 25].

In addition to affecting crystallization, depressor additives significantly influence the rheological properties of crude oil systems. The presence of inhibitor molecules reduces intermolecular interactions between paraffin crystals, leading to a decrease in apparent viscosity and yield stress. The reduction in crystal size and the disruption of the continuous paraffin network improve the mobility of the liquid phase and enhance flowability under pipeline conditions. Several studies have reported that effective depressor formulations are capable of reducing plastic viscosity and yield stress while simultaneously lowering the pour point temperature, which is particularly important for transportation of high-paraffin crude oils under low-temperature conditions.

Furthermore, the interaction between depressor molecules and resin–asphaltene components plays an important role in stabilizing dispersed structures and preventing aggregation of solid paraffin particles. This combined effect contributes to improved rheological stability and reduced intensity of wax deposition on cold surfaces. Therefore, understanding the relationship between additive composition, crystallization behavior, and rheological response is essential for the development of efficient multifunctional inhibitor systems.

In this context, the present study examines the effectiveness of a Difron-HY Combination (DHC) composite formulation designed to reduce wax-network formation and improve the low-temperature flow properties of high-paraffin crude oil. The proposed approach emphasizes microstructural modification of paraffin crystallization as a chemical alternative to energy-intensive thermal treatment methods.

Despite the considerable progress achieved in the development of wax inhibitors and depressor additives, many conventional single-component formulations exhibit limited efficiency when applied to crude oils with complex group composition. High-paraffin crude oils typically contain significant amounts of resins and asphaltenes, which influence intermolecular interactions and may reduce the effectiveness of depressor molecules. In such multicomponent systems, the inhibitor molecules may preferentially interact with certain hydrocarbon fractions, resulting in incomplete suppression of paraffin crystallization and only partial improvement of rheological behavior.

In addition, many traditional depressor additives are primarily designed to reduce pour point temperature and do not always provide sufficient inhibition of wax deposition on cold surfaces. As a result, flow assurance problems may persist during transportation and production of high-paraffin crude oils, particularly under low-temperature operating conditions. The complexity of interactions between paraffin crystals, resin–asphaltene structures, and dispersing media requires the development of multifunctional additive systems capable of simultaneously influencing crystallization kinetics, structural organization, and rheological properties.

Composite formulations combining depressor polymers with aromatic solvents and dispersing components have demonstrated the potential to enhance inhibition efficiency through synergistic effects between components. Aromatic solvents improve compatibility between additive molecules and heavy hydrocarbon fractions, while surface-active components promote dispersion of solid particles and prevent aggregation of paraffin crystals. Nevertheless, the optimal composition and interaction mechanisms of such multifunctional systems remain insufficiently studied, particularly for crude oils with elevated paraffin content.

Therefore, the present study aims to develop and investigate a DHC designed to improve rheological behaviour and reduce wax deposition intensity through combined physicochemical mechanisms. The proposed approach contributes to the development of more effective flow-assurance strategies for transportation of high-paraffin crude oils.

2 Materials and methods

2.1 Materials and sample preparation

A high-paraffin model crude oil was prepared under laboratory conditions by blending crude oil samples collected from several wells of the Palchig–Pilpilasi oil field. The physicochemical properties of the prepared oil, including density, resin, asphaltene, and paraffin contents, were determined using standard analytical methods and are summarized in Table 1 [25–29]. Resin and asphaltene contents were determined in accordance with GOST 11858-66, while paraffin content was measured following GOST 11851-85 [25, 29]. The elevated paraffin content of the crude oil accounts for its pronounced tendency toward wax crystallization and deposition.

Table 1 Physicochemical properties of the high-paraffin model oil sample

№	Indicator	Value	Test method
1	Density at 20°C, kg/m³	901.0	ASTM D1298-24 [26] / GOST 3900-85 [27]
2	Resin content, wt.%	4.3	GOST 11858-66 [25]
3	Asphaltene content, wt.%	0.18	ASTM D6560-22 [28]/ GOST 11858-66 [25]
4	Paraffin content, wt.%	15.2	GOST 11851-85 [29]

The model crude oil was prepared by blending crude oil samples obtained from several wells of the Palchig–Pilpilasi oil field in equal volume proportions (1:1:1). The mixture was homogenized under continuous stirring at 50 °C for 30 min to ensure uniform distribution of components prior to further analysis. The DHC composite formulation was prepared by sequential mixing of Difron-3971, HY-154, kerosene, and xylene in predetermined proportions. The components were combined under continuous magnetic stirring at 40 °C for 30 min to ensure complete homogenization of the mixture. The prepared composition was visually inspected to confirm the formation of a uniform single-phase system and was subsequently introduced into the crude oil samples at the required dosage.

Kinematic viscosity measurements were performed using an Unbeholden capillary viscometer in accordance with GOST 33-2016 and ISO 3104:2020 [30 31]. Measurements were carried out at controlled temperatures, and each experiment was repeated three to four times. The relative deviation between repeated measurements did not exceed 0.6%, indicating high reproducibility and measurement accuracy. Rheological properties of the crude oil samples were further evaluated using a Brookfield rotational rheometer following the requirements of GOST 1929-87. Rheological terminology and measurement principles were applied in accordance with ISO 3219-1:2021 and ISO 3219-2:2021 standards [32–34].

The inhibition of asphaltene–resin–paraffin deposits was investigated using the cold-finger method in a thermostatic stainless-steel vessel. Before the cold-finger measurements, the crude oil samples were preconditioned by heating to 60 °C to eliminate previous thermal history and ensure complete dissolution of paraffin crystals, followed by cooling to 20 °C under controlled conditions. This pretreatment step ensures identical initial conditions for all experiments. Subsequently, cold-finger tests were carried out in the temperature range of 0–30 °C for 120 min. A steel rod maintained at 3 °C was immersed into the oil under continuous stirring at 300 rpm, and deposition was allowed to proceed for 4 h. After completion of the experiment, the rod was removed, rinsed with acetone, and the deposited material was collected and weighed. The inhibition efficiency $W\%$ was calculated according to standard procedures [25, 29] using the expression.

$$W\% = \frac{m_0 - m}{m_0} \cdot 100 \quad (1)$$

where m_0 is the mass of asphaltene–resin–paraffin deposits formed in the untreated oil and m is the mass of deposits formed in the treated oil.

The hydrocarbon group composition of the crude oil was analyzed by gas chromatography (GC) using an Auto System LX chromatograph (PerkinElmer, USA) in accordance with GOST 13379-82 to determine the carbon-number distribution of hydrocarbon fractions relevant to wax crystallization and deposition behavior [35]. The properties and classification of petroleum paraffin waxes were interpreted with reference to GOST 23683-89 [36].

All experimental measurements were carried out under identical conditions, and the obtained results are presented as mean values. The consistency and repeatability of the experimental data were evaluated using established statistical approaches for repeatability analysis [37].

The physicochemical properties of the prepared model oil are summarized in Table 1.

As shown in Table 1, the crude oil is characterized by a high paraffin content, which accounts for its pronounced wax crystallization tendency and associated flow-assurance challenges. In this study, the depressor additives Difron-3971 and HY-154 were selected as the primary research objects, as they represent widely applied commercial formulations and serve as the base components for the development of the composite system. Their individual physicochemical properties were therefore evaluated to establish a reference framework for both single-additive performance and subsequent composite formulation design.

Difron-3971 and HY-154 exhibit distinct physical and chemical characteristics that influence their interaction with wax-forming fractions of crude oil. The systematic comparison of these additives provides the basis for assessing their standalone efficiency and for rationalizing their combined use in the composite formulation investigated in this work.

The structural characteristics of paraffin crystals in the crude oil samples were analyzed using X-ray diffraction (XRD) (Rigaku MiniFlex 600 diffractometer, Rigaku Corporation, Tokyo, Japan). Diffraction patterns were recorded using a θ–2θ scanning mode with Cu Kα radiation (λ = 1.5406 Å). The measurements were performed over a 2θ range of 5–50° with a scanning step of 0.02° and a scanning rate of 2°/min. The obtained diffraction patterns were used to evaluate changes in structural ordering of paraffin crystals in the presence of depressor additives and the composite formulation.

3 Results and discussion

3.1 Effect of temperature on wax deposition behaviour in the presence of individual depressor additives

The experimental investigation initially examined the wax-deposition behavior of the crude oil as a function of temperature. Due to the high paraffinic content of the investigated oil, a pronounced tendency toward wax precipitation was observed. Accordingly, the effect of temperature alone on the deposition process was evaluated in the first stage of the study.

Cold-finger experiments were conducted over a temperature range of 0–30 °C with an exposure time of 120 min. The mass of paraffin deposits formed at each temperature was determined, and the corresponding results are presented in Fig. 1. At 0 °C, the untreated crude oil formed 0.44 ± 0.15 g deposits after 120 min. In contrast, treatment with the DHC composite at a dosage of 600 g/t reduced the deposit mass to 0.10 ± 0.02 g (n = 3, which indicates that the experiment was performed in triplicate, and the reported values represent the mean ± standard deviation of three independent measurements), corresponding to a substantial decrease in wax deposition under the investigated conditions.

As shown in Fig. 1, asphaltene, resin, paraffin (ARP) deposition in the crude oil strongly depends on temperature and depressor treatment. Under reagent free conditions, the highest deposit masses are observed at low temperatures and prolonged exposure. With increasing temperature, the amount of deposited ARP decreases but is not completely eliminated within the investigated range.

The application of depressor additives leads to a systematic reduction in ARP deposition compared to the untreated sample. Difron-3971 shows a stronger inhibitory effect than HY-154 at equivalent dosages and the reduction becomes more pronounced with increasing additive concentration. At a dosage of 600 g/t, Difron-3971 provides the most effective suppression of ARP deposition across the studied temperatures, whereas HY-154 results in a more moderate reduction particularly at lower temperatures where residual deposition remains.

Effective control of ARP deposition is primarily determined by the application and dosage of chemical additives, while temperature increase alone is insufficient to suppress deposition.

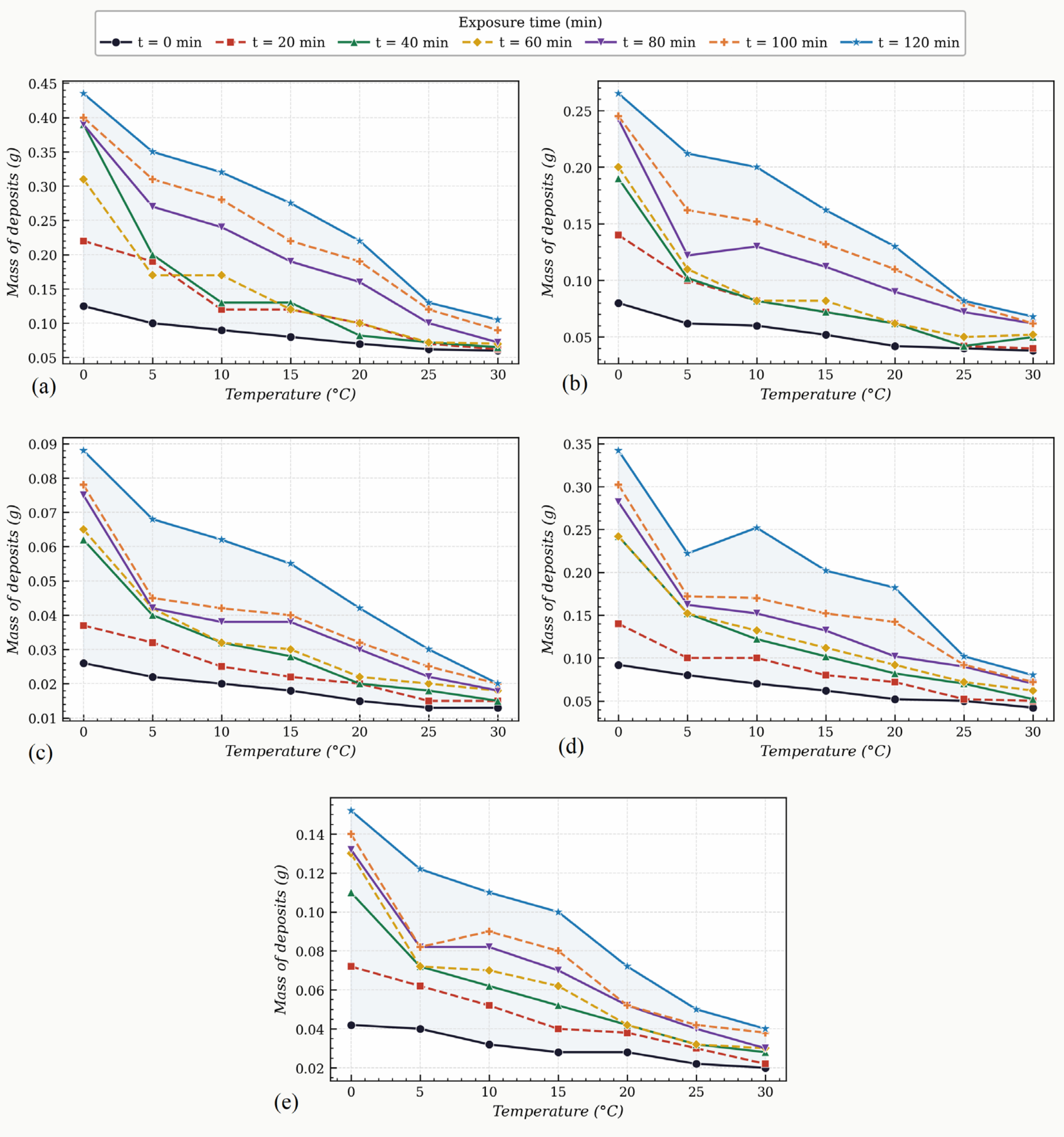

Fig. 1 Effect of temperature and depressor additives type on wax deposition in crude oil: (a) reagent-free, (b) Difron-3971, 300 g/t, (c) Difron-3971, 600 g/t, (d) HY-154, 300 g/t, (e) HY-154, 300 g/t

3.2 Rheological behaviour of crude oil treated with individual depressor additives

The subsequent stage of the study examined the temperature dependent rheological and flow behavior of the investigated crude oil under different treatment conditions. Measurements were first conducted for the reagent free sample to establish a reference baseline and were then compared with samples treated with chemical additives. The combined rheological results are presented in Fig. 2. At low temperatures, the untreated oil exhibits a high yield stress indicating the formation of a rigid internal structure. In contrast, treatment with the DHC composite at a dosage 600 g/t leads to a pronounced reduction in yield stress, decreasing from 0.162 ± 0.012 Pa to 0.020 ± 0.003 Pa at 0 °C ($n = 3$), which reflects a substantial weakening of the low temperature structural network.

Subsequent experiments were conducted using treatments at an increased dosage 600 g/t, with the corresponding results presented in Fig. 2.

Fig. 2 summarizes the temperature-dependent rheological behavior of the model high-paraffin crude oil under reagent-free and depressor-treated conditions. For the untreated sample, decreasing temperature leads to a pronounced increase in yield stress, apparent viscosity, and shear stress, reflecting the development of a rigid non-Newtonian structure. The low data scatter indicates good measurement repeatability.

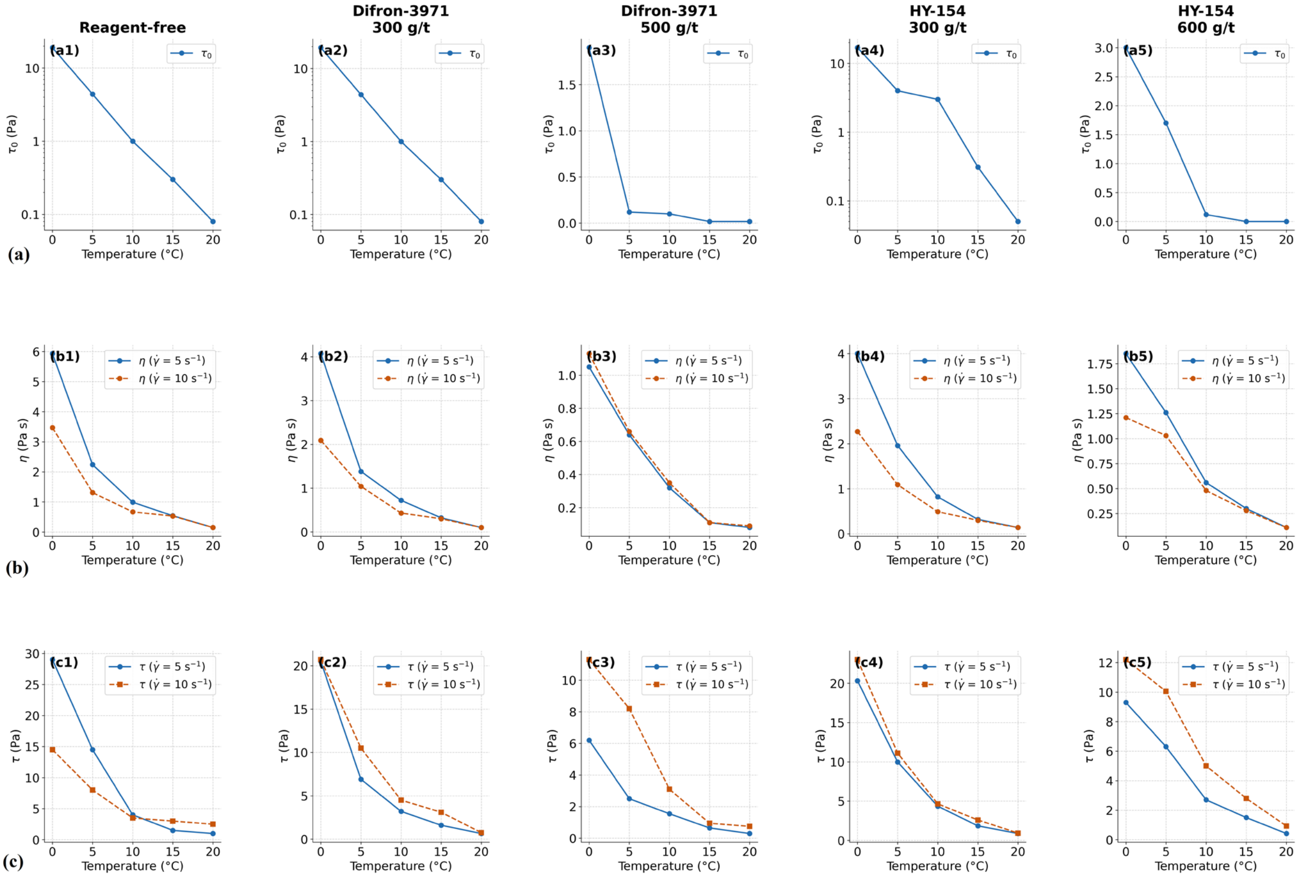

Fig. 2 Temperature-dependent rheological parameters of crude oil for reagent-free and depressor-treated samples (Difron-3971 and HY-154 at 300 and 600 g/t): (a) yield stress (τ_0); (b) apparent viscosity at $\gamma = 5$ s^{-1} and 10 s^{-1}; (c) shear stress at $\gamma = 5$ s^{-1} and 10 s^{-1}

The application of depressor additives substantially alters this response. Difron-3971 significantly reduces yield stress and apparent viscosity across the investigated temperature range, with enhanced effectiveness at higher dosage, as evidenced by suppressed structural buildup and reduced shear-rate sensitivity. In contrast, HY-154 produces a weaker rheological modification at equivalent concentrations, and residual non-Newtonian behavior persists at lower temperatures.

Rheological response is governed by the combined influence of temperature and chemical treatment, while the effectiveness of depressor additives depends strongly on their formulation and applied dosage. Among the evaluated systems, Difron-3971 exhibits the highest efficiency in limiting structural strengthening at low temperatures.

3.3 Effect of temperature on wax deposition and rheological behavior of the studied composition

Based on the combined wax-deposition and rheological assessments, a composite formulation exhibiting the most effective behavior under the investigated conditions was identified. This formulation, designated as the DHC composite, consists of Difron-3971 (25%), HY-154 (6%), kerosene (55%) and xylene (14%).

Following the evaluation of the individual reagents, the wax-deposition inhibition efficiency of the DHC composite was examined separately, and the corresponding results are presented in Fig. 3.

The results in Fig. 3 demonstrate that the DHC composite provides the most effective suppression of wax deposition

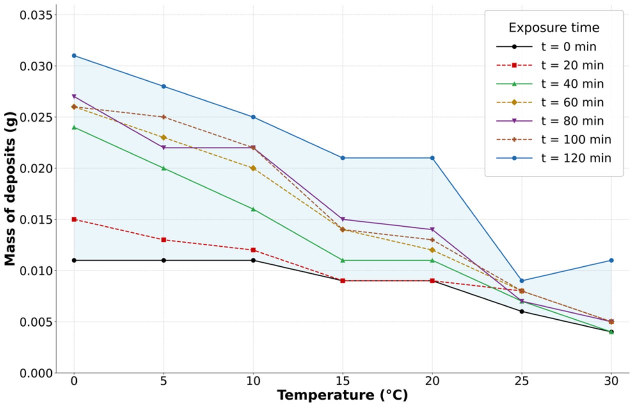

Fig. 3 Temperature dependence of paraffin deposit mass at different exposure times obtained by cold-finger tests of the model crude oil treated with the DHC composite

among the investigated treatments. Compared with both the reagent-free system and single-component depressor additives applied at the same total dosage, the DHC formulation results in a pronounced reduction in paraffin deposit mass across the entire temperature range. The low data scatter confirms good repeatability of the cold-finger measurements and supports the reliability of the observed trend.

Following the evaluation of wax-deposition behavior, the flow characteristics of the crude oil treated with the DHC composite were further investigated. The corresponding rheological results are presented in Fig. 4.

Fig. 4(a) shows that the yield stress of the crude oil treated with the DHC composite remains low across the investigated temperature range and increases only slightly at lower temperatures, indicating strong suppression of low-temperature structural development. The small data scatter confirms good measurement repeatability.

As illustrated in Fig. 4(b), the apparent viscosity at fixed shear rates decreases smoothly with increasing temperature and shows minimal dependence on shear rate, reflecting a pronounced weakening of shear-thinning behavior.

Fig. 4(c) demonstrates that shear stress remains low and decreases monotonically with increasing temperature, with only minor separation between curves obtained at different shear rates. This behavior indicates reduced internal structural resistance and confirms that the DHC composite provides the most pronounced improvement in rheological stability among the investigated treatments.

To further evaluate the reliability of the experimental results, wax-separation tests were conducted in triplicate (*n* = 3), and the corresponding mean values and standard deviations obtained at different temperatures are summarized in Tables 2 and 3. It should be noted that the tabulated values characterize the overall wax-precipitation tendency of the crude oil in the bulk phase prior to thermal

Table 2 Repeatability of bulk wax-precipitation measurements at different temperatures (*n* = 3)

Temperature (°C)	Mean total wax precipitation mass (g)	SD (g)
0	2.10	0.15
5	1.85	0.12
10	1.42	0.10
15	1.05	0.08
20	0.68	0.05
25	0.40	0.04
30	0.22	0.03

Table 3 Comparative effect of chemical additives on wax deposition and yield stress at different temperatures (mean ± SD, *n* = 3)

Temperature (°C)	Condition	Total wax precipitate mass (g)	Wax deposition (g)	Yield stress τ_0 (Pa)
0	Reagent-free	2.10 ± 0.15	0.44 ± 0.04	0.162 ± 0.012
	Difron-3971 (600 g/t)	0.95 ± 0.08	0.09 ± 0.01	0.072 ± 0.006
	DHC (600 g/t)	0.10 ± 0.02	0.03 ± 0.004	0.020 ± 0.003
10	Reagent-free	1.42 ± 0.10	0.32 ± 0.03	0.098 ± 0.009
	Difron-3971 (600 g/t)	0.62 ± 0.06	0.07 ± 0.008	0.041 ± 0.004
	DHC (600 g/t)	0.06 ± 0.01	0.025 ± 0.003	0.015 ± 0.002
20	Reagent-free	0.68 ± 0.05	0.22 ± 0.02	0.051 ± 0.005
	Difron-3971 (600 g/t)	0.28 ± 0.03	0.04 ± 0.005	0.023 ± 0.003
	DHC (600 g/t)	0.03 ± 0.01	0.016 ± 0.002	0.010 ± 0.001

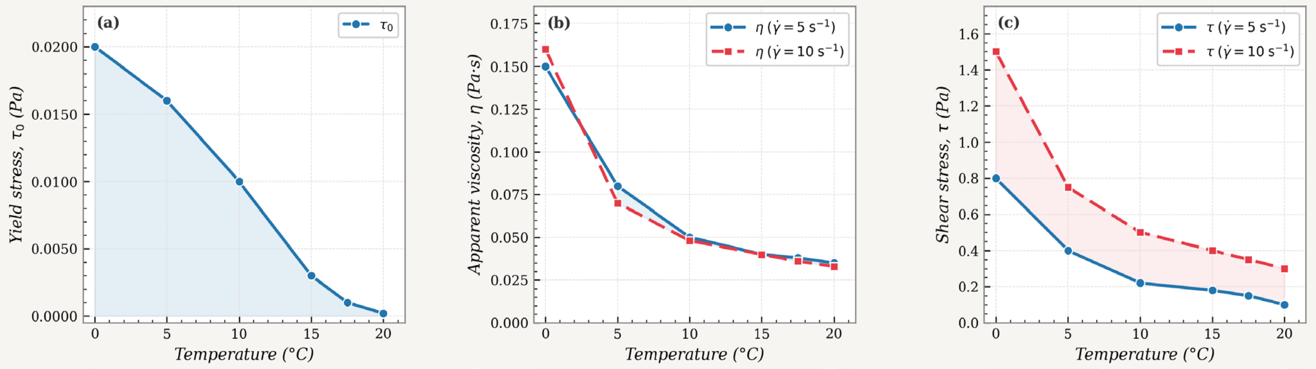

Fig. 4 Temperature-dependent rheological parameters of crude oil treated with the DHC composite (600 g/t): (a) yield stress; (b) apparent viscosity at $\gamma = 5$ and $10\ s^{-1}$; (c) shear stress at $\gamma = 5$ and $10\ s^{-1}$

conditioning, whereas Fig. 4 illustrates the mass of deposits accumulated on the cooled surface during the controlled deposition test. Because only a fraction of the precipitated paraffinic material is retained on the test surface, the surface deposit masses shown in Fig. 4 are lower than the total precipitate masses reported in Tables 2 and 3. This distinction explains the apparent difference in absolute values while confirming consistent temperature-dependent trends observed in both datasets.

The statistical analysis of the wax-separation experiments demonstrates a high level of repeatability across the entire investigated temperature range. As shown in Table 2, the standard deviation values remain consistently low at all temperatures, indicating that the observed trends are not the result of random experimental fluctuations but reflect stable and reproducible system behavior. This consistency supports the reliability of the error bars presented in Fig. 4 and confirms the robustness of the cold-finger measurements.

A comparative evaluation of chemical treatments summarized in Table 3 reveals a pronounced dependence of wax precipitation intensity and yield stress on both temperature and reagent composition. Under reagent-free conditions, a systematic decrease in precipitated wax mass with increasing temperature is observed, which is consistent with enhanced paraffin solubility and a reduced thermodynamic driving force for crystallization at elevated temperatures. Nevertheless, even at moderate temperatures, the untreated oil exhibits substantial wax precipitation and elevated yield-stress values, indicating a strong tendency toward structural buildup.

The introduction of the Difron-3971 depressor additive leads to a significant reduction in both precipitated wax mass and yield stress across the investigated temperature range. However, the persistence of measurable solid fractions and non-zero yield-stress values suggest that, when applied as a single-component additive, Difron-3971 reduces but does not fully suppress the formation of a three-dimensional paraffin–resin–asphaltene network, particularly under low-temperature conditions.

In contrast, the DHC composite exhibits the most pronounced inhibitory effect throughout the studied temperature range. As summarized in Table 3, the composite consistently yields the lowest wax-deposition masses and yield-stress values at all investigated temperatures. These results indicate a substantial weakening of non-Newtonian behavior under conditions where the untreated oil remains strongly structured. The enhanced performance of the composite is attributed to the synergistic action of its components, which collectively limit crystal nucleation, restrict crystal growth, and reduce interparticle aggregation, thereby suppressing the formation of an extended solid-like network.

Importantly, the superior performance of the DHC composite is not only reflected in the mean values but is also supported by the relatively low standard deviations obtained from repeated measurements. This observation indicates that the composite action is stable and reproducible rather than sporadic, reinforcing its relevance for low-temperature flow-assurance applications.

As shown in Fig. 5, the presence of chemical reagents leads to a systematic decrease in plastic viscosity K_p across the investigated temperature range, with the magnitude of the reduction depending on additive type and dosage. The relatively small scatter and narrow error ranges associated with the K_p values indicate good repeatability of the measurements and support the reliability of the observed trends [38].

Fig. 5 presents a comparative analysis of the temperature dependence of plastic viscosity for the model crude oil under reagent-free conditions and in the presence of various chemical additives at different dosages. In all cases, K_p decreases with increasing temperature; however, both the magnitude and rate of this decrease vary depending on the type of additive and its concentration. The relatively small scatter and narrow error ranges associated with the data indicate good repeatability of the measurements.

The reagent-free crude oil exhibits high plastic viscosity at low temperatures, with K_p values exceeding 1.0 Pa·s at 0 °C, followed by a gradual decrease as temperature increases. This behavior is characteristic of high-paraffin

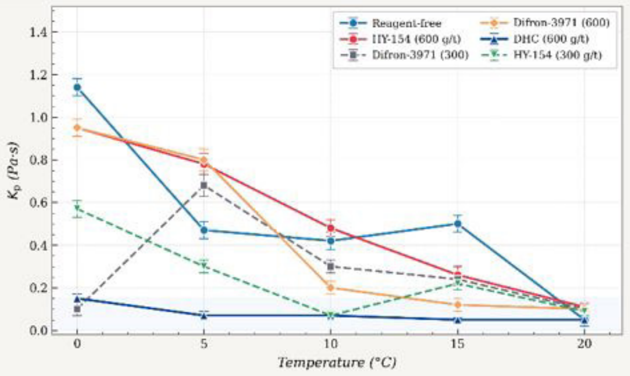

Fig. 5 Temperature-dependent plastic viscosity of high-paraffin crude oil under reagent-free and additive-treated conditions (Difron-3971, HY-154, and DHC at indicated dosages). Plastic viscosity was evaluated using the Bingham model [38]; error bars denote ±SD.

crude oils and reflects the development of an internal structure associated with paraffin crystallization.

The application of Difron-3971 and the DHC composite at a dosage of 600 g/t leads to a pronounced reduction in plastic viscosity over the entire temperature range. In particular, Difron-3971 at 600 g/t results in a minimum K_p within the 10–20 °C range, indicating a substantial improvement in flow plasticity. The consistency of the data across repeated measurements suggests that this effect is systematic rather than incidental.

The influence of HY-154 exhibits a clear dependence on dosage. At 600 g/t, HY-154 contributes to stabilization of K_p and yields reduced viscosity values, particularly in the intermediate temperature range. In contrast, at a dosage of 300 g/t, the reduction in K_p is less pronounced, especially at lower temperatures, indicating incomplete suppression of structural effects. This behavior highlights the importance of dosage optimization for effective rheological control.

Difron-3971 applied at 300 g/t produces a moderate decrease in plastic viscosity; however, a more stable dispersing effect is observed only at the higher dosage. This observation further confirms the decisive role of reagent concentration in regulating the plastic flow properties of high-paraffin crude oils.

Among the investigated treatments, the DHC composite at a dosage of 600 g/t demonstrates the most consistent reduction in K_p across the entire temperature range. The sustained decrease in plastic viscosity indicates a significant weakening of structural resistance to flow. The observed behavior reflects the combined action of the composite components, providing enhanced rheological control compared to single-component additives.

The results confirm that chemical treatment represents an effective approach for controlling the plastic viscosity of high-paraffin crude oils. While viscosity naturally decreases with increasing temperature, appropriate selection of reagent composition and dosage significantly enhances this effect, contributing to more stable and predictable flow behavior under low-temperature conditions.

Using gas chromatography, the variation in carbon-number distribution within asphaltene–resin–paraffin deposits under the influence of the composite at different temperatures was also investigated. The corresponding results are presented in Fig. 6.

Fig. 6 presents the carbon-number distribution of *n*-paraffins (C_{17}–C_{47}) in asphaltene–resin–paraffin deposits formed at 20–50 °C in the presence of the DHC composite, as determined by gas chromatography. The results show a clear temperature dependence of paraffin distribution, with dominant contributions from the C_{27}–C_{33} fraction across all conditions.

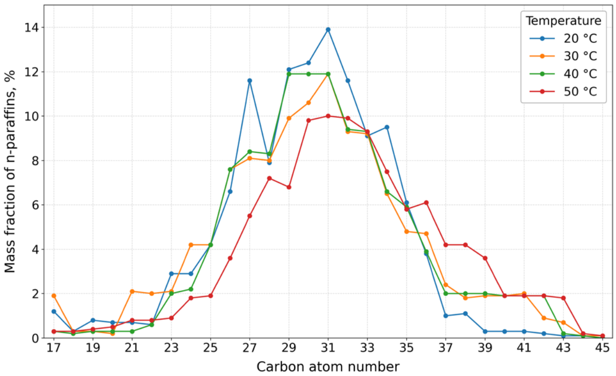

Fig. 6 Carbon-number distribution of n-paraffins (C_{17}–C_{47}) within asphaltene–resin–paraffin deposits obtained at different temperatures (20–50 °C) under the influence of the DHC composite, determined by gas chromatography

At 20 °C, paraffin crystallization is most pronounced, with peak concentrations in the C_{29}–C_{31} range reaching approximately 14%. Increasing temperature to 30–40 °C leads to a gradual reduction in peak intensities to about 10–11% and 9–10%, accompanied by smoother distribution profiles. At 50 °C, peak intensities further decrease to 8–9%, indicating enhanced solubility of paraffinic components and reduced crystallization propensity.

These results confirm that paraffin deposition is primarily governed by C_{27}–C_{33} hydrocarbons and is effectively suppressed by increasing temperature in combination with chemical treatment, consistent with the observed improvements in rheological behavior and wax-inhibition performance.

The subsequent section examines the structural characteristics of high-paraffin blended oil systems and the influence of chemical additives using X-ray diffraction analysis. The diffraction patterns presented in Fig. 7 illustrate the effect of reagent treatment on the degree of structural ordering and molecular arrangement within the oil matrix.

Fig. 7(a)–(d) presents the X-ray diffraction patterns of the reagent-free high-paraffin blended oil and of samples treated with Difron-3971, HY-154, and the DHC composite at a dosage of 600 g/t. The reagent-free system (Fig. 7(a)) is characterized by a broad diffraction halo in the 2θ range of approximately 18–25°, which is typical of predominantly amorphous hydrocarbon media containing disordered paraffin chains and weakly developed crystalline domains. The absence of sharp diffraction peaks indicates limited long-range molecular ordering despite the high paraffin content of the blended oil.

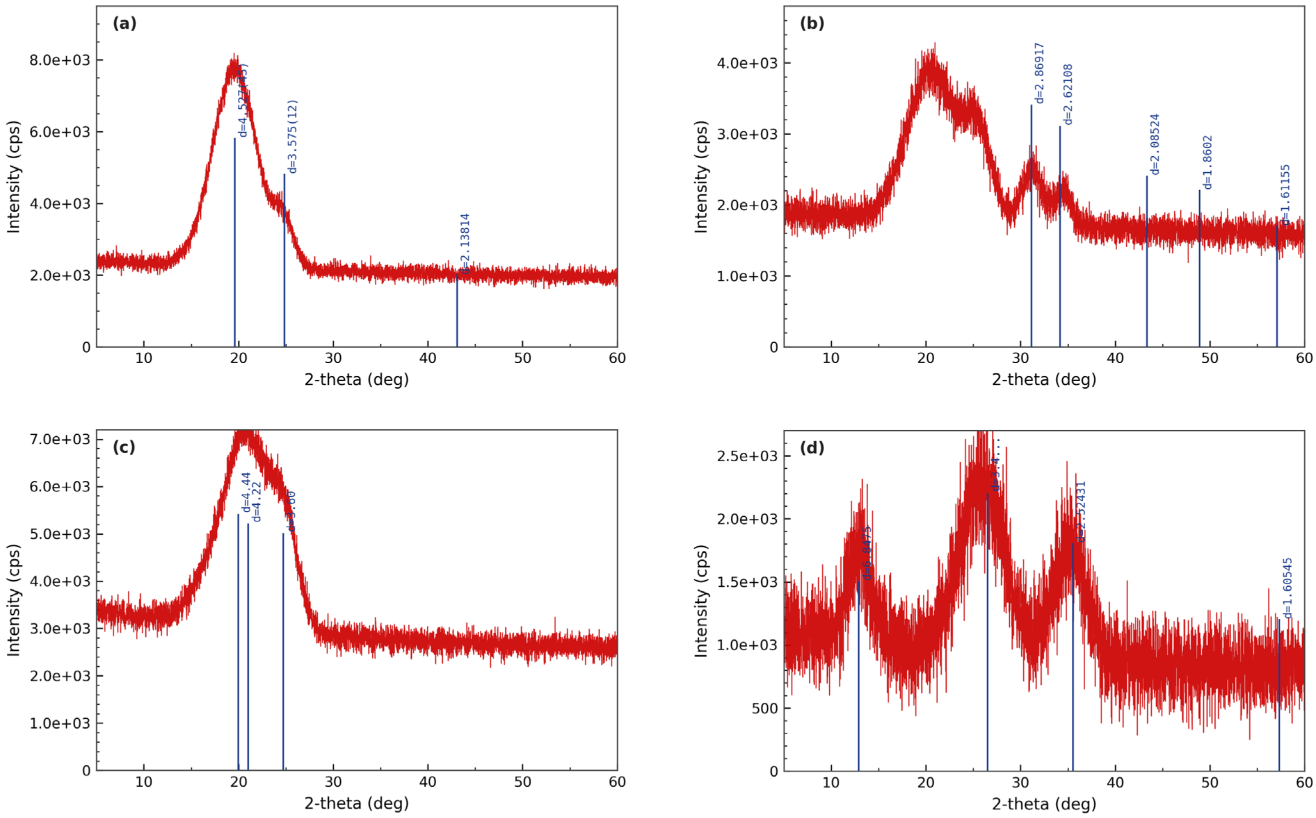

Fig. 7 X-ray diffraction patterns of high-paraffin model oil: (a) reagent-free sample, (b) Difron-3971 (600 g/t), (c) HY-154 (600 g/t), and (d) DHC composite (600 g/t)

Treatment with Difron-3971 (Fig. 7(b)) results in a noticeable decrease in the intensity of the primary diffraction halo accompanied by slight peak broadening. These features indicate a reduction in structural ordering and disruption of paraffin chain packing. The additive appears to inhibit the growth and stabilization of ordered paraffin domains, leading to a more disordered internal structure relative to the untreated system.

A comparable modification of the diffraction pattern is observed for the sample treated with HY-154 (Fig. 7(c)). Although a reduction in diffraction intensity is evident compared with the reagent-free blended oil, the effect is less pronounced than that observed for Difron-3971. This suggests that HY-154 partially suppresses paraffin ordering while allowing a degree of residual structural organization to persist within the oil matrix.

The most substantial structural modification is observed for the sample treated with the DHC composite (Fig. 7(d)). This diffraction pattern exhibits the lowest overall intensity and the broadest halo among all investigated systems, indicating a pronounced reduction in crystallinity and a high degree of structural disorder. Such behavior reflects the synergistic action of the composite formulation, which effectively disrupts paraffin chain alignment and prevents the formation of stable crystalline aggregates.

The XRD results demonstrate that chemical treatment modifies the internal structural organization of the high-paraffin blended oil by decreasing the degree of molecular ordering associated with paraffin crystallization. The progressive structural disruption observed in the sequence reagent-free < HY-154 < Difron-3971 < DHC composite is consistent with the rheological results, where increased structural disorder corresponds to lower viscosity, reduced shear stress, and improved low-temperature flow behavior.

The obtained results clearly demonstrate the pronounced effectiveness of the DHC composite formulation in suppressing wax deposition and improving the rheological behavior of high-paraffin crude oil. The inhibition efficiency achieved in this study reaches approximately 95% at low temperature, which exceeds the typical performance range reported for conventional single-component depressor additives. Previous investigations indicate that polymer-based wax inhibitors generally provide deposition reduction within 50–85%, depending on crude oil composition and experimental conditions. The significantly higher efficiency observed for the DHC system confirms the advantages of the proposed multifunctional formulation and highlights the importance of synergistic interactions between its components [39–41].

The enhanced performance of the composite system can be attributed to the combined action of depressor polymers and aromatic solvent fractions, which simultaneously influence nucleation, crystal growth, and aggregation processes of paraffin structures. The results indicate that the DHC formulation effectively disrupts the formation of a continuous three-dimensional network of interlocking paraffin crystals responsible for structural strengthening of crude oil at low temperatures. The substantial reduction in deposit mass, together with the observed decrease in viscosity and yield stress, confirms that the composite formulation significantly weakens intermolecular interactions governing the development of rigid paraffin networks.

Similar behaviour has been reported for multifunctional inhibitor systems in which synergistic effects between polymeric depressants and dispersing components enhance control of crystallization processes and improve flow characteristics. Compared with individual depressor additives such as Difron-type formulations, the DHC composite demonstrates superior ability to suppress wax crystallization and maintain stable flowability of high-paraffin crude oil. This improvement is associated with enhanced compatibility of the composite components with both paraffin fractions and resin–asphaltene structures, resulting in improved dispersion stability and reduced tendency toward crystal agglomeration.

From a physicochemical perspective, the effectiveness of the DHC formulation can be explained by cooperative interactions between its components and the complex hydrocarbon matrix of crude oil. Depressor molecules present in Difron-3971 and HY-154 contain long hydrocarbon chains capable of co-crystallizing with n-paraffin molecules, thereby disturbing the regular packing of crystal lattices and limiting crystal growth. This leads to the formation of smaller, less ordered paraffin crystals that are unable to form a strong interconnected network structure.

At the same time, aromatic solvent components such as xylene enhance compatibility between inhibitor molecules and heavy hydrocarbon fractions, facilitating dispersion of resin–asphaltene structures and preventing the formation of dense aggregates. Kerosene contributes to improved distribution of active components within the oil matrix and promotes more uniform interaction between inhibitor molecules and crystallizing paraffin structures. The combined action of these components results in simultaneous modification of crystallization kinetics, structural organization, and aggregation behaviour of paraffin particles. Consequently, paraffin crystals remain smaller, less interconnected, and more uniformly dispersed in the liquid phase, which significantly reduces structural viscosity and deposition intensity. The observed synergistic effect confirms that the developed composite formulation provides a more efficient strategy for controlling wax crystallization and improving the rheological stability of high-paraffin crude oils compared with conventional single-component depressor additives.

4 Conclusion

1. At a dosage of 600 g/t, the deposit mass at 0 °C decreased from 0.44 g to 0.10 g, corresponding to an inhibition efficiency of approximately 95%, demonstrating the superior effectiveness of the composite system compared with individual depressor additives. The obtained results confirm the strong ability of the DHC formulation to suppress paraffin crystallization and reduce the intensity of wax deposition under low-temperature conditions.
2. Under reagent-free conditions, shear stress increased sharply with decreasing temperature, and the difference between measurements at shear rates of 5 s^{-1} and 10 s^{-1} became significant, reflecting pronounced shear-rate sensitivity and structural strengthening of the crude oil. Treatment with Difron-3971 and HY-154 reduced shear stress but retained noticeable shear-rate dependence at low temperatures. In contrast, the DHC composite markedly lowered shear stress over the entire temperature range and minimized the separation between curves at different shear rates, indicating more effective suppression of temperature-induced structuring processes.
3. For the untreated oil, effective viscosity increased considerably with decreasing temperature and exhibited pronounced non-Newtonian shear-thinning behaviour. The application of Difron-3971 and HY-154 resulted in partial viscosity reduction; however, relatively high viscosity values persisted at low temperatures. The DHC composite reduced effective viscosity by approximately 3.5–4.0 times and significantly weakened its temperature sensitivity, providing the most stable flow behaviour among the investigated systems.
4. The obtained results demonstrate that the developed composite formulation can significantly improve flow assurance conditions during production and

pipeline transportation of high-paraffin crude oils. The substantial reduction in wax deposition intensity indicates a decreased risk of paraffin accumulation on pipeline walls, which contributes to lower hydraulic resistance and improved pumping efficiency. The improved rheological stability over a wide temperature range suggests reduced energy consumption during transportation and decreased probability of pipeline blockage under low-temperature operating conditions. Therefore, the proposed DHC composite represents a promising multifunctional additive for enhancing the reliability and efficiency of transportation of paraffinic crude oils.

Acknowledgment

The authors gratefully acknowledge the support of Azerbaijan State Oil and Industry University (ASOIU) for providing the research environment and laboratory facilities. The authors also thank SOCAR for assistance related to crude oil sampling and technical support.

References

[1] Ali, M. F., Alqam, M. H. "The role of asphaltenes, resins and other solids in the stabilization of water in oil emulsions and its effects on oil production in Saudi oil fields", Fuel, 79(11), pp. 1309–1316, 2000. https://doi.org/10.1016/S0016-2361(99)00268-9

[2] Kumar, A., Mahto, V., Sharma, V. P. "Reinforced preformed particle gel: synthesis, characterization and performance evaluation for water shut-off jobs in heterogeneous reservoirs", Journal of Petroleum Science and Engineering, 193, 107408, 2020. https://doi.org/10.1016/j.petrol.2020.107408

[3] Alnaimat, F., Ziauddin, M. "Wax deposition and prediction in petroleum pipelines", Journal of Petroleum Science and Engineering, 184, 106385, 2020. https://doi.org/10.1016/j.petrol.2019.106385

[4] Zhang, J., Xue, Q., Gao, H., Wang, P. "Biodegradation of paraffin wax by crude Aspergillus enzyme preparations for potential use in removing paraffin deposits", Journal of Basic Microbiology, 55(11), pp. 1326–1335, 2015. https://doi.org/10.1002/jobm.201500290

[5] Ismayilova, M., Mustafayev, I. I., Melikova, S. Z., Nurmammadova, F. N., Aliyeva, M. H. "Radiation-induced isomerization reaction mechanism of hydrocarbons on the surface of solid acid", Physics and Chemistry of Solid State, 24(3), pp. 460–466, 2023. https://doi.org/10.15330/pcss.24.3.460-466

[6] Martinyuk, G., Aksimentyeva, O., Skoreiko, N., Zakordonskyi, V. "Effect of filler nature on chemical resistance and microhardness of epoxy composite films", Physics and Chemistry of Solid State, 16(3), pp. 528–533, 2015. https://doi.org/10.15330/pcss.16.3.528-533

[7] Gasimzade, A. V. "Study of a multifunctional composition in the preparation and transportation of heavy oils", Voprosy Khimii i Khimicheskoi Tekhnologii, 2024(4), pp. 25–33, 2024. https://doi.org/10.32434/0321-4095-2024-155-4-25-33

[8] Jennings, D. W., Weispfennig, K. "Effects of shear and temperature on wax deposition: cold finger investigation with a Gulf of Mexico crude oil", Energy & Fuels, 19(4), pp. 1376–1386, 2005. https://doi.org/10.1021/ef049784i

[9] Matiyev, K. I., Agazade, A. D., Alsafarova, M. E., Akhmedov, F. M. "Pour-point depressant for high pour-point paraffinic oils", SOCAR Proceedings, 3, pp. 32–37, 2018. https://doi.org/10.5510/ogp20180300359

[10] Santos, R. G., Loh, W., Bannwart, A. C., Trevisan, O. V. "An overview of heavy oil properties and its recovery and transportation methods", Brazilian Journal of Chemical Engineering, 31(3), pp. 571–590, 2014. https://doi.org/10.1590/0104-6632.20140313s00001853

[11] Guerrero-Martin, C. A., Montes, D., Meneses, M., Guerrero-Martin, G. E., Salinas-Silva, R., Camacho-Galindo, S., Lucas, E. F., Szklo, A. "Asphaltene precipitation and deposition estimation and inhibition through nanotechnology: a comprehensive review", Energies, 16(13), 4859, 2023. https://doi.org/10.3390/en16134859

[12] Al-Sayyab, A. K., S., Abdulwahid, M. A. "Using injected additive materials to improve pipeline transportation: experimental and CFD study", Journal of Thermal Engineering, 10(4), pp. 826–835, 2024. https://doi.org/10.14744/thermal.0000834

[13] Nurullayev, V. H., Murvatov, F. T., Gasimzade, A. V. "Perspectives for development of the Siyazan monoclinal oil field of Azerbaijan", SOCAR Proceedings, SI1, pp. 84–89, 2022. https://doi.org/10.5510/ogp2022si100649

[14] Ibadzade, T. F. "Development of a new composition for prevention of asphaltene–paraffin–resin deposits", Scientific Petroleum, 2, 2024. https://doi.org/10.53404/sci.petro.20240200062

[15] Ala, B. S. K., Babu, P., Daraboina, N. "Impact of high pressure on wax deposition and paraffin inhibitor performance in a cold finger system", Energy & Fuels, 39(23), pp. 11024–11030, 2025. https://doi.org/10.1021/acs.energyfuels.5c01898

[16] Huang, H., Wang, D., Liu, H., Duan, J., Huang, Q., Long, X., Meng, J., Qi, Z., Gong, J. "Influence of oil components on the wax deposition of heavy oil", ACS Omega, 10(15), pp. 15065–15074, 2025. https://doi.org/10.1021/acsomega.4c10540

[17] Alhejaili, A., Daraboina, N. "Experimental analysis of paraffin deposition in slug flow", Energy & Fuels, 39(5), pp. 2500–2507, 2025. https://doi.org/10.1021/acs.energyfuels.4c05343

[18] Ala, B. S. K., Daraboina, N. "Decoding the flow dynamics and chemical inhibitors influence on wax deposition in oil transportation pipelines", Fuel, 412, 138123, 2026. https://doi.org/10.1016/j.fuel.2025.138123

[19] Chalita, M. A. "Robustness outside the laboratory: a thermodynamic framework for scientific practices", Foundations of Science, 2025.
https://doi.org/10.1007/s10699-025-09994-z

[20] Alhejaili, A., Bell, E., Daraboina, N. "Experimental analysis of paraffin deposition in multiphase stratified flow", Geoenergy Science and Engineering, 247, 213700, 2025.
https://doi.org/10.1016/j.geoen.2025.213700

[21] Kouhi, M. M., Shafiei, A., Bekkuzhina, T., Abutalip, M. "New intelligent models for predicting wax appearance temperature using experimental data – flow assurance implications", Fuel, 380, 133146, 2025.
https://doi.org/10.1016/j.fuel.2024.133146

[22] Sun, J., Xiu, Z., Li, L., Lv, K., Zhang, X., Wang, Z., Dai, Z., Xu, Z., Huang, N., Liu, J. "Application status and prospect of ionic liquids in oilfield chemistry", Petroleum, 10(1), pp. 11–18, 2024.
https://doi.org/10.1016/j.petlm.2023.08.001

[23] Gao, C. H. "Experimental research of paraffin deposition with flow loops", Reviews in Chemical Engineering, 40(6), pp. 765–783, 2024.
https://doi.org/10.1515/revce-2023-0041

[24] Boranbayeva, L., Boiko, G., Sharifullin, A., Lubchenko, N., Sarmurzina, R., Kozhamzharova, A., Mombekov, S. "Analysis of the processes of paraffin deposition of oil from the Kumkol group of fields in Kazakhstan", Processes, 12(6), 1052, 2024.
https://doi.org/10.3390/pr12061052

[25] GOST "GOST 11858-66. Petroleum and petroleum products – Method for determination of asphalt–resin substances", Gosudarstvennyy standart, Moscow, USSR, 1966.

[26] ASTM International "ASTM D1298-24. Standard Test Method for Density, Relative Density, or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method", ASTM International, West Conshohocken, PA, USA, 2024.
https://doi.org/10.1520/D1298-24

[27] GOST "GOST 3900-85. Petroleum and petroleum products. Method for determination of density", Gosudarstvennyy standart, Moscow, USSR, 1985.

[28] ASTM International "ASTM D6560-22. Standard Test Method for Determination of Asphaltenes (Heptane Insolubles) in Crude Petroleum and Petroleum Products", ASTM International, West Conshohocken, PA, USA, 2022.
https://doi.org/10.1520/D6560-22

[29] GOST "GOST 11851-85. Crude oil – Method for determination of paraffin (wax)", Gosudarstvennyy standart, Moscow, USSR, 1985.

[30] GOST "GOST 33-2016. Petroleum and petroleum products – Determination of kinematic and dynamic viscosity", Gosudarstvennyy standart, Moscow, Russia, 2016.

[31] ISO "ISO 3104:2020. Petroleum products – Determination of kinematic viscosity and calculation of dynamic viscosity", International Organization for Standardization, Geneva, Switzerland, 2020.

[32] GOST "GOST 1929-87. Petroleum products – Determination of dynamic viscosity by rotational viscometer", Gosudarstvennyy standart, Moscow, USSR, 1987.

[33] ISO "ISO 3219-1:2021. Rheology – Vocabulary and symbols", International Organization for Standardization, Geneva, Switzerland, 2021.

[34] ISO "ISO 3219-2:2021. Rheology – General principles of rotational and oscillatory rheometry", International Organization for Standardization, Geneva, Switzerland, 2021

[35] GOST "GOST 13379-82. Petroleum – Determination of C1–C6 hydrocarbons by gas chromatography", Gosudarstvennyy standart, Moscow, USSR, 1982.

[36] GOST "GOST 23683-89. Petroleum paraffin waxes – Specifications and test methods", Gosudarstvennyy standart, Moscow, USSR, 1989.

[37] Wang, Z., Bridgeford, E., Wang, S., Vogelstein, J. T., Caffo, B. "Statistical analysis of data repeatability measures", International Statistical Review, 93(3), pp. 517–543, 2024.
https://doi.org/10.1111/insr.12591

[38] Bingham, E. C. "Fluidity and Plasticity", McGraw-Hill, 1922.

[39] Matiyev, K. I., Samedov, A. M., Alsafarova, M. E., Hasanov, K. I., Nurullaev, V. K. "Prevention of asphaltene-resin-paraffin deposits in the process of oil transportation", SOCAR Proceedings, 2, pp. 101–104, 2024.
https://doi.org/10.5510/OGP20240200973

[40] Manafov, M. R., Shikhieva, F. R., Matiev, K. I., Karimli, V. I. "Study of the effect of asphaltene-resinous compounds on the separation of oil emulsions", Azerbaijan Chemical Journal, 2022(2), pp. 18–27, 2022.
https://doi.org/10.32737/0005-2531-2022-2-18-27

[41] Matiyev, K. I., Samedov, A. M., Akhmedov, F. M. "Development of pour point depressants for crude oil and study of their properties", SOCAR Proceedings, (1), pp. 90–96, 2021.
https://doi.org/10.5510/OGP20210100485