Nafta-Gaz 2025, no. 7, pp. 453–464, DOI: 10.18668/NG.2025.07.04

Investigation of the effect of various methods on the rheological parameters of high paraffinic oil

Badanie wpływu różnych metod na parametry reologiczne wysokoparafinowej ropy naftowej

Guseyn R. Gurbanov, Aysel V. Gasimzade, Leili A. Abbasova

Azerbaijan State Oil and Industry University

ABSTRACT: This article presents, for the first time, detailed information on the results of laboratory experiments examining the effects of ultrasound waves as a physical method and the Difron-3970 depressant additive as a chemical method – applied individually and in combination – on the rheological parameters of oil samples. These samples, characterized by a high content of heavy hydrocarbons, were obtained from the Narimanov field of the State Oil Company of the Republic of Azerbaijan (SOCAR). The experiments also investigated the amount of asphaltene-resin-paraffin deposits formed under different conditions. The influence of ultrasound waves on the oil samples was tested for 5, 10, and 15 minutes, with the optimal treatment time determined to be 15 minutes. The study employed varying concentrations of the Difron-3970 depressant additive (100, 200, 300, 400, 500, 600, and 700 g/t), and the optimal concentration was 700 g/t. For the combined effect of ultrasound waves and the depressant additive, the optimal dosage of Difron-3970 was found to be 500 g/t, while the optimal ultrasound exposure time was 10 minutes. The results of laboratory experiments has revealed that the combined physical-chemical method is more effective than the physical or chemical methods applied individually. Furthermore, during individual tests of the Difron-3970 depressant additive, it was observed that the optimal dosage was reduced by 200 g/t, and the optimal ultrasound exposure time was shortened by 5 minutes. This demonstrates that the combined physical-chemical method offers improved cost-efficiency. Therefore, we propose the application of both the Difron-3970 depressant additive and ultrasound waves in field conditions as an economically and environmentally viable method for improving the pipeline transport of high-viscosity, high-freezing-point crude oil.

Key words: ultrasound waves, Difron-3970 depressant additive, physical-chemical method, optimal concentration, optimal exposure time, dynamic viscosity, freezing point, shear gradient, shear stress.

STRESZCZENIE: Niniejszy artykuł po raz pierwszy przedstawia szczegółowe informacje dotyczące wyników eksperymentów laboratoryjnych, w których badano wpływ fal ultradźwiękowych jako metody fizycznej oraz dodatku depresatora Difron-3970 jako metody chemicznej, stosowanych indywidualnie i w połączeniu, na parametry reologiczne próbek ropy naftowej. Próbki te, charakteryzujące się wysoką zawartością ciężkich węglowodorów, zostały pozyskane ze złoża ropy naftowej Narimanov należącego do Azerskiej Państwowej Spółki Naftowej (SOCAR). W eksperymentach badano również ilość osadów asfaltenowo-żywiczno-parafinowych, wytrąconych w różnych warunkach. Wpływ fal ultradźwiękowych na próbki ropy testowano przez 5, 10 i 15 minut, przy czym optymalny czas obróbki określono na 15 minut. W badaniu zastosowano różne stężenia dodatku depresatora Difron-3970 (100, 200, 300, 400, 500, 600 i 700 g/t), a optymalne stężenie ustalono na poziomie 700 g/t. W przypadku połączonego działania fal ultradźwiękowych i dodatku depresatora, optymalną dawkę Difron-3970 ustalono na poziomie 500 g/t, natomiast optymalny czas ekspozycji na ultradźwięki wynosił 10 minut. Analiza licznych eksperymentów laboratoryjnych wykazała, że metoda fizyczno-chemiczna jest bardziej efektywna niż stosowanie metod fizycznych lub chemicznych oddzielnie. Ponadto, podczas indywidualnych testów dodatku Difron-3970 zaobserwowano, że optymalna dawka zmniejszyła się o 200 g/t, a optymalny czas ekspozycji na ultradźwięki uległ skróceniu o 5 minut. Wskazuje to, że metoda fizyczno-chemiczna jest bardziej ekonomiczna. W związku z tym proponujemy stosowanie połączonego działania dodatku depresatora Difron-3970 oraz fal ultradźwiękowych w warunkach polowych jako ekonomicznej i ekologicznej metody poprawy transportu ropy o wysokiej lepkości i wysokiej temperaturze krzepnięcia za pomocą systemu rurociągowego.

Słowa kluczowe: fale ultradźwiękowe, dodatek depresatora Difron-3970, metoda fizyczno-chemiczna, optymalne stężenie, optymalny czas ekspozycji, lepkość dynamiczna, temperatura krzepnięcia, gradient ścinania, naprężenie ścinające.

Corresponding author: G.R. Gurbanov, e-mail: *huseyn.gurbanov@asoiu.edu.az*

Article contributed to the Editor: 19.10.2024. Approved for publication: 29.05.2025.

Introduction

Currently, the oil industry in developed countries is experiencing increasing complexity in the processes of oil extraction, collection, preparation for transportation, and transportation itself. This complexity is mainly due to the presence of asphaltene, resin, and paraffin compounds, which are key components of oil (Loskutova and Yudina, 2006). It should be noted that the share of light oil dispersions produced worldwide is decreasing, while the production of high-viscosity, high-freezing-point oils is increasing. During the transportation of such oils through pipelines, a decrease in ambient temperature leads to the gradual accumulation of asphaltene-resin-paraffin deposits on the inner surface of the pipeline, leading to a narrowing of the pipeline's cross-sectional area and a reduction in fluid flow velocity (Samadov et al., 2017). In some cases, this process may result in the complete cessation of flow within the pipeline (Gurbanov and Gasimzade, 2022).

Researchers have proposed various methods to improve the transportation of high-viscosity, high-freezing-point oils through pipelines. One of the effective methods is the thermochemical approach (Gurbanov and Sardarova, 2022). It is based on heating the oil to a temperature that results in the melting of solid paraffin hydrocarbons, followed by the addition of a predetermined amount of a chemical reagent for each ton of oil through a dosing device, as determined under laboratory conditions (Gurbanov et al., 2021, 2024a).

In modern technology, one of the most effective approaches is the combined physical–chemical method, which involves the simultaneous application of ultrasound waves and chemical reagents. This approach is the subject of numerous studies and is considered more promising from technological, economic, and environmental perspectives (Iskandarov et al., 2024).

Based on the above considerations, this study aims to investigate, the effects of ultrasound waves (as a physical method) and the Difron-3970 (manufactured by EKOS-1, Russian Federation) depressant additive (as a chemical reagent) on several rheological parameters, including the amount of asphaltene-resin-paraffin deposits, in high-viscosity, high-freezing-point oil samples, both individually and in combination (Gurbanov et al., 2024b).

Materials and methods

To examine the separate and combined effects of physical and chemical methods, oil samples with the physical-chemical characteristics listed in Table 1 were used.

As shown in Table 1, the oil solidifies at high temperature and is characterized by a high percentage of asphaltene-resin-paraffin components. In the laboratory environment, the the paraffin deposition process in the studied oil sample was quantitatively assessed using the apparatus shown in Figure 1, which is capable of performing the "cold finger" method. The apparatus consists of a metal tube, cooled by a cooling

Table 1. Physical-chemical properties of the oil sample

Tabela 1. Właściwości fizykochemiczne próbki ropy naftowej

Parameters	Narimonov crude oil sample
Density 20°C [kg/m^3]	986.4
Dynamic viscosity 20°C [mP·s]	1563
Water content [mass %]	38
Chloride salt content [mg/l]	502
Mechanical impurity content [mass %]	5.6
Resin content [mass %]	9.2
Asphaltene content [mass %]	4.24
Paraffin content [mass %]	15.4
Freezing point [°C]	18

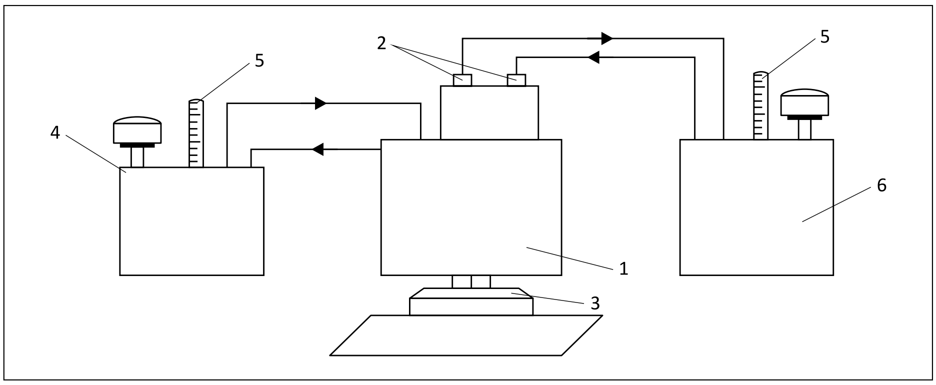

Figure 1. Schematic diagram of a special device for determining paraffin deposition using the "cold finger" method at various temperatures: 1 – heating vessel; 2 – cold tube; 3 – mixer; 4 – heater; 5 – thermometer; 6 – chiller (RD 39-3-812-82)

Rysunek 1. Schemat urządzenia do określania osadzania parafiny metodą „zimnego palca" w różnych temperaturach: 1 – naczynie grzewcze; 2 – chłodzona rurka; 3 – mieszadło; 4 – grzałka; 5 – termometr; 6 – chłodziarka (RD 39-3-812-82) agent to the desired temperature. Distilled water, maintained in a thermostat, was used as the heat carrier (GOST 1987).

During the experiments, a noticeable significant temperature difference was created between the dispersed oil system and the cold pipe tube, allowing for clearer observation of the processes. The optimal working regime was established, with the duration of the experiment set at 1 hour, and the weight of the oil sample at 40 grams. The weight of the paraffin deposits was determined using the gravimetric method. The average of two parallel experiments was taken as the final result, with an experimental error of ±0.1 grams (ASTM, 1995).

For the "cold finger" method experiments, U-shaped metal tubes with a diameter of 36 mm and a total arm length of 130 mm were prepared, along with a pre-determined number of chemical beakers. U-shaped steel tubes (outer diameter: 15 mm) were used, with each vertical arm measuring 55 mm in length, resulting in a total height of 110 mm, including the curved section. The portion of the tube immersed in the oil (effective surface area) was approximately 70 mm (ASTM, 2009).

The U-shaped tubes were connected to a circulatory thermostat (cryostat), and the temperature was regulated by the cold agent circulating within it. The experiments were conducted both with and without external treatments (ultrasound exposure, addition of the Difron-3970 depressant). Upon completion of the process, the magnetic stirrers were turned off. The U-shaped tubes were then removed from the beakers and placed into a cooled acetone solution. The oil deposits on the surface of the tube were subsequently melted by heating. The mass of the paraffin deposits on the tube surface was weighted using an analytical balance. The relative experimental error using this method was ±1–3% (GOST, 1982a).

The freezing point of the oil was determined in accordance with the RD 39-3-812-82 methodology. Spherical-bottom test tubes with a diameter of 20 mm and a height of 160 mm were filled with a model oil, heated to a temperature of 55–60°C, and subjected to external influence, and then gradually cooled to 30–40°C (for comparison, one test tube was not subjected to any external influence). The test tubes were then placed in a thermostat to continue the cooling process. As the temperature decreased, every three degrees, the test tubes were held at a 45-degree angle. In these sequential tests, the temperature at which the oil level remained stationary in the test tubes was recorded. The test tube was held horizontally for five seconds, and the complete solidification of the liquid was determined based on the immobility of the upper layer of the liquid (RD 39-3-812-82).

Viscometric measurements were conducted using the Reotest-2 rotational viscometer. The investigation was carried out over a wide temperature range (5°C, 10°C, 15°C, 20°C, 30°C, 40°C, 50°C, 60°C) and within the shear rate range of 50 to 500 s^{-1} (GOST, 1982a). Based on the results of the experiments, curves of shear stress versus shear rate and effective viscosity versus shear rate were plotted (GOST, 1982a).

Results and discusion

The dependence of shear stress on shear rate of the oil sample was investigated under the influence of ultrasound waves, the Difron-3970 depressant additive (applied individually, and in combination) and various temperatures. The results obtained are illustrated in Figures 2–7.

Figure 2 shows the dependence of shear stress on shear rate at low temperatures following 15 minutes of ultrasound exposure, while Figure 3 presents the corresponding data at higher temperatures. As shown in Figure 2, after 15 minutes of exposure to ultrasound waves, the shear stress values within the shear rate range of 50–500 s^{-1} fall within the following intervals: at 5°C, shear stress ranges from 52 to 112 Pa; at 10°C, from 23 to 61 Pa; and at 15°C, from 11 to 31 Pa.

Figure 3 shows that, within the shear rate interval of 50–500 s^{-1}, following 15 minutes of exposure to ultrasound waves, the shear stress values range from 2 to 12 Pa at 20°C, from 0.9 to 4.8 Pa at 30°C, from 0.7 to 3.0 Pa at 40°C, from 0.6 to 2.5 Pa at 50°C and from 0.4 to 1.7 Pa at 60°C.

Figures 4 and 5 illustrate the shear stress dependence on shear rate for oil samples with a high freezing point treated with

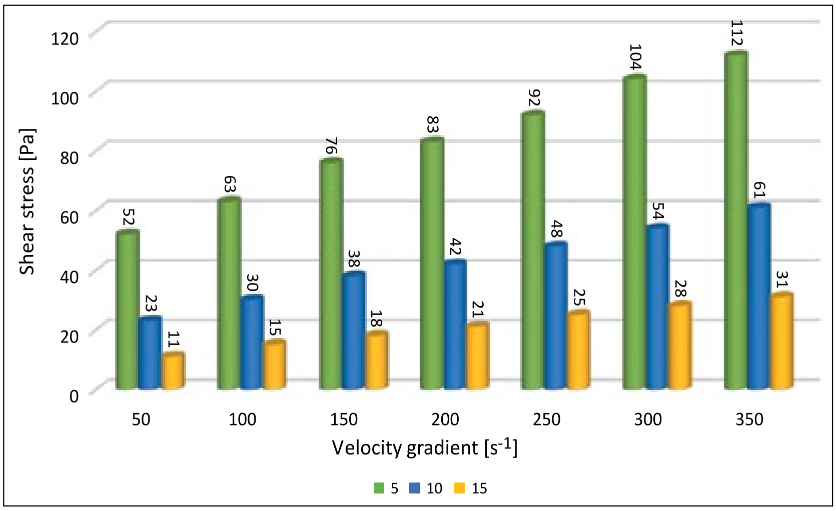

Figure 2. Dependence of the oil's shear stress on the velocity gradient after 15 minutes of ultrasound treatment at at low temperatures (5–15°C)

Rysunek 2. Zależność naprężenia ścinającego dla ropy naftowej od gradientu prędkości po 15 minutach ekspozycji na ultradźwięki w niskich temperaturach (5–15°C)

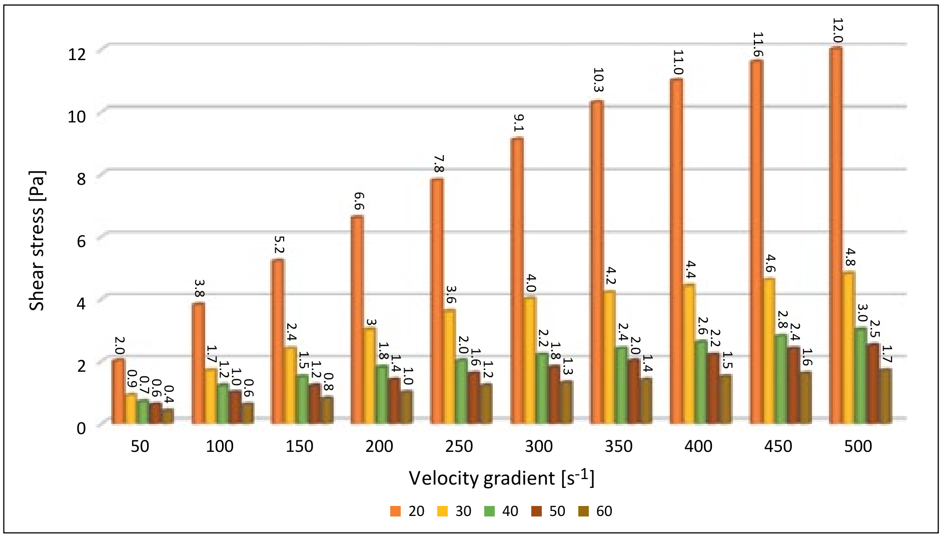

Figure 3. Dependence of the oil's shear stress on the velocity gradient after 15 minutes of ultrasound treatment at high temperatures (20–60°C)

Rysunek 3. Zależność naprężenia ścinającego ropy naftowej od gradientu prędkości po 15 minutach ekspozycji na ultradźwięki wysokich temperaturach (20–60°C)

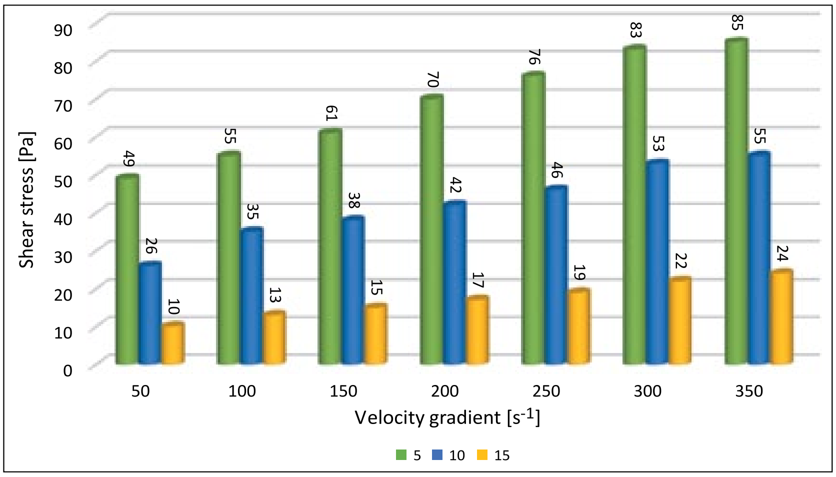

Figure 4. Dependence of the oil's shear stress on the velocity gradient after treatment with the optimal concentration of Difron-3970 depressant (700 g/t) at at low temperatures (5–15°C)

Rysunek 4. Zależność naprężenia ścinającego ropy naftowej od gradientu prędkości po zastosowaniu optymalnego stężenia środka Difron-3970 (700 g/t) w niskich temperaturach (5–15°C)

optimal concentration (700 g/t) of the Difron-3970 depressant additive, at low and high temperatures, respectively.

Figure 4 shows that within the velocity gradient range of 50–350 s^{-1}, the presence of the optimal concentration of the Difron-3970 depressant additive at 700 g/t results in shear stress values ranging from 49 to 85 Pa at 5°C, 26 to 55 Pa at 10°C, and 10 to 24 Pa at 15°C.

The results presented in Figure 5 demonstrate the influence of the Difron-3970 depressant additive on the shear stress of the oil sample at various temperatures, under optimal conditions with a concentration of 700 g/t. The results show that as the temperature increases, the shear stress decreases across the different temperature ranges. Specifically, at 20°C, the shear stress values ranged from 1.7 to 6.1 Pa at 30°C, from 0.7 to 2.5 Pa at 40°C, from 0.5 to 2.3 Pa at 50°C, from 0.3 to 1.3 Pa and at 60°C, from 0.2 to 1.1 Pa – all within the shear rate range of 50–500 s^{-1}. These observations align with the general expectation that temperature plays a key role in reducing the viscosity and shear stress of oil. As the temperature rises, the oil becomes less viscous, which in turn leads to reduced shear stress at the same shear rate. This is due to the increase in thermal energy, which allows the oil molecules to move more freely and experience less resistance to flow.

Furthermore, the data indicate that the Difron-3970 depressant additive effectively reduces shear stress across all tested temperatures, suggesting its potential to modify the rheological properties of the oil. This reduction in shear stress suggests that the additive plays a significant role in enhancing flowability and reducing friction within the oil – particularly beneficial in scenarios such as pipeline transportation or the pumping of crude oil under challenging conditions.

It is worth noting that while the depressant additive achieves significant reductions in shear stress, the effect of temperature on the oil's rheological properties appears to be even more pronounced. This indicates that temperature control is crucial for optimizing the performance of the depressant additive, as higher temperatures enhance its effectiveness in reducing shear stress. Therefore, a combined treatment strategy involving both temperature optimization and the use of depressant additives

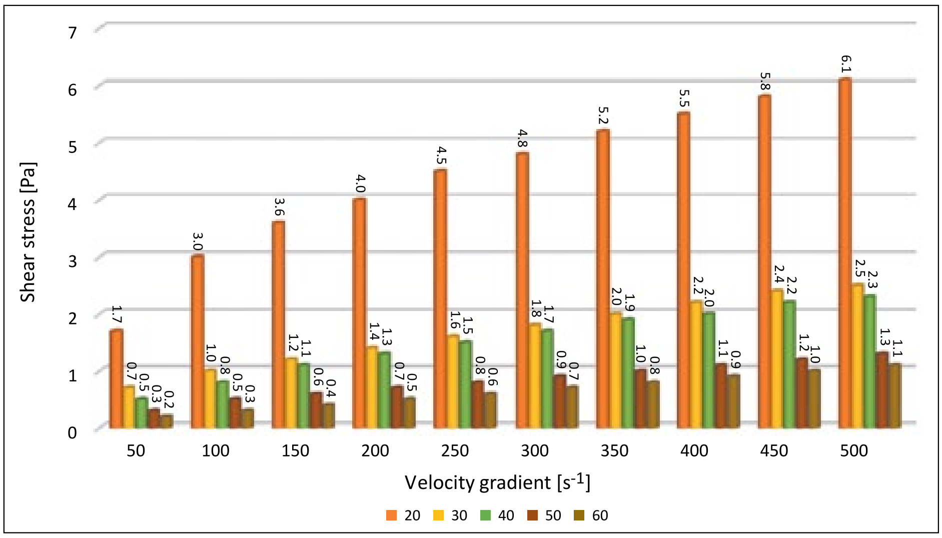

Figure 5. Dependence of the oil's shear stress on the velocity gradient after treatment with the optimal concentration of Difron-3970 depressant (700 g/t) at high temperatures (20–60°C)

Rysunek 5. Zależność naprężenia ścinającego ropy naftowej od gradientu prędkości po zastosowaniu optymalnego stężenia środka Difron-3970 (700 g/t) w wysokich temperaturach (20–60°C)

may be the most effective approach for improving the overall flow characteristics of crude oil. In summary, these findings demonstrate that both the concentration of the depressant additive and the temperature are critical parameters in determining the rheological behavior of oil. The results also highlight the potential benefits of using temperature regulation in combination with depressant additives to improve the transportation and handling of crude oil – particularly in cold environments where oil becomes highly viscous and difficult to move.

In Figure 6, the dependence of shear stress on the shear rate is presented for the oil sample analyzed at low temperatures of 5°C, 10°C, and 15°C. As the temperature decreases, the shear stress increases, which is expected due to the increased viscosity of the oil at lower temperatures. These results highlight the influence of temperature on the rheological behavior of the oil. Figure 6 shows that after the combined effect of the Difron-3970 depressant additive and ultrasound waves, within the shear rate range of 50–500 s^{-1}, the shear stress values for the oil sample are in the range of 42–82 Pa at 5°C, 16–43 Pa at 10°C, and 5–14 Pa at 15°C.

In Figure 7, the shear stress values for the oil sample at higher temperatures (20°C, 30°C, 40°C, 50°C, and 60°C) are shown when exposed to the combined effect of the Difron-3970 depressant additive and ultrasound waves. It is important to note that during the combined treatment, the concentration of the Difron-3970 additive was set at 500 g/t, and the ultrasound wave exposure time was 10 minutes. These treatments resulted in a noticeable reduction in shear stress, indicating improved flow properties of the oil, especially at higher temperatures. The combined treatment of ultrasound and the depressant additive significantly reduces the shear stress, which may be attributed to the synergistic effect of the two methods in breaking down the oil's molecular structure, reducing viscosity, and enhancing flow. The results presented in Figure 7 show that, within the shear rate range of 50–500 s^{-1}, the shear stress values for the oil sample, after the combined effect of the Difron-3970 depressant additive and ultrasound waves, range between

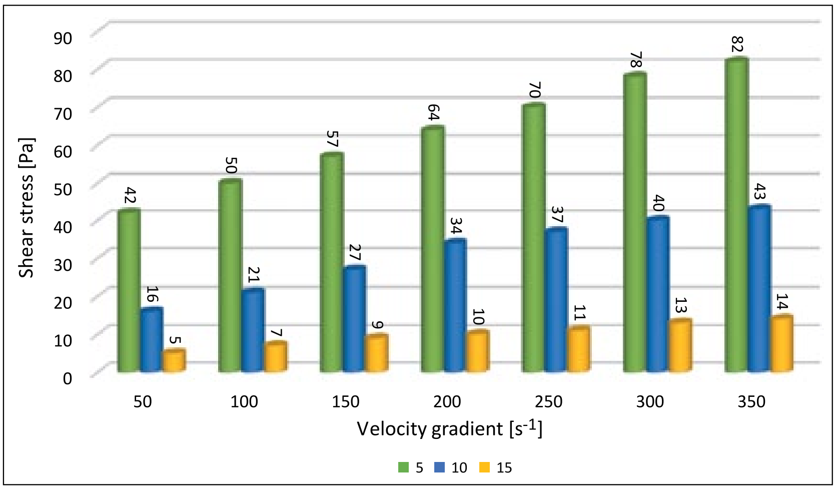

Figure 6. Dependence of the oil's shear stress on the velocity gradient after the combined effect of ultrasound and the Difron-3970 depressant at low temperatures (ultrasound exposition = 10 min, reagent concentration = 500 g/t)

Rysunek 6. Zależność naprężenia ścinającego ropy naftowej od gradientu prędkości po zastosowaniu zarówno ultradźwięków, jak i środka Difron-3970 w niskich temperaturach (czas ekspozycji na ultradźwięki = 10 min, stężenie reagentu = 500 g/t)

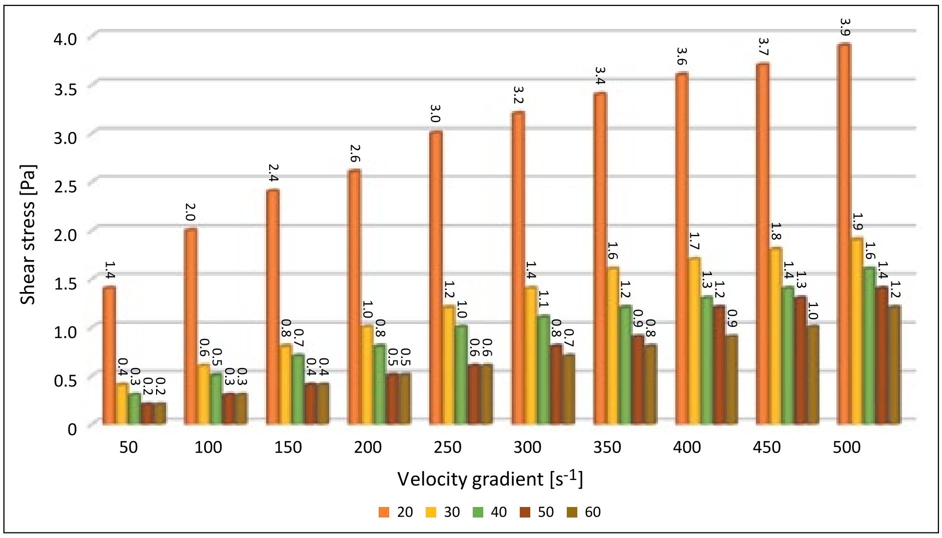

Figure 7. Dependence of the oil's shear stress on the velocity gradient after the combined effect of ultrasound and the Difron-3970 depressant at high temperatures (ultrasound duration = 10 min, reagent concentration = 500 g/t)

Rysunek 7. Zależność naprężenia ścinającego ropy naftowej od gradientu prędkości po zastosowaniu zarówno ultradźwięków, jak i środka Difron-3970 w wysokich temperaturach (czas ekspozycji na ultradźwięki = 10 min, stężenie reagentu = 500 g/t)

1.4–3.9 Pa at 20°C, 0.4–1.9 Pa at 30°C, 0.3–1.6 Pa at 40°C, 0.2–1.4 Pa at 50°C, and 0.2–1.2 Pa at 60°C.

Thus, based on the results of numerous experiments conducted under laboratory conditions, the dynamic viscosity of the analyzed oil sample was calculated for both low and high temperatures using the values of shear stress and shear rate obtained under the individual and combined treatments of ultrasound waves and the Difron-3970 depressant additive. The dependence of dynamic viscosity on shear rate is illustrated in Figures 8–16. The results presented in Figures 8 and 9 can be characterized as follows:

1. In the temperature of 5°C, 10°C, and 15°C, the dynamic viscosity of the oil sample decreases in the ranges of 1040–320 mPa·s, 460–174 mPa·s, and 220–88.6 mPa·s, respectively, after 15 minutes of ultrasound wave exposure, with an increase in the shear rate from 50 to 350 s^{-1}. These results indicate that the dynamic viscosity is reduced by approximately 3.25-fold at 5°C, 2.65-fold at 10°C, and 2.5-fold at 15°C, compared to the initial values at the lowest shear rate (50 s^{-1}).
2. In the temperature of 20°C, 30°C, 40°C, 50°C, and 60°C, the dynamic viscosity of the oil sample decreases in the ranges of 40–24 mPa·s, 18–9.6 mPa·s, 14–6.0 mPa·s, 12–5.0 mPa·s, and 8.0–2.4 mPa·s, respectively, after 15 minutes of ultrasound wave exposure, with an increase in the shear rate from 50 to 500 s^{-1}. This suggests that at these temperatures, the dynamic viscosity of the oil sample decreases by 1.7, 1.9, 2.3, 2.4, and 3.5 fold, respectively.

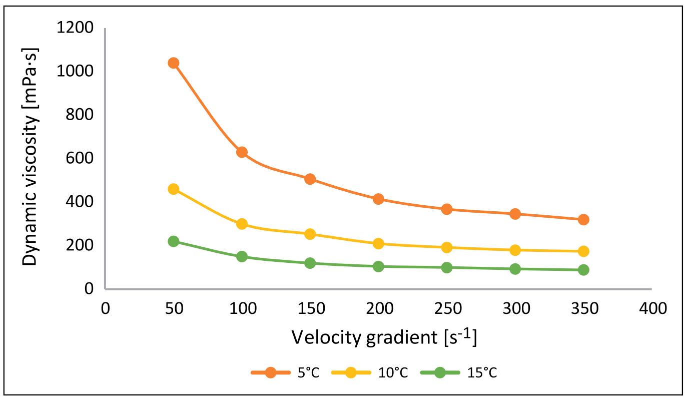

Figure 8. Dependence of oil viscosity on shear gradient after 15 minutes of ultrasound treatment at at low temperatures (5–15°C)

Rysunek 8. Zależność lepkości ropy naftowej od gradientu ścinania po 15 minutach działania ultradźwięków w niskich temperaturach (5–15°C)

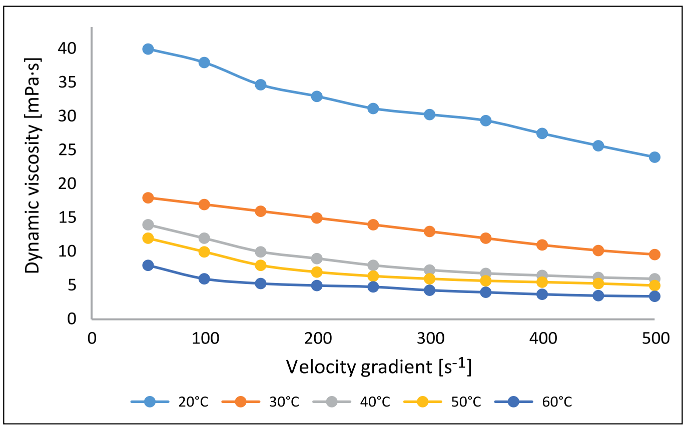

Figure 9. Dependence of oil viscosity on shear gradient after 15 minutes of ultrasound treatment at high temperatures (20–60°C)

Rysunek 9. Zależność lepkości ropy naftowej od gradientu ścinania po 15 minutach działania ultradźwięków w wysokich temperaturach (20–60°C)

The results presented in Figures 10 and 11 can be characterized as follows:

1. With an increase in the shear rate from 50 to 350 s^{-1} at temperatures of 5°C, 10°C, and 15°C, the dynamic viscosity of the oil sample decreases to 980–243 mPa·s, 520–157 mPa·s, and 200–68.6 mPa·s, respectively, under the influence of the optimal concentration of the Difron-3979 depressant additive. This indicates that at these temperatures, the dynamic viscosity of the oil sample decreased by approximately 4.0, 3.3, and 2.9 fold, respectively.
2. With an increase in the shear rate from 50 to 500 s^{-1} at temperatures of 20°C, 30°C, 40°C, 50°C, and 60°C, the dynamic viscosity of the oil sample decreases to 34–12.2 mPa·s, 14–5.0 mPa·s, 10–4.6 mPa·s, 6.0–2.5 mPa·s, and 4.0–2.1 mPa·s, respectively, under the influence of the optimal concentration of the Difron-3979 depressant additive. This suggests that at these temperatures, the dynamic viscosity of the oil sample decreased by approximately 2.8, 2.8, 2.2, 2.4, and 1.9 fold, respectively.

The results presented in Figures 12 and 13 can be characterized as follows:

1. With an increase in the shear rate from 50 to 350 s^{-1} at temperatures of 5°C, 10°C, and 15°C, the dynamic viscosity of the oil sample decreases to 840–234 mPa·s, 320–123 mPa·s, and 100–40 mPa·s, respectively, after the combined effect of the Difron-3979 depressant additive and ultrasound waves. This indicates that at these temperatures, the dynamic viscosity of the oil sample decreases by factors of 3.6, 2.6, and 2.5, respectively.

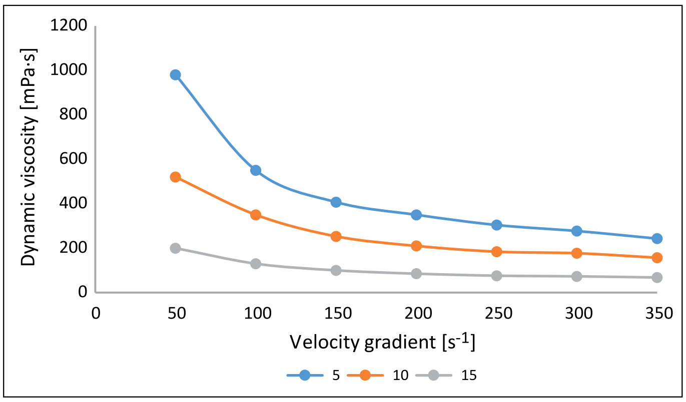

Figure 10. Dependence of oil viscosity on shear gradient after treatment with optimal concentration of Difron-3970 additive (700 g/t) at at low temperatures (5–15°C)

Rysunek 10. Zależność lepkości ropy naftowej od gradientu ścinania po zastosowaniu optymalnego stężenia dodatku Difron-3970 (700 g/t) w niskich temperaturach (5–15°C)

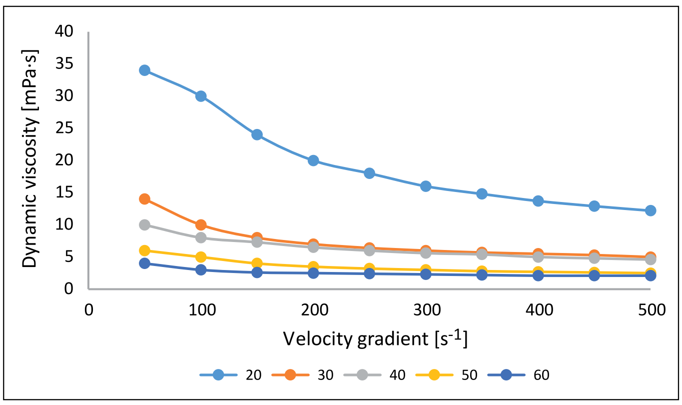

Figure 11. Dependence of oil viscosity on shear gradient after treatment with optimal concentration of Difron-3970 additive (700 g/t) at high temperatures (20–60°C)

Rysunek 11. Zależność lepkości ropy naftowej od gradientu ścinania po zastosowaniu optymalnego stężenia dodatku Difron-3970 (700 g/t) w wysokich temperaturach (20–60°C)

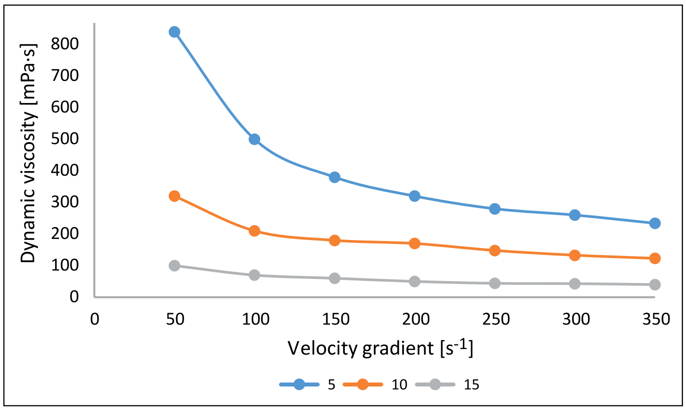

Figure 12. Dependence of oil viscosity on shear gradient after combined treatment with Difron-3970 additive and ultrasound at low temperatures (5–15°C, $C_{reagent}$ = 500 g/t, $t_{ultrasound}$ = 10 min)

Rysunek 12. Zależność lepkości ropy naftowej od gradientu ścinania po zastosowaniu zarówno dodatku „Difron-3970, jak i ultradźwięków w niskich temperaturach (5–15°C, $C_{odczynnik}$ = 500 g/t, $t_{ultradźwięk}$ = 10 minut)

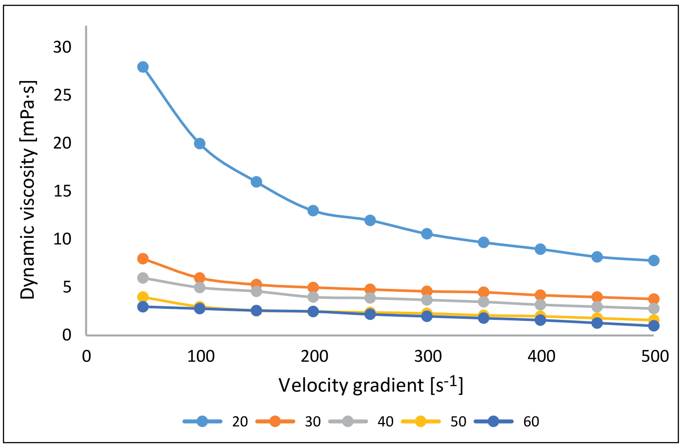

Figure 13. Dependence of oil viscosity on shear gradient after combined treatment with Difron-3970 additive and ultrasound at high temperatures (20–60°C, $C_{reagent}$ = 500 g/t, $t_{ultrasound}$ = 10 min)

Rysunek 13. Zależność lepkości ropy naftowej od gradientu ścinania po zastosowaniu zarówno dodatku Difron-3970, jak i ultradźwięków w wysokich temperaturach (20–60°C, $C_{odczynnik}$ = 500 g/t, $t_{ultradźwięk}$ = 10 minut)

2. With an increase in the shear rate from 50 to 500 s^{-1} at temperatures of 20°C, 30°C, 40°C, 50°C, and 60°C, the dynamic viscosity of the oil sample decreases to 28–7.8 mPa·s, 8.0–3.8 mPa·s, 6.0–2.8 mPa·s, 4.0–1.6 mPa·s, and 3.0–1.0 mPa·s, respectively, after the combined effect of the Difron-3979 depressant additive and ultrasound waves. This suggests that at these temperatures, the dynamic viscosity of the oil sample decreased by approximately 3.6, 2.1, 2.2, 2.5, and 3.0 fold, respectively.

Additionally, the effect of ultrasound waves and the Difron-3970 depressant additive, both individually and in combination, on paraffin deposition in the studied oil sample was investigated using the "cold finger" method. The process was conducted over 120 minutes at surface temperatures of 0°C, 5°C, 10°C, 15°C, 20°C, 25°C, and 30°C. For comparative analysis, the experiment was also performed on the untreated oil sample (Table 2).

As seen in Table 2, over time intervals of 0, 20, 40, 60, 80, 100, and 120 minutes, within the tube surface temperature range of 0°C to 30°C, the amount of paraffin deposition decreased by 1.68, 2.28, 2.88, 3.54, 3.90, 3.88, and 3.99 fold, respectively. However, in the temperature range of 0°C, 5°C, 10°C, 15°C, 20°C, 25°C, and 30°C over the 0–120 minute interval, the amount of paraffin deposition increased by 2.6, 2.2, 1.8, 1.85, 1.84, 1.09, and 1.08 fold, respectively.

Table 3 presents the results of the impact of ultrasound waves on paraffin deposition in the oil sample after 15 minutes of exposure using the "cold finger" method.

As seen in Table 3, following the application of ultrasound waves, at time intervals of 0, 20, 40, 60, 80, 100, and 120 minutes, the amount of paraffin deposition on the tube surface of the pipe, within the temperature range of 0°C to 30°C, decreases from 0.080 g to 0.046 g, 0.109 g to 0.047 g, 0.138 g to 0.048 g, 0.174 g to 0.049 g, 0.192 g to 0.050 g, 0.197 g to 0.052 g, and 0.202 g to 0.053 g, respectively. However, across the temperature range of 0°C, 5°C, 10°C, 15°C, 20°C, 25°C, and 30°C over the 0–120 minute interval, the amount of paraffin deposition varies between 0.080 g to 0.202 g, 0.073 g to 0.159 g, 0.069 g to 0.125 g, 0.066 g to 0.122 g, 0.062 g to 0.112 g, 0.061 g to 0.069 g, and 0.046 g to 0.053 g, respectively.

Table 4 presents the results of the effect of the optimal concentration of the Difron-3970 depressant additive on paraffin deposition in the oil sample using the "cold finger" method.

As shown in Table 4, following the application of the optimal concentration of the Difron-3970 depressant additive, the amount of paraffin deposition on the tube surface at time intervals of 0, 20, 40, 60, 80, 100, and 120 minutes and within a temperature range of 0°C to 30°C, decreases from 0.024 g to 0.012 g, 0.033 g to 0.012 g, 0.040 g to 0.013 g, 0.053 g to 0.014 g, 0.058 g to 0.014 g, 0.059 g to 0.015 g, and 0.061 g to 0.015 g, respectively. However, across the temperature range of 0°C, 5°C, 10°C, 15°C, 20°C, 25°C, and 30°C over the 0–120 minute interval, the amount of paraffin deposition varies between 0.024 g to 0.061 g, 0.022 g to 0.047 g, 0.020 g to 0.038 g, 0.019 g to 0.037 g, 0.018 g to 0.034 g, 0.017 g to 0.021 g, and 0.012 g to 0.015 g, respectively.

Table 5 presents the results of the effect of the Difron-3970 depressant additive, in combined with ultrasound waves, on paraffin deposition in the oil sample using the "cold finger"method.

As indicated in Table 5, following the combined application of ultrasound waves and the Difron-3970 depressant additive, the amount of paraffin deposition on the tube surface decreases over time intervals of 0, 20, 40, 60, 80, 100, and 120 minutes within a temperature range of 0°C to 30°C, specifically from 0.007 g to 0.0037 g, 0.009 g to 0.0038 g, 0.011 g to 0.0039 g, 0.013 g to 0.0040 g, 0.015 g to 0.0040 g, 0.016 g to 0.0041 g, and 0.017 g to 0.0042 g, respectively. However, across the temperature range of 0°C, 5°C, 10°C, 15°C, 20°C, 25°C, and 30°C over the 0–120 minute interval, the amount of paraffin deposition varies between 0.007 g to 0.017 g, 0.006 g to 0.014 g, 0.005 g to 0.011 g, 0.005 g to 0.011 g, 0.004 g to 0.010 g, 0.004 g to 0.009 g, and 0.0037 g to 0.0042 g, respectively.

Table 2. The mass of paraffin deposits accumulated on the surface of the "cold finger" from the investigated oil sample (without external influence)

Tabela 2. Masa osadów parafinowych wytąconych na powierzchni chłodzonej rurki z badanej próbki ropy (bez udziału czynników zewnętrznych)

Time [min]	The amount [g] of paraffin deposits accumulated at temperature of the "cold finger"						
	0°C	5°C	10°C	15°C	20°C	25°C	30°C
0	0.158	0.144	0.136	0.131	0.123	0.121	0.094
20	0.217	0.197	0.159	0.154	0.148	0.122	0.095
40	0.277	0.226	0.194	0.189	0.177	0.123	0.096
60	0.347	0.238	0.217	0.213	0.192	0.125	0.098
80	0.387	0.247	0.226	0.221	0.213	0.127	0.099
100	0.392	0.307	0.247	0.242	0.214	0.129	0.101
120	0.407	0.317	0.248	0.243	0.227	0.132	0.102

Table 3. The mass of paraffin deposits accumulated on the surface of the "cold finger" after ultrasound treatment ($t_{ultrasound}$ = 15 min)

Tabela 3. Masa osadów parafinowych wytrąconych na powierzchni chłodzonej rurki po zastosowaniu ultradźwięków ($t_{ultradźwięki}$ = 15 min)

Time [min]	The amount [g] of paraffin deposits accumulated at temperature of the "cold finger"						
	0°C	5°C	10°C	15°C	20°C	25°C	30°C
0	0.080	0.073	0.069	0.066	0.062	0.061	0.046
20	0.109	0.099	0.080	0.078	0.074	0.062	0.047
40	0.138	0.115	0.096	0.094	0.089	0.064	0.048
60	0.174	0.119	0.109	0.107	0.096	0.065	0.049
80	0.192	0.123	0.115	0.111	0.106	0.066	0.050
100	0.197	0.153	0.123	0.121	0.107	0.068	0.052
120	0.202	0.159	0.125	0.122	0.112	0.069	0.053

Table 4. The mass of paraffin deposits accumulated on the surface of the "cold finger" after the application of the optimal concentration of Difron-3970 additive ($C_{reagent}$ = 700 g/t)

Tabela 4. Masa osadów parafinowych wytrąconych na powierzchni chłodzonej rurki po zastosowaniu dodatku Difron-3970 w optymalnym stężeniu ($C_{odczynnik}$ = 700 g/t)

Time [min]	The amount [g] of paraffin deposits accumulated at temperature of the "cold finger"						
	0°C	5°C	10°C	15°C	20°C	25°C	30°C
0	0.024	0.022	0.020	0.019	0.018	0.017	0.012
20	0.033	0.029	0.024	0.022	0.021	0.016	0.012
40	0.040	0.034	0.030	0.028	0.026	0.017	0.013
60	0.053	0.036	0.032	0.031	0.029	0.018	0.014
80	0.058	0.037	0.034	0.033	0.031	0.019	0.014
100	0.059	0.046	0.037	0.036	0.032	0.020	0.015
120	0.061	0.047	0.038	0.037	0.034	0.021	0.015

Table 5. The mass of paraffin deposits accumulated on the surface of the "cold finger" after the combined effect of Difron-3970 additive and ultrasound waves ($C_{reagent}$ = 500 g/t, $t_{ultrasound}$ = 10 min)

Tabela 5. Masa osadów parafinowych wytrąconych na powierzchni chłodzonej rurki po zastosowaniu dodatku Difron-3970 wraz z ultradźwiękami ($C_{odczynnik}$ = 500 g/t, $t_{ultradźwięk}$ = 10 min)

Time [min]	The amount [g] of paraffin deposits accumulated at temperature of the "cold finger"						
	0°C	5°C	10°C	15°C	20°C	25°C	30°C
0	0.007	0.006	0.005	0.005	0.004	0.004	0.0037
20	0.009	0.008	0.006	0.006	0.005	0.005	0.0038
40	0.011	0.009	0.008	0.007	0.007	0.005	0.0039
60	0.013	0.010	0.009	0.008	0.007	0.006	0.0040
80	0.015	0.011	0.010	0.009	0.008	0.007	0.0040
100	0.016	0.013	0.011	0.010	0.009	0.008	0.0041
120	0.017	0.014	0.012	0.011	0.010	0.009	0.0042

Based on numerous experiments conducted under laboratory conditions using the "cold finger" method, the effectiveness of ultrasound waves and the Difron-3970 depressant additive, both individually and in combination, against paraffin deposition has been calculated using the following equation (1) (Gurbanov et al., 2025):

$$K = \frac{m_1 - m_2}{m_1} \cdot 100\% \quad (1)$$

where:

K – effectiveness of the method,
m_1 – mass of paraffin deposits in an unaffected medium [g],
m_2 – mass of paraffin deposits in a treated medium [g].

Figure 14 presents the effectiveness of ultrasound waves against paraffin deposition after 10, and 15 minutes of application.

As illustrated in Figure 14, the effectiveness of ultrasound waves against paraffin deposition in the oil sample increases with the duration of exposure. Specifically, the effectiveness after 5 minutes of ultrasound exposure is 36%, after 10 minutes it is 42%, and after 15 minutes it reaches 55%. It can therefore be concluded that the effectiveness of ultrasound wave is relatively limited.

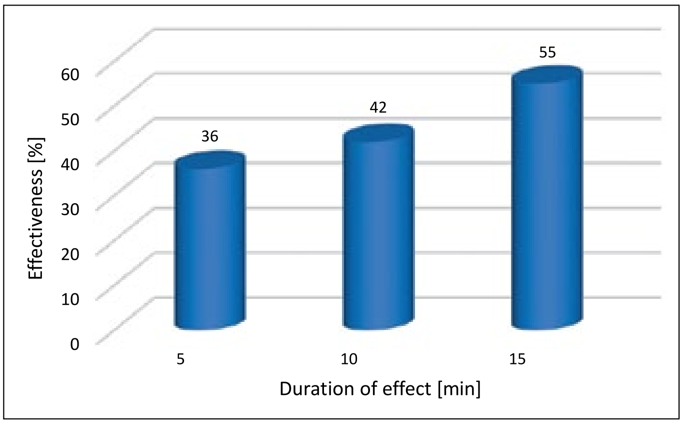

Figure 14. Effectiveness of ultrasound waves against paraffin deposits

Rysunek 14. Skuteczność fal ultradźwiękowych w usuwaniu osadów parafinowych

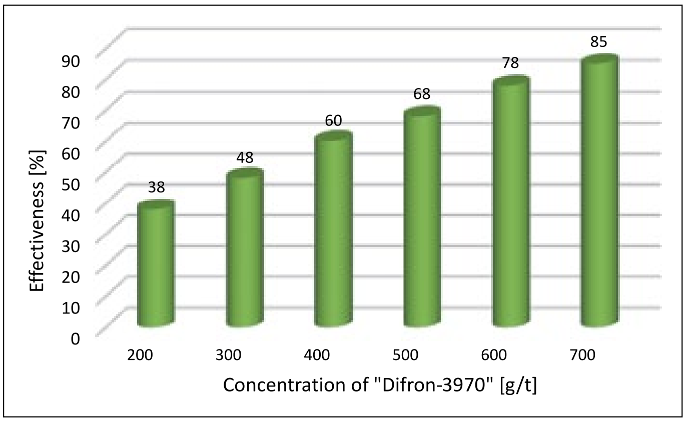

Figure 15. Effectiveness of the Difron-3970 depressant additive against paraffin deposits

Rysunek 15. Skuteczność dodatku Difron-3970 w usuwaniu osadów parafinowych

Figure 15 presents the effectiveness of various concentrations of the Difron-3970 depressant additive against paraffin deposition.

The results presented in Figure 15 indicate that the addition of varying concentrations of the depressant additive to the oil sample reduces the precipitation of paraffin crystals. Compared to an untreated medium, the application of the depressant additive concentrations of 200, 300, 400, 500, 600, and 700 g/t reduces paraffin precipitation by 38%, 48%, 60%, 68%, 78%, and 85%, respectively. The most significant reduction is observed at a concentration of 700 g/t, which is identified as optimal concentration of the Difron-3970 depressant additive.

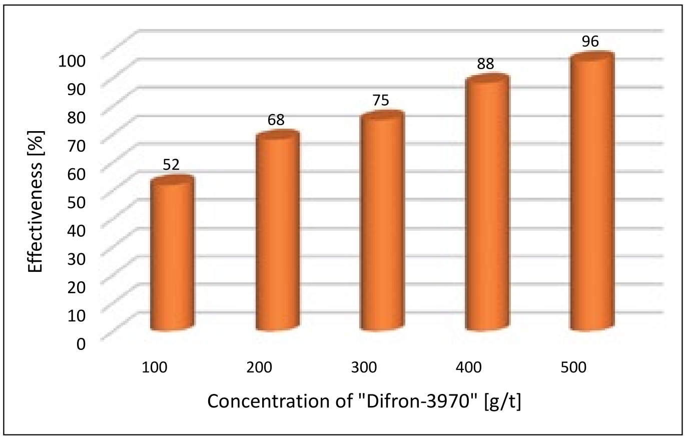

Figure 16. Effectiveness of the combined action of Difron-3970 additive and ultrasound waves agains paraffin deposits ($C_{reagent}$ = = 500 g/t, $t_{ultrasound}$ = const = 10 minute)

Rysunek 16. Skuteczność połączonego działania dodatku Difron-3970 oraz fal ultradźwiękowych w usuwaniu osadów parafinowych ($C_{odczynnik}$ = 500 g/t, $t_{ultradźwięk}$ = const = 10 minut)

Figure 16 illustrates the combined effectiveness of the Difron-3970 depressant additive and ultrasound waves against paraffin deposition. As shown in Figure 16, the combined approach was more effective compared to the use of ultrasound waves or the Difron-3970 depressant additive alone. Specifically, during the combined treatment, the effectiveness of the depressant additive at concentrations of 100, 200, 300, 400, and 500 g/t (with ultrasound maintained at a constant duration of 10 minutes) was 52%, 68%, 75%, 88%, and 96%, respectively.

It is also noteworthy that the impact of ultrasound waves and the Difron-3970 depressant additive both individually and in combination on the freezing temperature of the oil sample has been investigated in accordance with the established methodology. The experimental results are presented in Figures 17–19.

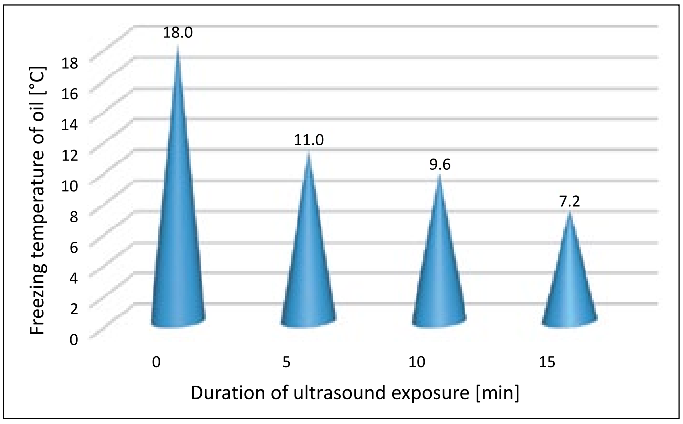

Figure 17. The effect of ultrasound wave duration on the freezing point of oil

Rysunek 17. Wpływ czasu ekspozycji na fale ultradźwiękowe na punkt krzepnięcia ropy

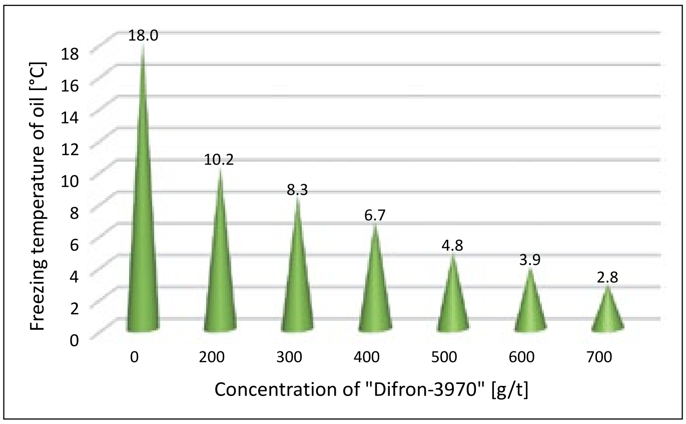

Figure 18. Effect of the Difron-3970 additive concentration on the freezing point of oil

Rysunek 18. Wpływ stężenia dodatku Difron-3970 na punkt krzepnięcia ropy

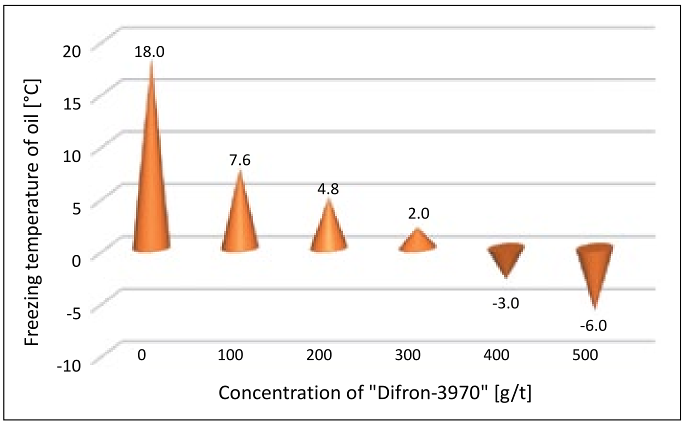

Figure 19. The combined effect of Difron-3970 and ultrasound (10 min) on the freezing point of oil

Rysunek 19. Łączny wpływ Difron-3970 i ultradźwięków na punkt krzepnięcia ropy

As illustrated in Figure 17, the freezing temperature of the oil sample decreases from +18°C to +11°C, +9.6°C, and +7.2°C following exposure to ultrasound waves for durations of 5, 10, and 15 minutes, respectively. This corresponds to reductions in the freezing temperature by 39%, 47%, and 60% for the respective exposure durations.

As shown in Figure 18, the addition of the Difron-3970 depressor at concentrations of 200, 300, 400, 500, 600, and 700 g/t results in a decrease in the freezing temperature of the oil sample from +18°C to +10.2°C, +8.3°C, +6.7°C, +4.8°C, +3.9°C, and +2.8°C, respectively. This corresponds to reductions in freezing temperature by 43%, 54%, 63%, 73%, 78%, and 85% at the specified concentrations.

As illustrated in Figure 19, laboratory results show that with combined application of the depressant at concentrations of 100, 200, 300, 400, and 500 g/t (with ultrasound exposure maintained constant at 10 minutes), the freezing temperature of the oil decreases from +18°C to +7.6°C, +4.8°C, +2.0°C, –3.0°C, and –6.0°C, respectively. These changes correspond to reductions in the freezing temperature of 10.4, 13.2, 16, 21, and 24°C, respectively.

Thus, the combined treatment on the rheological parameters of high-paraffin oil samples is more effective than applying either method individually.

Conclusions

1. The dynamic viscosity, freezing temperature, and paraffin deposition of a crude oil sample characterized by a high percentage of its main components and a high freezing temperature were investigated under the individual and combined treatments of ultrasound waves and the Difron-3970 depressant additive. The optimal exposure time for ultrasound waves and the optimal concentration of the depressant additive were determined for both separate and combined approaches. It was found that the optimal ultrasound exposure time was 15 minutes for the individual treatment and 10 minutes for the combined one, while the optimal concentrations of the depressant additive were 700 g/t and 500 g/t, respectively.
2. The separate and combined effects of ultrasound waves and the Difron-3970 depressant additive on the dynamic viscosity of the crude oil sample were studied at low (5°C, 10°C, 15°C) and high temperatures (20°C, 30°C, 40°C, 50°C, 60°C). The greatest reduction in the dynamic viscosity of the oil sample occurred during the combined treatment.
3. The effectiveness of ultrasound waves against paraffin deposition was shown to be 36% after 5 minutes, 42% after 10 minutes, and 55% after 15 minutes. The effectiveness of the Difron-3970 depressant additive at concentrations of 200 g/t, 300 g/t, 400 g/t, 500 g/t, 600 g/t, and 700 g/t was 38%, 48%, 60%, 68%, 78%, and 85%, respectively. For the combined application, the effectiveness of the depressant additive at concentrations of 100 g/t, 200 g/t, 300 g/t, 400 g/t, and 500 g/t (with ultrasound maintained constant for 10 minutes) was 52%, 68%, 75%, 88%, and 96%, respectively.
4. It was determined that the freezing temperature of the oil sample decreased from +18°C to +11°C, +9.6°C, and +7.2°C after exposure to ultrasound for 5, 10, and 15 minutes, respectively. After the addition of the "Difron-3970" depressant additive at concentrations of 200 g/t, 300 g/t, 400 g/t, 500 g/t, 600 g/t, and 700 g/t, the freezing temperature decreased from +18°C to +10.2°C, +8.3°C, +6.7°C, +4.8°C, +3.9°C, and +2.8°C, respectively. During the combined application with the depressant additive at concentrations of 100 g/t, 200 g/t, 300 g/t, 400 g/t, and 500 g/t (with ultrasound maintained constant for 10 minutes), the freezing temperature

decreased to +7.6°C, +4.8°C, +2.0°C, –3.0°C, and –6.0°C, respectively.

5. The analysis of the results from numerous experiments has shown that the effect of combination of ultrasound waves and the depressant additive is more effective compared than the individual methods. Therefore, the broad application of this combined physical-chemical approach under mining conditions in the oil industry is recommended.

References

Gurbanov A.N., Sardarova I.Z. 2022. Optimization Problem of Measurements In Experimental Research of Gas-Lift Wells. *Applied and Computational Mathematics*, 2: 223–228.

Gurbanov A.N., Sardarova I.Z., Damirova J.R., 2021. Analysis of gas preparation processes for improvement of gas transportation technology. *EUREKA: Physics and Engineering*, 6. DOI: 10.21303/2461-2021.002081.

Gurbanov G.R., Gasimzade A.V., 2022. Research of the impact of new compositions on the decomposition of stable water-oil emulsions of heavy oils. *Voprosy Khimii i Khimicheskoi Tekhnologii*, 6: 19–28.

Gurbanov G.R., Gasimzade A.V., Abbasova L.A., 2024a. Investigation of the effect of the combined methods on the rheological properties of high-paraffin oils. *Nafta-Gaz*, 80(7): 427–433. DOI: 10.18668/NG.2024.07.04.

Gurbanov G.R., Gasimzade A.V., Alikishiyeva-Balamiyeva S.F., 2025. Research of bactericide-inhibitor properties of new compositions based on gossypol resin and chloroprene. *Nafta-Gaz*, 81(1): 58–66. DOI: 10.18668/NG.2025.01.05.

Gurbanov G.R., Nurullayev V.Kh., Gasimzade A.V., 2024b. The effect of formation temperature and constituent components on rheological parameters of water-oil emulsions. *Nafta-Gaz*, 80(5): 301–311. DOI: 10.18668/NG.2024.05.06.

Iskandarov E.Kh., Baghirov A.N., Shikhiyeva L.M., 2024. Method for assessing the hydrate formation from a mixture of natural gas flows of varying degrees of moisture content. *Nafta-Gaz*, 80(1): 39–44. DOI: 10.18668/NG.2024.01.05.

Loskutova Y.V., Yudina N.V., 2006. Rheological behaviour of oils in magnetic field. *Engineering Physical Journal*, 1: 102–110.

Samadov A.M., Agazadeh A.D., Alsafarova M.E., 2017. Study of inhibitory properties of new reagents of NDP type with respect to depressor and paraffin sludge. *Azerbaijan Oil Industry Journal*, 6: 43–47.

Legislative acts and normative documents

ASTM D5853-95, 1995. Standard Test Method for Pour Point of Crude Oils.

ASTM D97-09, 2009. Standard Test Method for Pour Point of Petroleum Products.

GOST 20287-74, 1987. Petroleum products Methods of determination of pour point.

GOST 25276-82, 1982b. Method for determination of viscosity by rotary viscometer at a certain shear rate.

GOST 33768-2015, 1982a. Method of determination of kinematic viscosity and calculation of dynamic viscosity.

RD 39-3-812-82, 1982. Methodology for determination of solidification temperature of paraffinic oils. Rheological properties.

Prof. Guseyn Ramazan GURBANOV, Ph.D.
Head of the Department of Oil and Gas Transportation and Storage
Azerbaijan State Oil and Industry University
16/21 Azadliq Ave., AZ1010 Baku, Azerbaijan
E-mail: *huseyn.gurbanov@asoiu.edu.az*

Aysel Valiyaddin GASIMZADE, Ph.D.
Associate Professor at the Department of Oil and Gas Transportation and Storage
Azerbaijan State Oil and İndustry University
31 Khagani Street, AZ1010 Baku, Azerbaijan
E-mail: *qasimzade92@inbox.ru*

Leili Adil ABBASOVA, M.Sc.
Doctoral student; lecturer at the Department of Oil and Gas Transportation and Storage
Azerbaijan State Oil and Industry University
31 Khagani Street, AZ1010 Baku, Azerbaijan
E-mail: *leyli.abbasova.work@gmail.com*