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Research on the impact of Difron-3970 additive and ultrasound waves on the rheological parameters of high-paraffin resin oil

Badanie wpływu dodatku Difron-3970 oraz fal ultradźwiękowych na parametry reologiczne wysokoparafinowej ropy żywicznej

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ABSTRACT: The article presents the research results of the effects of the Difron-3970 depressant additive and ultrasonic waves, both separately and in combination, on the dynamic viscosity and freezing point of high paraffinic, resinous crude and refined oil samples taken from the Bulla-Deniz field of State Oil Company of Azerbaijan Republic (SOCAR). Laboratory experiments were conducted to evaluate the impact of physical and chemical treatments on the dynamic viscosity of the Bulla-Deniz crude oil and refined oil samples at temperatures of 5°C, 10°C, and 20°C. The Difron-3970 depressant additive was used as the chemical treatment, while ultrasonic waves were applied as the physical treatment. The effects of varying concentration of the Difron-3970 depressant additive (250, 350, 450, 650, and 750 g/t) as well as different durations of ultrasonic wave exposure (5, 10, and 15 minutes) on the dynamic viscosity and freezing point of the oil were studied. The optimal concentration of the Difron-3970 depressant additive was found to be 750 g/t when applied separately, and 500 g/t when used in combination with ultrasonic waves. The optimal duration for the ultrasonic treatment, when applied separately, was found to be 15 minutes, while for the combined treatment had an optimal duration of 10 minutes. Thus, the results from numerous laboratory tests showed that the most significant reduction in the dynamic viscosity and freezing point of the high paraffinic, resinous oil from the Bulla-Deniz field occurred during the combined physical-chemical treatment. Therefore, based on the ecological and economic efficiency of the combined application of the Difron-3970 depressant additive with ultrasonic waves, it is proposed that this method be widely implemented under field conditions in the oil industry.

Key words: depressant additive, ultrasonic waves, physical-chemical method, dynamic viscosity, shear rate, freezing point, high paraffinic oil.

STRESZCZENIE: Artykuł przedstawia wyniki badań nad wpływem depresatora Difron-3970 oraz fal ultradźwiękowych – stosowanych zarówno oddzielnie, jak i w połączeniu – na lepkość dynamiczną oraz temperaturę krzepnięcia wysokoparafinowych, żywicznych próbek surowej i rafinowanej ropy naftowej, pochodzących z pola naftowego Bulla-Deniz, należącego do Państwowego Przedsiębiorstwa Naftowego Republiki Azerbejdżanu (SOCAR). Eksperymenty przeprowadzono w celu oceny wpływu zabiegów fizycznych i chemicznych na lepkość dynamiczną próbek surowej i rafinowanej ropy naftowej z pola Bulla-Deniz w temperaturach 5°C, 10°C i 20°C. Zabieg chemiczny opierał się na zastosowaniu depresatora Difron-3970, natomiast fizyczny – na użyciu fal ultradźwiękowych. Zbadano wpływ różnych stężeń dodatku Difron-3970 (250, 350, 450, 650 oraz 750 g/t) a także czasu działania fal ultradźwiękowych (5, 10 i 15 minut) na lepkość dynamiczną oraz temperaturę krzepnięcia ropy. Optymalną dawkę dodatku Difron-3970, przy stosowaniu go samodzielnie, ustalono na poziomie 750 g/t, natomiast w połączeniu z falami ultradźwiękowymi – na poziomie 500 g/t. Optymalny czas oddziaływania fal ultradźwiękowych, przy ich samodzielnym zastosowaniu, wynosił 15 minut, natomiast w przypadku zabiegu łączonego – 10 minut. Wyniki licznych testów laboratoryjnych wykazały, że najistotniejsze obniżenie lepkości dynamicznej oraz temperatury krzepnięcia wysokoparafinowej, żywicznej ropy z pola Bulla-Deniz miało miejsce w przypadku połączonego zastosowania zabiegów fizycznego i chemicznego. W związku z tym, biorąc pod uwagę efektywność ekologiczną i ekonomiczną łącznego stosowania dodatku Difron-3970 i fal ultradźwiękowych, proponuje się szerokie wdrożenie tej metody w warunkach polowych w przemyśle naftowym.

Słowa kluczowe: depresator, fale ultradźwiękowe, zabiegi fizykochemiczne, lepkość dynamiczna, szybkość ścinania, temperatura krzepnięcia, ropa wysokoparafinowa.

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Introduction

It is well known that one of the characteristics of high paraffinic oils is their relatively high freezing temperatures. The freezing point mainly depends on the content of paraffins and light fractions in the oil. As the amount of paraffins increases, the freezing point of the oil also rises, whereas an increase in the amount of light fractions lowers the freezing point. Additionally, an increase in resin components also lowers the freezing point of the oil (Loskutov and Yudina, 2006). The non-Newtonian properties of high paraffinic oils are linked to the formation of a crystalline structure in paraffin hydrocarbons. At very high temperatures, paraffins exist in a molecularly dispersed state in liquid hydrocarbon mixtures. As the oil cools and the temperature approaches the crystallization point of normal-structured paraffins, initial crystallization centers form, where crystals grow. Further temperature decreases lead to the formation of a spatial lattice, causing high paraffinic oil to lose its flow properties and freeze (Huang et al., 2018; Olajire, 2021; Gurbanov et al., 2021).

In general, it should be noted that the transportation of high paraffinic oils via pipelines using conventional methods is inefficient. The hydraulic resistance changes depending on the ambient temperature. The improvement of flow properties, reduction of viscosity, and increase in pipeline throughput capacity of high paraffinic oils remain a focus of oil scientists in countries with developed oil industries (Gurbanov and Gasimzade, 2022). Numerous studies have been conducted in this direction, and various methods have been developed. Currently, the most widely used method in practice is the combined physical-chemical method for high paraffinic oils (Gurbanov and Sardarova, 2022).

As a chemical method, depressant additives are often used. Depressant additives are chemical agents that reduce the viscosity, static and dynamic shear stress, and, most importantly, the freezing point of high paraffinic oils. Their action allows the oil to maintain its fluidity at lower temperatures. The chemical composition of depressant additives is kept secret by manufacturing companies and is marketed under various brand names (Gurbanov et al., 2024a). However, despite this, the structure of all depressant additives is similar. A part of the chain is structurally similar to paraffin molecules, while the other part resembles the hydrocarbon backbone of crude oil. This allows depressant additives to block the growth process of the paraffin crystalline lattice, thereby regulating the rheological parameters of high paraffinic oil and producing a positive effect. The main advantages of depressant additives are the simplicity of their application, their compatibility with other additives used in systems for the extraction, transportation, and storage of high-viscosity oils, and the high economic efficiency they provide. These substances do not dissolve the paraffin crystals in the oil or reduce their amount, but change the size, shape, and structure of the dispersed phase particles in the oil system, creating an energetic barrier on the surface of the paraffin crystals that prevents their sedimentation. Furthermore, the effectiveness of depressant additives depends on the physical and chemical characteristics of crude oils and their rheological parameters (such as: viscosity, yield stress, and flow behavior), as well as the content of paraffin, resin, asphaltene, water, mineral salts, and other mechanical impurities (Kané et al., 2003; Kirbizhekova et al., 2016; Chi et al., 2017; Li et al., 2018; Martínez-Palou et al., 2021).

Improving the flow properties of highly paraffinic oils presents significant challenges and typically necessitates a case-by-case approach; therefore, a variety of treatment methods are employed to address this issue effectively. In addition to the use of various depressant reagents, physical methods, such as the application of magnetic fields and ultrasonic waves, are also utilized (Iskandarov et al., 2024; Kané et al., 2024).

In recent years, the interest of oil engineers in the combined method, specifically the joint application of physical and chemical methods, to intensify the extraction and transportation of high paraffinic oils via pipelines has increased. The advantages of this method include low energy consumption, high efficiency, and both technical and ecological safety. The combined physical-chemical method allows the improvement of the flow properties of high paraffinic oil at temperatures below the freezing point, reduces hydraulic losses, decreases the amount of APRC (asphaltene, paraffin, and resin compounds) on the internal surfaces of pipelines and equipment, and simplifies operating conditions. For these reasons, the combined physical-chemical method is currently considered one of the most effective and promising methods for the pipeline transportation of high paraffinic oils (Gurbanov et al., 2024b).

The purpose of this research is to study the effects of the Difron-3970 depressant additive and ultrasonic waves, both separately and in combination, on the rheological parameters of the high paraffinic, resinous oil from the Bulla-Deniz field.

Materials and methods

To test the separate and combined effects of the Difron-3970 depressant additive and ultrasonic waves on the rheological parameters of the oil dispersive system under laboratory conditions, crude and refined forms of the oil sample from the Bulla-Deniz field of SOCAR were used. First, the physical and chemical characteristics of the Bulla-Deniz oil sample, in both its crude and refined forms, were studied using known methods, and the obtained results are presented in Table 1

Table 1. Physical and chemical characteristics of the Bulla-Deniz Oil Samples
Tabela 1. Fizykochemiczne właściwości próbek ropy naftowej z pola Bulla-Deniz

Parameters	Bulla-Deniz	Methodology
Crude oil sample		
Density 20°C [kg/m³]	973.8	ASTM D1217-15 Pycnometer method or ISO 3838
Dynamic viscosity 20°C [P]	244.58	ASTM D445 Capillary viscometer
Water quantity [mass %]	35	ASTM D4006 Distillation or ASTM D4377 – Centrifugation
Amount of chloride salts [mg/l]	493.8	ASTM D6470 Potentiometric titration method
Amount of mechanical mixtures [mass %]	4.53	GOST 6370 or ASTM D4807 Filtration and gravimetric determination
Amount of resins [mass %]	8.9	IP 143 or GOST 11858 Precipitation with n-heptane
Amount of asphaltenes [mass %]	0.16	ASTM D6560 n-heptane precipitation
Amount of paraffins [mass %]	12.2	UOP 46 or GOST 11851 Solvent precipitation method
Freezing temperature [°C]	12	GOST 20287 or ASTM D2386 Cooling method
Refined oil sample		
Density 20°C [kg/m³]	842.1	ASTM D1217-15 Pycnometer method or ISO 3838
Water quantity [mass %]	0.3	ASTM D4006 Distillation or ASTM D4377 – Centrifugation
Amount of chloride salts [mg/l]	138.6	ASTM D6470 Potentiometric titration method
Amount of mechanical mixtures [mass %]	0.007	GOST 6370 or ASTM D4807 Filtration and gravimetric determination
Amount of resins [mass %]	9.6	IP 143 or GOST 11858 Precipitation with n-heptane
Amount of asphaltenes [mass %]	0.22	ASTM D6560 n-heptane precipitation
Amount of paraffins [mass %]	13.1	UOP 46 or GOST 11851 Solvent precipitation method
Freezing temperature [°C]	12	GOST 20287 or ASTM D2386 Cooling method

(ASTM, 1995, ASTM, 2009, GOST, 1987, GOST, 1982a, GOST, 1982b, RD, 1982).

As seen from Table 1, the Bulla-Deniz oil sample used as the research object is characterized by a high content of paraffin and resin. However, the amount of asphaltenes is quite low. Additionally, the freezing point of the oil is relatively high, at 12°C. Therefore, due to such physical and chemical characteristics, complications arise during the transportation of this type of oil through pipelines, depending on the temperature factor. For this reason, various methods, either applied separately or in combination, are used to ensure the efficient transportation of such oils.

Under laboratory conditions, the individual and combined effects of the Difron-3970 depressant additive, produced by the EKOS company (Russian Federation), and ultrasonic waves on the Bulla-Deniz oil sample were studied. The effects of physical and chemical methods on the dynamic viscosity of the Bulla-Deniz oil sample were carried out at temperatures of 5°C, 10°C, and 20°C. In the research process, different amounts of the Difron-3970 depressant additive were used: 250, 350, 450, 650, and 750 g/t. The exposure to ultrasonic waves lasted for 5, 10, and 15 minutes, with the ultrasonic wave radiation frequency set at 45 kHz. The physical and chemical characteristics of the Difron-3970 depressant additive are presented in Table 2.

Table 2. Physico-chemical properties characteristics of the Difron-3970 depressant additive
Tabela 2. Fizykochemiczne właściwości dodatku depresatora Difron-3970

Parameters	Difron-3907
External appearance	transparent yellowish (brown) liquid
Density, 20°C	940 kg/m³
Ignition temperature in a closed container	above 65°C
Solubility in water	insoluble
Solubility in aromatic solvents	soluble
Active ingredients	esters, long-chain alkyl acrylates, aromatic hydrocarbons
Auxiliary components	petroleum distillate solvents, functional additives
Mechanism of action	inhibits the growth and agglomeration of paraffin crystals
Application area	high-paraffin crude oil, fuel oil

Under laboratory conditions, the freezing point of the high-paraffin resinous Bulla-Deniz oil was determined according to the RD 39-3-812-82 methodology (RD 39-3-812-82, 1982). Oil samples were poured into test tubes with a spherical base, having a diameter of 20 mm and a height of 160 mm, heated to 55–60°C, and then various concentrations of depressant additives were added. The oil samples were gradually cooled to 30–40°C. It should be noted that, for comparison, one test tube was left without any additives or physical treatment. Afterward, the test tubes were placed in a thermostat to continue the cooling process. During the temperature drop, the test tubes were held at a 45-degree angle every three degrees (GOST 25276-82, 1982a). In these sequential tests, the temperature at which the oil level in the test tubes remained static was recorded, and the complete solidification of the liquid was determined based on the immobility of the upper layer of the liquid when the test tube was held horizontally for five seconds (GOST 20287-74, 1987). Viscosimetric studies were performed using a Reotest-2 rotational viscometer (GOST 33768-2015, 1982b). In the laboratory, the investigation process on the Reotest-2 viscometer was carried out at temperatures of 5°C, 10°C, and 20°C, with a shear rate gradient ranging from 0.3 to 145.8 s^{-1} (ASTM D5853-95, 1995). The dynamic viscosity of the oil was calculated based on the results of these experiments (ASTM D97-09, 2009).

Table 3. Variation of the dynamic viscosity of Bulla-Deniz crude oil at different temperatures (without reagents)

Tabela 3. Zmiana dynamicznej lepkości surowej ropy z pola Bulla-Deniz w różnych temperaturach (bez reagentów)

Velocity gradient [s^{-1}]	Dynamic viscosity of Bulla-Deniz crude oil sample [P]		
	20 [°C]	10 [°C]	5 [°C]
0.3	878.6	982.7	1542.8
0.6	742.9	875.9	1255.9
1.0	511.7	688.8	937.8
1.8	233.5	455.4	735.7
3.0	127.6	320.6	512.9
5.4	53.2	191.9	201.3
9.0	40.8	71.8	77.8
16.2	20.7	42.6	48.6
27.0	7.8	17.8	28.3
48.6	4.9	9.7	11.7
81.0	3.6	6.1	8.4
145.8	2.5	4.8	5.9

Table 4. Variation of the dynamic viscosity of Bulla-Deniz refined oil at different temperatures (without reagents)

Tabela 4. Zmiana dynamicznej lepkości rafinowanej ropy z pola Bulla-Deniz w różnych temperaturach (bez reagentów)

Velocity gradient [s^{-1}]	Dynamic viscosity of Bulla-Deniz refined oil sample [P]		
	20 [°C]	10 [°C]	5 [°C]
0.3	593.7	886.8	1048.6
0.6	377.8	591.3	670.2
1.0	230.3	485.8	517.8
1.8	118.7	226.9	290.4
3.0	71.6	137.2	177.9
5.4	42.3	80.6	108.3
9.0	25.7	48.7	57.6
16.2	11.6	21.3	31.7
27.0	5.8	10.8	17.8
48.6	3.9	6.9	10.4
81.0	2.1	4.7	6.9
145.8	1.6	3.5	5.2

Results and discussion

First, the changes in dynamic viscosity of both crude and commercial forms of Bulla-Deniz oil, under no external influence, were studied at 5°C, 10°C, and 20°C, and within the shear rate gradient interval of 0.3–145.8 s^{-1}. The results of numerous experiments are reflected in Tables 3 and 4 accordingly.

Based on the results shown in Table 3, it is observed that within the shear rate interval of 0.3–145.8 s^{-1}, the dynamic viscosity of the crude oil sample from the Bulla-Deniz field decreases at 5°C, 10°C, and 20°C, respectively, ranging from 1542.8–5.9 P, 982.7–4.8 P, and 878.6–2.5 P. This indicates a reduction in viscosity with increasing shear rate and temperature.

The results presented in Table 4 demonstrate that within the shear rate interval of 0.3-145.8 s^{-1}, the dynamic viscosity of the commercial oil sample from the Bulla-Deniz field decreases at 5°C, 10°C, and 20°C, with values ranging from 1048.6–5.2 P, 886.8–3.5 P, and 593.7–1.6 P, respectively.

Following this, the effect of various concentrations of the Difron-3970 depressant additive on the dynamic viscosity of both the crude and commercial forms of the Bulla-Deniz oil sample was studied. It was determined that the optimal concentration of the depressant is 750 g/t. Tables 5 and 6 provide the results of the effect of 750 g/t of the Difron-3970 depressant on the dynamic viscosity of the crude and commercial forms of the Bulla-Deniz oil sample, respectively.

The results presented in Table 5 show that the Difron-3970 depressant additive, at its optimal concentration, has a positive effect on the dynamic viscosity of the high-paraffin, resin-rich crude oil sample from the Bulla-Deniz field at all three temperatures, significantly reducing it. As indicated by the results from the laboratory tests in Table 5, within the shear rate interval of 0.3–145.8 s^{-1}, the dynamic viscosity of the Bulla-

Table 5. The effect of the Difron-3970 additive on the dynamic viscosity of Bulla-Deniz crude oil

Tabela 5. Wpływ dodatku Difron-3970 na dynamiczną lepkość surowej ropy z pola Bulla-Deniz

Velocity gradient [s^{-1}]	Dynamic viscosity of Bulla-Deniz crude oil [P] after adding 750 g/t of Difron-3970 reagent		
	20 [°C]	10 [°C]	5 [°C]
0.3	784.6	802.4	1156.8
0.6	630.8	656.4	924.7
1.0	450.7	530.8	698.6
1.8	224.2	310.6	402.3
3.0	90.4	198.7	278.4
5.4	38.1	88.4	148.5
9.0	29.6	52.6	64.3
16.2	12.3	28.5	37.9
27.0	4.6	9.8	16.2
48.6	2.4	4.2	6.8
81.0	1.9	2.7	3.1
145.8	0.7	0.9	1.2

Table 6. The effect of the Difron-3970 additive on the dynamic viscosity of Bulla-Deniz refined oil

Tabela 6. Wpływ dodatku Difron-3970 na dynamiczną lepkość rafinowanej ropy z pola Bulla-Deniz

Velocity gradient [s^{-1}]	Dynamic viscosity of Bulla-Deniz refined oil sample [P]		
	20 [°C]	10 [°C]	5 [°C]
0.3	501.4	606.3	702.6
0.6	292.5	297.2	423.1
1.0	198.6	325.7	398.3
1.8	81.2	102.8	202.6
3.0	58.3	65.3	108.5
5.4	21.2	42.1	62.4
9.0	14.8	23.6	32.6
16.2	7.1	11.7	18.7
27.0	3.6	5.4	8.9
48.6	1.9	3.2	5.7
81.0	0.9	1.4	2.9
145.8	0.3	0.5	0.9

Deniz crude oil sample at 5°C, 10°C, and 20°C, in the presence of the optimal concentration of the Difron-3970 depressant additive, decreases to values ranging between 1156.8–1.2 P, 802.4–0.9 P, and 784.6–0.7 P, respectively.

The results presented in Table 6 indicate that, compared to the crude oil sample, the Difron-3970 depressant additive has a more favorable effect on the dynamic viscosity of the Bulla-Deniz refined oil sample, reducing it to a minimum at all three temperatures. As shown in the Table 6, within the shear rate interval of 0.3–145.8 s^{-1}, at 5°C, 10°C, and 20°C, the dynamic viscosity of the Bulla-Deniz refined oil sample with the optimal concentration of the Difron-3970 depressant additive changes to values of 702.6–0.9 P, 606.3–0.5 P, and 501.4–0.3 P, respectively.

Tables 7 and 8 present the effects of ultrasound waves on the dynamic viscosity of the crude and refined oil samples, respectively. It is important to note that the ultrasound effect was applied for 15 minutes, with a frequency of 45 kHz.

Table 7. The effect of ultrasonic waves on the dynamic viscosity of Bulla-Deniz crude oil

Tabela 7. Wpływ fal ultradźwiękowych na lepkość dynamiczną surowej ropy z pola Bulla-Deniz

Velocity gradient [s^{-1}]	The viscosity of the Bulla-Deniz crude oil [P] during the effect of ultrasonic waves for 15 minutes (frequency of radiation 45 kHz)		
	20 [°C]	10 [°C]	5 [°C]
0.3	803.6	845.3	1210.4
0.6	667.2	700.3	976.3
1.0	480.5	567.2	734.9
1.8	298.7	356.4	388.5
3.0	134.6	210.5	234.6
5.4	62.3	132.1	109.8
9.0	40.1	68.7	73.2
16.2	21.0	39.3	46.5
27.0	7.4	14.1	19.7
48.6	3.8	6.3	9.6
81.0	2.5	3.4	5.4
145.8	0.9	1.3	1.5

Table 8. The effect of ultrasonic waves on the dynamic viscosity of Bulla-Deniz refined oil

Tabela 8. Wpływ fal ultradźwiękowych na lepkość dynamiczną rafinowanej ropy z pola Bulla-Deniz

Velocity gradient [s^{-1}]	The viscosity of the Bulla-Deniz refined oil [P] during the effect of ultrasonic waves for 15 minutes (radiation frequency 45 kHz)		
	20 [°C]	10 [°C]	5 [°C]
0.3	532.3	637.5	734.8
0.6	310.1	330.6	450.3
1.0	235.4	360.0	411.2
1.8	93.6	121.2	220.8
3.0	64.7	78.4	132.7
5.4	29.6	50.0	70.1
9.0	18.9	28.1	39.4
16.2	9.7	17.3	22.5
27.0	4.8	6.0	10.0
48.6	2.4	3.8	6.2
81.0	1.4	1.9	3.2
145.8	0.5	0.7	1.4

The results presented in Table 7 characterize the effect of ultrasound waves on the dynamic viscosity of Bulla-Deniz crude oil at various temperatures over a duration of fifteen minutes as follows:

1. At a shear rate interval of 0.3–145.8 s^{-1} and a temperature of 5°C, the dynamic viscosity of the Bulla-Deniz crude oil sample decreases from 1210.4 to 1.5 P.
2. At a shear rate interval of 0.3–145.8 s^{-1} and a temperature of 10°C, the dynamic viscosity of the Bulla-Deniz crude oil sample decreases from 845.3 to 1.3 P.
3. At a shear rate interval of 0.3–145.8 s^{-1} and a temperature of 20°C, the dynamic viscosity of the Bulla-Deniz crude oil sample decreases from 803.6 to 0.9 P.

The laboratory results presented in Table 8 can be characterized as follows: at shear rate intervals of 0.3–145.8 s^{-1}, the dynamic viscosity of the Bulla-Deniz commercial oil sample decreases over a fifteen-minute period under the influence of ultrasound waves at temperatures of 5°C, 10°C, and 20°C, obtaining values of 734.8–1.4 P, 637.5–0.7 P, and 532.3–0.5 P, respectively.

Tables 9 and 10 show the combined effect of the Difron-3970 depressor additive and ultrasound waves on the dynamic viscosity of both crude and commercial oil samples. It should be noted that the ultrasound effect lasted for ten minutes, with a frequency of 45 kHz and an additive concentration of 500 g/t.

Table 9 presents the results of the effect of the Difron-3970 depressor additive combined with ultrasound on the dynamic viscosity of Bulla-Deniz crude oil at various temperatures, characterized as follows:

Table 9. The combined effect of the Difron-3970 additive and ultrasonic waves on the dynamic viscosity of Bulla-Deniz crude oil

Tabela 9. Łączny wpływ dodatku Difron-3970 i fal ultradźwiękowych na lepkość dynamiczną surowej ropy z pola Bulla-Deniz

Velocity gradient [s^{-1}]	Dynamic viscosity of the Bulla-Deniz crude oil [P] after the combined effect of the Difron-3970 reagent and ultrasonic waves		
	20 [°C]	10 [°C]	5 [°C]
0.3	630.6	722.1	998.6
0.6	520.4	560.7	876.3
1.0	370.9	460.0	510.6
1.8	160.5	289.7	356.4
3.0	72.3	134.2	210.4
5.4	25.6	60.4	110.0
9.0	18.3	35.2	43.7
16.2	8.7	18.5	22.8
27.0	2.4	5.9	12.1
48.6	1.3	3.8	4.2
81.0	0.5	1.2	1.8
145.8	0.2	0.3	0.4

1. At a shear rate interval of 0.3–145.8 s^{-1} and a temperature of 5°C, the dynamic viscosity of the Bulla-Deniz crude oil sample decreases, ranging from 998.6 to 0.4 P.
2. At a shear rate interval of 0.3–145.8 s^{-1} and a temperature of 10°C, under the influence of ultrasound for fifteen minutes, the dynamic viscosity of the Bulla-Deniz crude oil sample changes to a range of 722.1 to 0.3 P.
3. At a shear rate interval of 0.3–145.8 s^{-1} and a temperature of 20°C, during the fifteen-minute ultrasound treatment, the dynamic viscosity of the Bulla-Deniz crude oil sample decreases to a minimum value, ranging from 630.6 to 0.2 P.

Table 10 presents multiple laboratory results characterized as follows: at a shear rate interval of 0.3–145.8 s^{-1}, during the combined treatment at temperatures of 5°C, 10°C, and 20°C, the dynamic viscosity of the Bulla-Deniz refined oil sample ranges from 623.4 to 0.5 P, 510.8 to 0.3 P, and 430.8 to 0.1 P, respectively.

Table 10. The combined effect of the Difron-3970 additive and ultrasonic waves on the dynamic viscosity of Bulla-Deniz refined oil

Tabela 10. Łączny wpływ dodatku Difron-3970 i fal ultradźwiękowych na lepkość dynamiczną rafinowanej ropy z pola Bulla-Deniz

Velocity gradient [s^{-1}]	Dynamic viscosity of the Bulla-Deniz refined oil [P] after the combined effect of the Difron-3970 reagent and ultrasonic waves		
	20 [°C]	10 [°C]	5 [°C]
0.3	430.8	510.8	623.4
0.6	197.4	201.8	354.2
1.0	120.5	240.6	290.0
1.8	57.3	86.4	140.7
3.0	42.1	52.6	87.8
5.4	15.6	32.3	48.9
9.0	10.6	18.7	23.1
16.2	5.4	8.3	10.9
27.0	2.3	3.1	5.3
48.6	1.0	1.9	2.4
81.0	0.3	0.5	0.9
145.8	0.1	0.3	0.5

Figures 1 and 2 provide a comparative analysis of the dynamic viscosity values of the Bulla-Deniz crude and refined oil samples at a shear rate of 145.8 s^{-1} for temperatures of 5°C, 10°C, and 20°C. The comparisons include treatments without reagents, with the optimal concentration of Difron-3970 depressor additive at 750 g/t, the effect of ultrasound for fifteen minutes, and the combined effect of the depressor additive and ultrasounds.

The results of numerous laboratory experiments presented in Figure 1 can be interpreted as follows:

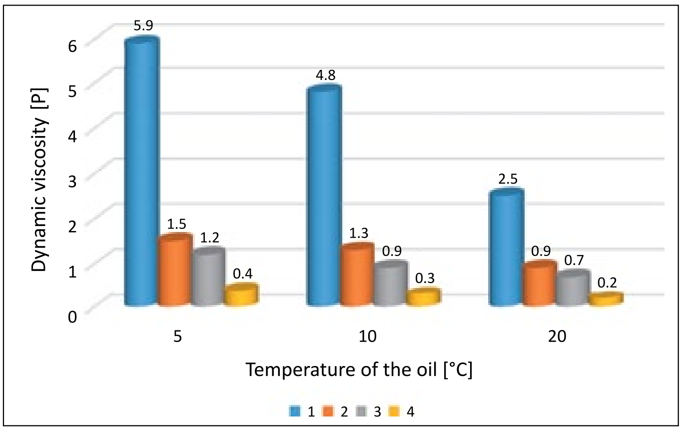

Figure 1. Dynamic viscosity of Bulla-Deniz crude oil at a shear rate of 145.8 s^{-1}: 1 – without reagent; 2 – after ultrasonic waves treatment; 3 – after the Difron-3970 additive treatment; 4 – after combined treatment of Difron-3970 additive and ultrasonic waves

Rysunek 1. Lepkość dynamiczna surowej ropy z pola Bulla-Deniz przy szybkości ścinania 145,8 s^{-1}: 1 – bez reagentu; 2 – po działaniu fal ultradźwiękowych; 3 – po działaniu dodatku Difron-3970; 4 – po połączonym działaniu dodatku Difron-3970 i fal ultradźwiękowych

1. At a shear rate of 145.8 s^{-1}, without any external influences, the dynamic viscosity of the high-paraffin Bulla-Deniz crude oil sample at temperatures of 5°C, 10°C, and 20°C is measured at 5.9, 4.8, and 2.5 P, respectively.
2. After 15 minutes of ultrasound treatment at the same shear rate and temperatures, the dynamic viscosity values decrease to 1.5, 1.3, and 0.9 P.
3. Following the application of the optimal concentration of Difron-3970 depressor additive at a shear rate of 145.8 s^{-1}, the dynamic viscosity values further decrease to 1.2, 0.9, and 0.7 P for the respective temperatures.
4. When both the Difron-3970 depressor and ultrasound are used together, the dynamic viscosity of the high-paraffin Bulla-Deniz crude oil is significantly reduced to 0.4, 0.3, and 0.2 P.

In summary, the ultrasound treatment results in viscosity reductions of 74.5%, 73%, and 64% at 5°C, 10°C, and 20°C, respectively. The optimal concentration of Difron-3970 leads to viscosity reductions of 80%, 81%, and 72% at these temperatures. Furthermore, the combined effect of the depressor additive and ultrasound achieves even greater reductions in dynamic viscosity, with decreases of 93.2%, 93.7%, and 92% at the same temperatures.

The results of numerous laboratory experiments presented in Figure 2 can be characterized as follows:

1. At a shear rate of 145.8 s^{-1}, without any external influence, the dynamic viscosity of the high-paraffin Bulla-Deniz refined oil sample at temperatures of 5°C, 10°C, and 20°C is measured at 5.2, 3.5, and 1.6 P, respectively.
2. After 15 minutes of ultrasound treatment at the same shear rate and temperatures, the dynamic viscosity values decrease to 1.4, 0.7, and 0.5 P.
3. Following the application of the optimal concentration of Difron-3970 depressor additive at a shear rate of 145.8 s^{-1}, the dynamic viscosity values further decrease to 0.9, 0.5, and 0.3 P.
4. When both the Difron-3970 depressor and ultrasound are used together, the dynamic viscosity of the high-paraffin Bulla-Deniz refined oil is significantly reduced to 0.5, 0.3, and 0.1 P.

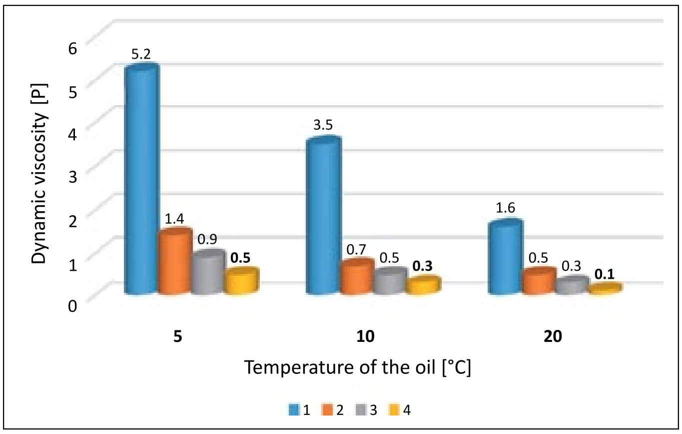

Figure 2. Dynamic viscosity of Bulla-Deniz refined oil at a shear rate of 145.8 s^{-1}: 1 –without reagent; 2 – after ultrasonic waves treatment; 3 – after the Difron-3970 additive treatment; 4 – after combined treatment of Difron-3970 additive and ultrasonic waves

Rysunek 2. Lepkość dynamiczna rafinowanej ropy z pola Bulla-Deniz przy szybkości ścinania 145,8 s^{-1}: 1 – bez reagentu; 2 – po działaniu fal ultradźwiękowych; 3 – po działaniu dodatku Difron-3970; 4 – po połączonym działaniu dodatku Difron-3970 i fal ultradźwiękowych

The results indicate that after 15 minutes of ultrasound treatment, the dynamic viscosity decreases by 73%, 80%, and 68.7% at 5°C, 10°C, and 20°C, respectively. The optimal concentration of Difron-3970 leads to viscosity reductions of 82.7%, 85.7%, and 81.3% at these temperatures. Furthermore, the combined effect of the depressor additive and ultrasound achieves even greater reductions in dynamic viscosity, with decreases of 90.4%, 91.5%, and 93.7% at the same temperatures.

In the course of the research, the effects of the Difron-3970 depressor additive and ultrasound waves, both separately and in combination, on the freezing temperature of the Bulla-Deniz refined oil sample were studied according to the established methodology, with the results shown in Figures 3 to 5.

Figure 3 illustrates that as the concentration of the Difron-3970 depressor additive increases in high-paraffin Bulla-Deniz oil, its freezing temperature decreases, reaching a minimum at 750 g/t. Specifically, the freezing temperature

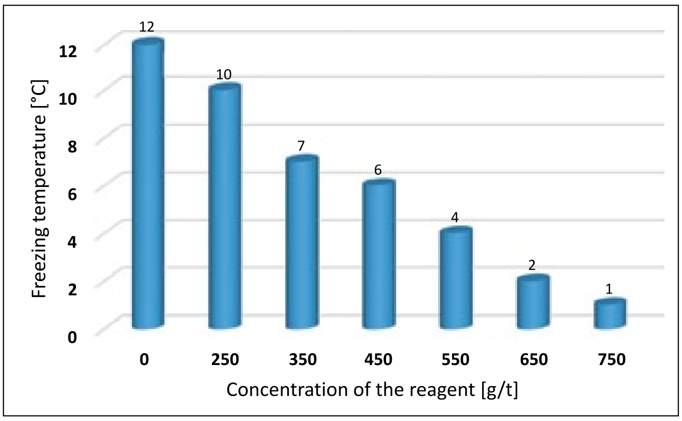

Figure 3. Dependence of the concentration of the Difron-3970 additive on the freezing temperature of Bulla-Deniz oil

Rysunek 3. Zależność pomiędzy stężeniem dodatku Difron-3970 a temperaturą krzepnięcia ropy z pola Bulla-Deniz

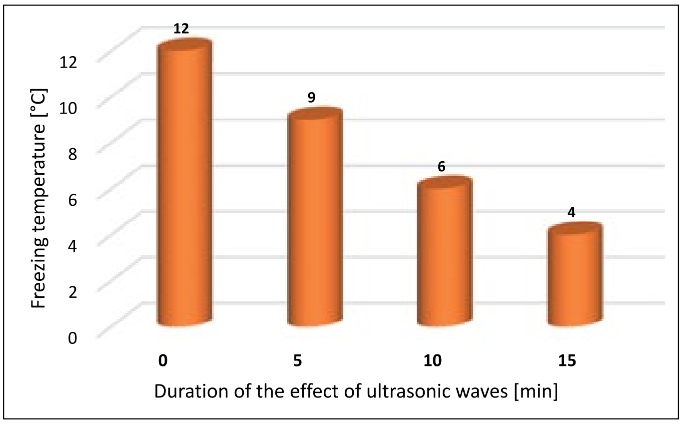

Figure 4. Dependence of the duration of the ultrasonic waves' effect on the freezing temperature of Bulla-Deniz oil

Rysunek 4. Zależność pomiędzy czasem oddziaływania fal ultradźwiękowych a temperaturą krzepnięcia ropy z pola Bulla-Deniz

of the oil sample changes from 12°C to 10°C, 7°C, 6°C, 4°C, 2°C, and finally to 1°C as the concentrations of 250, 350, 450, 550, 650, and 750 g/t are applied.

Thus, the addition of the optimal concentration of 750 g/t of Difron-3970 demonstrates a significant effectiveness, reducing the freezing temperature by 91.7% and ensuring the fluidity of the high-paraffin oil at 1°C.

Figure 4 illustrates the effect of ultrasound waves on the freezing temperature of high-paraffin Bulla-Deniz oil. Although ultrasound significantly influences the freezing temperature of the oil, its effect is relatively weaker compared to the impact of the Difron-3970 depressor additive.

From the graph, it can be observed that after exposing the oil sample to ultrasound for 5, 10, and 15 minutes, the freezing temperature decreases from 12°C to 9°C, 6°C, and 4°C, respectively. As a result, ultrasound treatment for the optimal duration of 15 minutes reduces the freezing temperature of the high-paraffin oil by 66.7%. This demonstrates that while ultrasound is effective, it may be considered more ecologically and economically beneficial when combined with other methods.

Figure 5 presents the results of the effect of the Difron-3970 additive on the freezing temperature of high-paraffin Bulla-Deniz crude oil in conjunction with ultrasound. The following conclusions can be drawn:

1. Effectiveness of Combined Action: The combined physical-chemical effect is significantly more effective than the individual physical and chemical effects. This approach allows for the use of Difron-3970 depressor additive at reduced dosages (200–500 g/t) and saves on the ultrasound exposure time of 5 minutes.
2. Reduction of Freezing Temperature: During the joint action of the Difron-3970 additive at concentrations of 100, 200, 300, 400, and 500 g/t, and the effect of ultrasound for 10 minutes, the freezing temperature of high-paraffin Bulla-Deniz crude oil sharply decreases from 12°C to 8°C, 5°C, 1°C, –4°C, and –7°C.

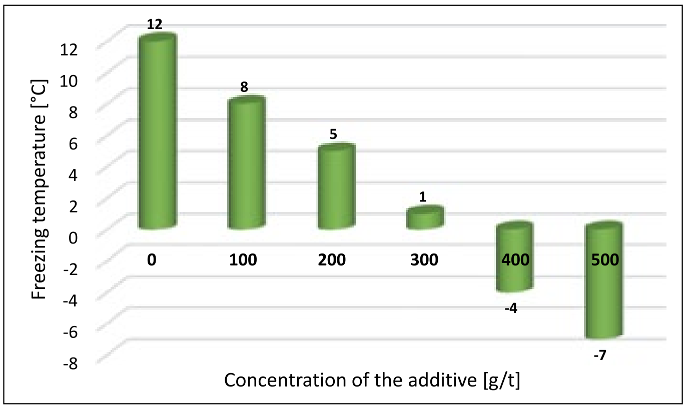

Figure 5. Effect of the Difron-3970 additive combined with ultrasonic waves on the freezing temperature of Bulla-Deniz oil (ultrasound = 10 min, C = 500 g/t)

Rysunek 5. Wpływ połącznego działania dodatku Difron-3970 i fal ultradźwiękowych na temperaturę krzepnięcia ropy z pola Bulla-Deniz (czas działania ultradźwięków = 10 min, stężenie = 500 g/t)

3. Ecological and Economic Efficiency: The combined effect of the Difron-3970 additive with ultrasound is considered efficient from both ecological and economic perspectives, suggesting its application in mining conditions within the oil industry.

Thus, the analysis of the results obtained from numerous laboratory tests conducted on high-paraffin crude and commercial oil samples from the Bulla-Deniz field by SOCAR indicates that the significant reduction in the dynamic viscosity and freezing temperature of both forms of oil occurs precisely due to the influence of the combined physical-chemical method.

The rheological behavior of the crude oil before the addition of the depressant corresponded to a Bingham plastic model, characterized by a distinct yield stress due to the formation of paraffin crystal networks. After the introduction of Difron-3970, the paraffin structures were disrupted, leading to a flow regime more consistent with Newtonian behavior, where the shear stress became linearly dependent on the shear rate. This shift resulted in a significant reduction in viscosity and improved flow properties, which is beneficial for transportation and processing.

Comparison with other depressants reported in the literature

Although direct comparability of depressant efficiency is limited by the specificity of each crude oil sample – especially in terms of paraffin content, resin-asphaltene ratio, and wax appearance temperature – a contextual evaluation can still be informative.

In our study, the application of Difron-3970 resulted in a notable decrease in dynamic viscosity and preserved the pour point at 12°C while maintaining paraffin dispersion. Compared to findings in the literature, this performance is consistent with or superior to several widely used depressants under similar testing conditions:

- polymeric depressants such as EVA (ethylene-vinyl acetate) and PPD-type (pour point depressant-type) copolymers have shown viscosity reductions in the range of 40–60% and pour point depressions of 5–10°C in light and medium waxy oils (Ali and Alqam, 2000; Demirbash, 2016);
- aromatic ester-based depressants, similar in chemical nature to Difron-3970, demonstrated enhanced wax dispersion with viscosity reductions of up to 70%, though often at higher dosages and under optimized mixing regimes (Girma et al., 2018);
- in high-wax crude oils such as those from the Western Siberian and Indian fields, commercial products like Amdet-101, WAXTREAT, and PourPoint D-321 were effective primarily at temperatures above 15°C, and viscosity reduction efficiencies varied significantly between 45–80% depending on the crude composition (Nebogina et al., 2008; Yang et al., 2015).

In this context, Difron-3970 displayed comparable or higher efficiency in terms of rheological improvement and solid phase dispersion, particularly under minimal mechanical agitation and moderate temperature ranges. Moreover, its low dosage requirement and chemical compatibility with the resin-paraffin matrix of Bulla-Deniz-type crude oil appear to be advantageous.

Overall, while direct comparison must be made cautiously, the efficiency of Difron-3970 aligns well with – and in some cases surpasses – that of established commercial depressants reported in the literature. This suggests its potential for broader field application in similar high-wax, medium-viscosity crude systems.

Conclusion

1. For the first time, the dynamic viscosity and freezing temperature of high-paraffin resin crude and commercial oil samples taken from the Bulla-Deniz field by SOCAR have been studied concerning the effects of the Difron-3970 depressor additive and ultrasound waves, both separately and in combination. It has been determined that the optimal dosage of the Difron-3970 depressor additive and the ultrasound waves during their separate and combined action are 750 g/t, 500 g/t, and the optimal exposure times are 15 and 10 minutes, respectively.
2. It has been shown that at a shear rate of 145.8 s^{-1}, the effect of the optimal concentration of the Difron-3970 depressor additive results in a reduction in the dynamic viscosity of crude oil by 80%, 81%, and 72% at temperatures of 5°C, 10°C, and 20°C, respectively. For commercial oil, the reductions are 82.7%, 85.7%, and 81.3%. After 15 minutes of ultrasound treatment, the reductions are 74.5%, 73%, and 64% for crude oil, and 73%, 80%, and 68.7% for commercial oil. In the case of combined effects, the reductions are 93.2%, 93.7%, and 92% for crude oil, and 90.4%, 91.5%, and 93.7% for commercial oil.
3. It has been determined that following the optimal concentration of the Difron-3970 depressor additive, the optimal exposure time of the ultrasound waves, and the combined physical-chemical effects, the freezing temperature of the high-paraffin resin Bulla-Deniz oil sample decreases from 12°C to 1°C, 4°C, and –7°C.

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