

Article

Enhancing the Information Content of IR Spectroscopy of High-Viscosity Oil in the Field Using Ultrasonic Sample Preparation

Vladislav Filatov ^{1,*}, Irina Rastvorova ^{1,*} and Fedor Chmilenko ²

¹ Department of Electronic Systems, Empress Catherine II Saint Petersburg Mining University, 199106 Saint Petersburg, Russia

² Department of Electrical Technology and Converter Engineering, Saint Petersburg Electrotechnical University "LETI", 197022 Saint Petersburg, Russia; fvchmilenko@etu.ru

* Correspondence: vladislav-fil01@mail.ru (V.F.); rastvorova_ii@pers.spmi.ru (I.R.)

Abstract

Heavy and highly viscous oils account for a significant proportion of the world's hydrocarbon reserves. The development of these reserves in harsh climates is associated with technological risks due to paraffin deposits and equipment corrosion. Ensuring reliable transportation requires operational monitoring of the physical and chemical properties of fluids directly at the wellhead. Traditional laboratory methods such as SARA fractionation and gas chromatography (GC) are time-consuming and can yield to distortions in the sample composition during transportation. Field optical methods, such as an infrared (IR) spectroscopy are complicated by the optical heterogeneity of crude oils due to emulsified water, supramolecular associations of resins, asphaltenes, and paraffins. In this paper, ultrasonic (US) sample preparation for high-viscosity oils is justified as a method for increasing the reliability and information content of field IR spectroscopic analysis by unmasking the diagnostic extrema of absorption bands that are initially distorted by emulsified water, baseline scattering, and radiation scattering from large resin–asphaltene–paraffin aggregates. The technique is based on cavitation-induced destruction of emulsion shells and disaggregation of the structural framework without volume thermal heating. Experimental data obtained from watered high-viscosity oil has shown that 9 min of the US exposure reduces the light scattering index I_{tr} by 92.83%, bringing the system into a less heterogeneous state. Statistical correlation analysis confirmed that emulsions and aggregates are the main scattering centers, and their destruction correlates directly with the transparency of the medium. Stability of spectral indices $I_{\text{CH}_3/\text{CH}_2}$, I_{foc} and $I_{\text{C=O}}$ indicates the absence of chemical degradation or oxidation at the US exposure intensity of 0.12 W/mL, confirming the physical nature of the effect. The proposed method makes it possible to implement automated monitoring of the properties of high-viscosity oil directly at the wellhead, minimizing logistic costs and risks of the sample degradation. The practical significance of the proposed method is to improve the reliability and information content of wellhead monitoring by reducing optical heterogeneity and making diagnostic significant IR absorption extremes more distinguishable for further interpretation.

Keywords: high-viscosity oil; ultrasonic treatment; on-site monitoring; infrared spectroscopy; process reliability; sample preparation; oil transportation; field development; optical homogeneity



Academic Editor: Dameng Liu

Received: 2 June 2026

Revised: 22 June 2026

Accepted: 24 June 2026

Published: 27 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The modern structure of the world's hydrocarbon reserves is dominated by heavy and highly viscous oils, which make up at least half of the recoverable resources. Their development, especially in harsh climatic conditions—in the fields of Northern Canada, the Far North of Russia and Alaska—is associated with significant technological barriers [1–3]. High density and high content of asphaltene–resinous components, paraffins, and low surrounding temperature cause significant viscosity in products, which necessitates strict control of physical and chemical properties at all stages of extraction and preparation [4].

Ensuring the reliability of main pipelines, preventing paraffin deposits and minimizing the corrosive aggressiveness of the fluid critically depend on the ability to quickly choose the optimal transportation mode, which in turn requires reliable knowledge of the properties of the pumped medium [2,5,6]. That is why the determination of oil quality and composition is a prerequisite not only for managing production processes, but also for all subsequent logistics. However, the specificity of field development is that oil is a dynamic system, and as the reservoir is depleted and the operating conditions change, its physical and chemical properties naturally vary [7,8]. The oil produced even in neighboring wells within the same field can significantly vary, making it impossible to use universal preparation algorithms. Under the operating conditions of highly water-flooded wells, this situation is complicated by the formation of three-phase emulsion systems [9–11].

Traditional laboratory methods of oil analysis, such as SARA according to ASTM D4124 and IP 469 and GC according to D2887, provide high detail of chemical composition, but they have limitations when used in field conditions. The process of sampling at the wellhead, conservation and transportation of the samples to a laboratory inevitably leads to distortions in the physico-chemical properties of fluids [12–14]. Destabilizing factors include evaporation of light hydrocarbons, adsorption of active components on container walls and disruption of phase equilibrium in emulsions [15]. Meanwhile, ensuring reliability of pipelines and minimizing risks of corrosion and paraffin deposition require operational quality control of raw materials [16]. In accordance with the requirements of GOST 34396-2018, obtaining reliable data on the composition of products in real time is a key condition for selecting transportation modes. Logistical barriers typical for remote fields in the Arctic zone make the classical laboratory approach ineffective for operational monitoring of the stages of the oil cycle [15,17]. In this context, the transition to expert analysis methods is a promising direction. The conceptual foundations of automated spectral monitoring presented in ASTM D6122 demonstrate the possibility of using the IR spectrometers directly in the technological process [18]. Nevertheless, implementation of this approach for high-viscosity crude oil faces several fundamental obstacles. High optical heterogeneity of the samples due to emulsified water and supramolecular asphaltene–paraffin aggregates provokes intense scattering of radiation. These factors lead to spectral overlap of analytical absorption bands and deterioration of the signal-to-noise ratio, which significantly reduces the information content and reliability of the interpretation of spectral data [19,20].

Today, the development of portable IR systems for rapid oil analysis in the field is focused on three main technological areas.

The first direction relates to the development of optical devices for measuring rheological properties of oil, such as density, viscosity, and surface tension. Despite the correlation between optical characteristics and viscosity, there are problems with technical implementation, including instability of radiation sources, limited sensitivity in a wide wavelength range [15], and insufficient development of techniques for analyzing highly viscous oils with low fluidity [21].

The second direction is based on the use of portable IR Fourier spectrometers to determine the composition [22] and classify oils [23,24]. However, testing on representative samples of viscous oils revealed a low predictive power of the method for analyzing resins, saturated and aromatic hydrocarbons. This is due to the neglect of structural features of petroleum media that significantly affect the optical response.

The third area, which is the most widespread and largest in terms of the number of publications, focuses on improving the mathematical methods for processing spectral data. These include deep learning [25], the method of principal components and support vector regression [26], the Fourier method with partial least squares [27], Mahalanobis distance [28], and convolutional neural networks [29]. Nevertheless, mathematical transformations cannot completely eliminate spectral distortions because the nature of oil media and its structural heterogeneity is stochastic in nature.

The main limitation of these approaches is the attempt to compensate for fundamental physical signal distortions, such as light scattering and optical heterogeneity, using exclusively software or instrumental sensitivity. Since the cause of distortion is the physical condition of the sample, the solution to the problem lies in preliminary physical preparation of the sample. Correction of signal distortions using mathematical methods inevitably leads to a loss of reliability, whereas restoration of the true spectral pattern is only possible by physical homogenization of the sample.

Despite the known potential of US to enhance demulsification and structural disruption [19,21], its application in in situ IR spectroscopic systems is limited by several practical considerations: additional power requirements, the need for thermal control, the reproducibility of cavitation in small-volume cells, and the potential for uncontrolled sample alteration under high acoustic exposure. Consequently, the development of a low-intensity, reproducible US pretreatment protocol is essential for implementing this technique in portable or field-based analytical systems.

The solution to this problem requires the development of a preliminary sample preparation stage integrated into the technological cycle of oil treatment. In this paper, the US sample processing is proposed as an approach that modifies the structural and rheological characteristics of the oil medium. Studies have shown that the US technologies are highly effective in solving problems such as demulsification [30], viscosity reduction [31], and intensification of mass transfer processes [32,33]. The fundamental basis for these effects is acoustic cavitation, which is accompanied by the generation of shock waves, cumulative microjets, and significant local pressure gradients [34,35]. In contrast to volumetric thermal heating, cavitation energy is released locally, which makes it possible to initiate a structural change in the system while maintaining a moderate temperature of the treated volume [36]. The controllability of the process, achieved by regulating the supplied power and using pulsed exposure modes [37,38], is of fundamental importance for low-temperature treatment of high-viscosity oils typical of fields in the Far North. Under these conditions, traditional methods of phase separation and homogenization are ineffective, while the US exposure allows for the implementation of mechanisms to disaggregate supramolecular complexes and redistribute components.

It is assumed that controlled US treatment will ensure the destruction of emulsion structures and the disaggregation of supramolecular resin–asphaltene–paraffin complexes. This will lead to a decrease in the optical heterogeneity of the medium, which is a prerequisite for the clear manifestation of diagnostic absorption bands of hydrocarbons in the IR spectra. To verify this approach, two types of oils were selected as research objects: crude ultra-viscous oil and dehydrated viscous oil. The use of samples contrasting in composition and properties allows for the contributions of the aqueous and solid phases to the distortion

of recorded spectral signals to be differentiated and for the effectiveness of the proposed sample preparation method to be evaluated.

The aim of this study is to experimentally substantiate the possibility of using the US treatment as an express method for preparing samples of high-viscosity oils in order to increase the reliability of interpreting the results of the IR spectroscopic analysis. The scientific novelty of the work lies in a comprehensive study of the US exposure as an independent analytical stage that ensures the transition of heterogeneous oil systems to a more homogeneous state suitable for high-precision spectral analysis. The practical significance of the study is confirmed by the development of a field device that implements the IR spectroscopy method in combination with the US sample preparation. This technical solution provides an increase in efficiency and metrological accuracy for monitoring high-viscosity oil outside laboratory conditions, opening up new opportunities for well product monitoring.

2. Materials and Methods

2.1. The Structure of the Experiment

The main techniques used in the experimental studies include the US treatment, the IR spectroscopy and a transmission microscopy analysis. Two high-viscosity oil samples from different regions of the Far North were used as research materials: a sample from the Tazovsky District in the Yamalo-Nenetsky Autonomous Okrug and a sample from the Turukhansky District in the Krasnoyarsk Territory. The oil samples were not degassed prior to the experiments. Table 1 represents the main characteristics of the samples and equipment parameters.

Table 1. Materials and equipment of the experiment (created by the authors).

Equipment		Materials	
Name	Parameters	Name	Characteristics at $\tau = 15\text{ }^{\circ}\text{C}$
Steel US bath	DADI 968 (DADI, Shenzhen, China) ($16 \times 8 \times 3.8\text{ cm}$); $f = 40\text{ kHz}$; $P = 30\text{ W}$; $V_{\max} = 500\text{ mL}$	Sample 1	Dehydrated viscous paraffin oil; $\mu = 99.78\text{ mPa}\cdot\text{s}$; $V = 750\text{ mL}$; $\rho = 0.902\text{ g/cm}^3$; Paraffins—3.70%; resins—7.20%; sulfur—0.17%; asphaltenes—6.30%; water—0%
IR spectrometer	IRAffinity-1 (Shimadzu Corporation, Kyoto, Japan); $k = 350 \dots 7800\text{ cm}^{-1}$; $SNR = 15,000$; $\sigma = \pm 1.0\%$		
Rotational viscometer	ViscoQC (Anton Paar GmbH, Graz, Austria) $\mu_{\min} \dots \mu_{\max} = 0.1 \dots 10 \cdot 10^6\text{ mPa}\cdot\text{s}$; $\sigma = \pm 1.0\%$	Sample 2	Crude resinous high-paraffin oil; $\mu = 712.4\text{ mPa}\cdot\text{s}$; $V = 0.75\text{ L}$; $\rho = 0.961\text{ g/cm}^3$; Paraffins—8.80%; resins—22.21%; asphaltenes—6.10%; water—7.10%
Temperature sensor	Pt100 (Anton Paar GmbH, Graz, Austria) $\tau_{\min} \dots \tau_{\max} = -60 \dots +300\text{ }^{\circ}\text{C}$; $\sigma = \pm 0.5\text{ }^{\circ}\text{C}$		

Auxiliary equipment included Pasteur pipettes (Capacity: 1.0 mL, tube diameter: 0.7 mm) for sample dosing, a water bath, and a refrigerator for sample thermal stabilization. The heating temperature was additionally monitored using a high-precision LT-300 thermometer.

The oil sample 2 is the main object of the study, and less viscous dehydrated oil (sample 1) is used as a reference. A comparison of the spectral characteristics of the sample

2 with the reference spectrum of the sample 1 allows to evaluate the effectiveness of the US sample preparation.

The experimental part was divided into three stages. The experimental design is shown in Figure 1.

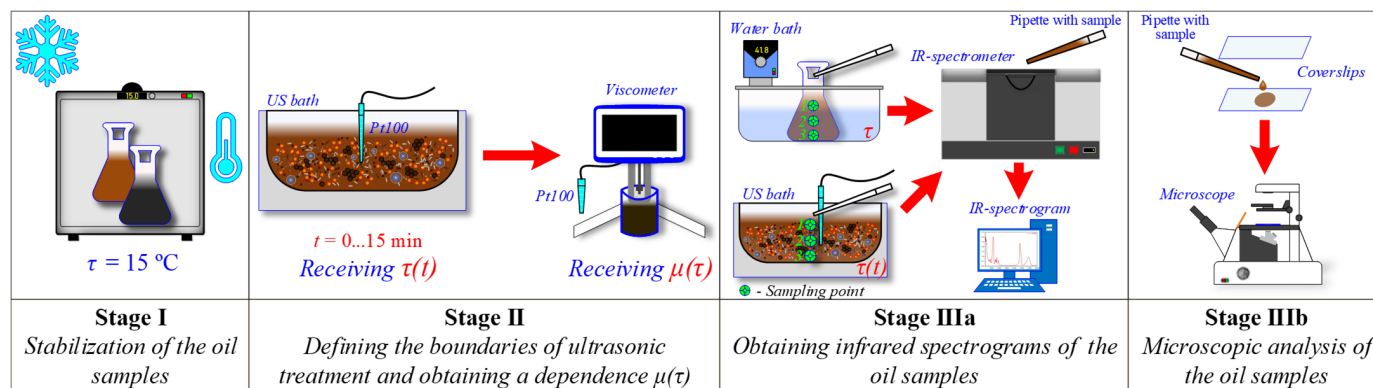


Figure 1. The scheme of the experiment (created by the authors).

At the first stage, 750 mL oil samples were divided into three aliquots of 250 mL each, sealed and stabilized for 12 h at 15 °C in the refrigeration chamber. This prepared three samples of oil for further analysis: one for the second stage and two for the third stage. The choice of temperature was determined by several factors. Firstly, it was based on field conditions (approximately 10–15 °C at the wellhead); secondly, on the requirements of GOST ISO 5024-2013 [39], which established standard conditions for crude oil testing; and thirdly, to minimize the temperature difference with the laboratory environment ($20 \pm 1\text{ }^{\circ}\text{C}$).

The second stage of the study aims at a quantitative and qualitative assessment of the thermal effects occurring during the US treatment of paraffin oil, as well as determining the effectiveness of the selected regime in terms of reducing its viscosity. This stage is of fundamental importance, as, in modern scientific and technical literature, the question of the effect of US on the viscous properties of paraffinic oils is highlighted ambiguously. A number of authors report a significant decrease in viscosity due to destruction of paraffin aggregates and partial disruption of their spatial structure [40,41], whereas other works indicate an absence of a consistent effect or even an increase in viscosity following US exposure, associated with local heating, repeated recombination of structures, or changes in the dispersity of the system [42–44]. The results obtained make it possible to clarify the conditions under which the US provides a stable decrease in viscosity and to identify the temperature limits of the applicability of this method [45]. After thermostating, one aliquot of each sample was alternately placed in the US bath and processed continuously. The temperature was recorded with a Pt100 sensor immersed in the central region of the sample without touching the bottom of the US bath. The viscosity μ and temperature τ were measured at the US treatment time points $t = \{0; 1; 3; 6; \dots, 15\}$ using the rotational viscometer. A spindle was selected empirically to reach a torque of 90% of maximum. Aliquots used in the second stage were not further utilized.

At the third stage, the initial IR spectrum was recorded at three sampling points for the first time. The sample was then subjected to the US, and at times $t = \{1, 3, \dots, 15\}$, the samples were taken from three points using clean pipettes as shown in Figure 1. The sampling points 1 and 2 were used as the main analytical points for evaluating the IR spectrum of the upper and middle parts of the oil volume, where the dehydrated and more optically homogeneous oil phase was expected after the US treatment. The sampling point 3 was located near the bottom of the bath and was introduced primarily as a water

sedimentation monitoring point. At the initial measurement, spectra from all three points were included in averaging because no difference between the points was observed. During further treatment of the sample 2, spectra from point 3 could become distorted by the water-rich bottom layer; in this case, they were excluded from the averaged analytical spectrum and used as independent evidence of water phase sedimentation. For the sample 1, point 3 was not excluded because no water-related sedimentation was observed. A second aliquot was heated to temperatures obtained in the second stage in a water bath, and the samples were also taken with clean pipettes from sampling points 1, 2, and 3 as shown in Figure 1. Selected samples were sequentially applied to a crystal of the IR spectrometer. The recording of each spectrum took less than 1 min. After each measurement, the cell was cleaned with hexane and dried. The remaining parts of pipetted samples were subjected to microscopic examination.

2.2. The US Sample Preparation

A frequency of 40 kHz was selected for the US sample processing. According to studies conducted in [46,47], in the low-frequency range of 20–35 kHz, an increase in the resonant radius of cavitation bubbles leads to an increase in their collapse energy. This creates conditions for intense local overheating, which can contribute to the evaporation of light hydrocarbon fractions and undesirable chemical modification of the sample [48]. At the frequency of 40 kHz, the threshold energy of cavitation and the intensity of hydrodynamic shear stresses decrease, which minimizes thermal degradation. At the same time, previous studies on the treatment of heavy oil with the US waves with a main harmonic frequency in the range of 20–60 kHz have confirmed that this frequency range is effective in modifying the structure and viscosity of heavy oils [30]. Therefore, the chosen frequency of 40 kHz has been considered a compromise between sufficient cavitation activity to disrupt emulsions and supramolecular structures and a moderate acoustic effect that does not lead to uncontrolled chemical changes. In addition, the frequency of 40 kHz is widely used in standard laboratory equipment, which ensures the reproducibility of the technique and its scalability. The power density of the US exposure in the experiment was 0.12 W/mL. The US treatment was performed in continuous mode. All experiments were carried out under strictly identical standard conditions, including the same sample volume, the same processing vessel, and the same fixed position of the sample in the US bath. This treatment mode was chosen to ensure effective degassing and demulsification of the samples without initiating chemical degradation processes or uncontrolled changes in the group composition of oil.

2.3. Recording of the IR Spectra

The IR spectra of the samples were recorded using an IRAffinity-1 Fourier spectrometer equipped with a Quest disruptive total internal reflection accessory with a diamond crystal. The spectra were recorded in the range of 400–4000 cm^{-1} at a resolution of 1.93 cm^{-1} with an average of 32 scans. A background spectrum of air was recorded before each set of measurements to eliminate the contribution from atmospheric interference.

2.4. Microscopic Analysis of the Oil Samples

Visualization of structural changes in oil emulsions and confirmation of the IR spectroscopy data were performed using optical microscopy in transmitted light. The main purpose of the analysis was to evaluate the dispersion of the aqueous phase and the state of aggregates of high-molecular components in initial and US-treated samples. Microscopic analysis directly visualizes microdroplets and spatial distribution of phases in the system and serves as an additional confirmation when interpreting the IR spectroscopy results. The role of microscopy in this study was auxiliary. Water deposition was primarily controlled

using sampling point 3, with microscopy confirming that visible water droplets were absent from analytical aliquots where IR analysis showed no water.

The microscopic analysis technique consists of several stages. In step IIIa, a portion of the sample is pipetted from sampling point 1 and placed between a slide and cover glass immediately after the US exposure to form a thin layer. Microscopic analysis is then performed using an optical microscope FRD-6C (COSSIM Inc., Beijing, China) with a halogen light source (6 V/30 W). The macrometric screws are used to adjust the lens and focus to obtain a clear microscopic image of the specimen. The total magnification of the system is $400\times$ ($40\times$ lens, $10\times$ ocular).

2.5. The IR Spectra Processing

The primary processing of spectra, including baseline correction and axis alignment, was performed using IRsolution software version 1.10, and calculations were done in MS Excel. Final spectra were obtained by averaging data from three sample points, assuming that the positions of the extremes in the analyzed range were identical. Emissions were identified using the Dickson Q-criterion ($n = 3, p = 95\%$). Spectra of the samples obtained at sampling point 3 that were emissions were excluded from further averaging and were used as evidence for water sedimentation.

To account for the possible drift of the baseline due to radiation scattering on the micro-uniformities of the sample, all spectra were processed using the calculation of integral absorption intensity [49]. The integral intensity in each selected range was calculated as follows: for a discrete data set defined by pairs of coordinates (k_i, Cla_i) , the area $S_{[x;y]}$ in the selected interval was determined as the sum of areas of elementary trapezoids according to Equation (1). Using integral areas rather than peak intensities minimizes errors associated with instrumental instability. For high-viscosity crude oil, the direct use of peak shape parameters such as symmetry or half-width at half maximum is limited because diagnostic absorption bands are broad and partially overlapping, affected by baseline scattering. Therefore, increased spectral information content has been evaluated using integral band areas and normalized spectral indices instead of isolated peak shape parameters. In this study, improved spectral information is understood as unmasking diagnostic absorption extrema, reducing the contribution of baseline scattering and more reliably calculating relative spectral indices.

$$S_{[x;y]} = \sum_{i=1}^{n-1} \frac{(Cla_i + Cla_{i+1})}{2} \cdot (k_{i+1} - k_i) \quad (1)$$

The ranges of spectra traditionally used for oil analysis [50,51] are shown in Table 2.

Table 2. Areas of the main analyzed regions of the IR spectrum of oil (created by the authors).

Name of the Area	Range, [cm ⁻¹]
Physical background (scattering)	400...650
Rocking vibrations of CH ₂	710...730
Symmetric bending of CH ₃	1355...1395
Deformation vibrations of CH ₃ /CH ₂	1440...1480
Deformation vibrations of H-O-H	1620...1680
Carbonyl stretching vibration C=O	1700...1750
Asymmetric stretching vibrations of CO ₂	2320...2380
Asymmetric stretching vibrations of CH ₃	2950...2970

To quantify the spectra and eliminate the influence of random variations in the thickness of the oil layer in the cell, as well as density fluctuations, a normalization system based

on internal standards was used [52]. The choice of standard was made depending on the range of analyzed band:

- The band characterizing the total hydrocarbon content $S_{[1440;1480]}$ was used as a reference for indices located in the mid-frequency range.
- The most intense band $S_{[2910;2930]}$ was used to characterize physical effects and is located in the high-frequency region, which minimizes instrumental error and ensures the comparability of results.

Indexes were calculated using Equations (2)–(9).

1. I_{H_2O} —quantitative assessment of the relative water content:

$$I_{H_2O} = \frac{S_{[1620;1680]}}{S_{[1440;1480]}}. \quad (2)$$

2. I_{par} —estimation of the relative content of long paraffin chains [53]:

$$I_{par} = \frac{S_{[710;730]}}{S_{[1440;1480]}}. \quad (3)$$

3. I_{arom} —assessment of the relative content of aromatic structures:

$$I_{arom} = \frac{S_{[1580;1620]}}{S_{[1440;1480]}}. \quad (4)$$

4. I_{gas} —monitoring of dissolved CO₂ dynamics:

$$I_{gas} = \frac{S_{[2320;2380]}}{S_{[2910;2930]}}. \quad (5)$$

5. I_{foc} —a structural parameter characterizing both the degree of branching of hydrocarbons and the susceptibility of the carbon skeleton to degradation [53]:

$$I_{foc} = \frac{S_{[1365;1385]}}{S_{[1440;1480]}}. \quad (6)$$

6. I_{trs} —a measure of the scattering of the IR radiation by micro-uniformities. To avoid mutual overlap with the band I_{par} , the scattering range has been redefined. Instead of a continuous area of 400–900 cm^{−1}, a region of 400–650 cm^{−1} was used, which ensures spectral independence of this index:

$$I_{trs} = \frac{S_{[400;650]}}{S_{[2910;2930]}}. \quad (7)$$

7. I_{CH_3/CH_2} is the branching coefficient, reflecting the ratio of asymmetric stretching vibrations of methyl and methylene groups [54]. The stability of this index confirms the preservation of the average molecular weight and the absence of cracking processes:

$$I_{CH_3/CH_2} = \frac{S_{[2950;2970]}}{S_{[2910;2930]}}. \quad (8)$$

8. $I_{C=O}$ is an analytical marker of thermo-oxidative degradation processes [55]:

$$I_{C=O} = \frac{S_{[1700;1750]}}{S_{[1440;1480]}}. \quad (9)$$

To assess the interrelationships between the studied processes, the Pearson linear correlation coefficient was used. It was calculated using Formula (10).

$$r = \frac{\sum_{i=1}^n (I_{xi} - \bar{I}_x) \cdot (I_{yi} - \bar{I}_y)}{\sqrt{\sum_{i=1}^n (I_{xi} - \bar{I}_x)^2 \cdot \sum_{i=1}^n (I_{yi} - \bar{I}_y)^2}}. \quad (10)$$

With the sample size of $n = 7$ and the number of degrees of freedom of $df = n - 2 = 5$, the critical value of the correlation coefficient for a significance level of $\alpha = 0.05$ is 0.754. The correlation was considered to be statistically significant under condition $|r| > 0.754$.

Statistical verification of the significance of changes in indices and coefficients was carried out in the following sequence:

1. Calculation of the arithmetic mean $\bar{I}_x$:

$$\bar{I}_x = \frac{\sum I_{xi}}{n}. \quad (11)$$

2. Calculation of standard deviation SD :

$$SD = \sqrt{\frac{\sum (I_{xi} - \bar{I}_x)^2}{n - 1}}. \quad (12)$$

3. Determination of the coefficient of variation RSD :

$$RSD = \frac{SD}{\bar{I}_x} \cdot 100\%. \quad (13)$$

4. Calculation of the confidence interval with a 95% confidence probability:

$$CI = \bar{I}_x \pm t_{0.05;6} \cdot \frac{SD}{\sqrt{n}}. \quad (14)$$

The critical value of Student's t -test was selected depending on the sample size. For $n = 7$ ($t_{0.05;6} = 2.447$) and for $n = 5$ ($t_{0.05;4} = 2.776$).

3. Results

To ensure the statistical reliability of the data obtained, experimental studies were conducted three times. Measurements of the characteristics $\mu(\tau)$ and $\tau(t)$ showed high reproducibility of the results. The IR spectroscopic data demonstrate the identity of qualitative trends and patterns of structural restructuring of oil under the US exposure in all series of experiments. Slight variability in the absolute values of calculated indices is due to natural heterogeneity of crude oil and inhomogeneity of aliquots, which is typical when working with highly viscous emulsion systems. However, the general nature of spectral changes remains confirming the reproducibility of physico-chemical effects established.

3.1. The Results of Measuring the Dependencies $\mu(\tau)$ and $\tau(t)$

Figure 2a shows the dependence of the temperature of the oil samples on the US treatment time. For the sample 1, a monotonic decrease in heating rate is observed as exposure duration increases. Physically, this dynamic is due to the fact that initial paraffin oil with moderate resin–asphaltenic component content has an insufficiently developed network structure capable of undergoing radical restructuring during heating. At the initial time, the absorption coefficient for the US energy is the maximum, but as temperature increases, viscosity of medium decreases and dissipative losses of acoustic wave energy decrease. As a result, efficiency of conversion of the US energy into heat energy gradually decreases, manifested by consistent decrease in temperature increase.

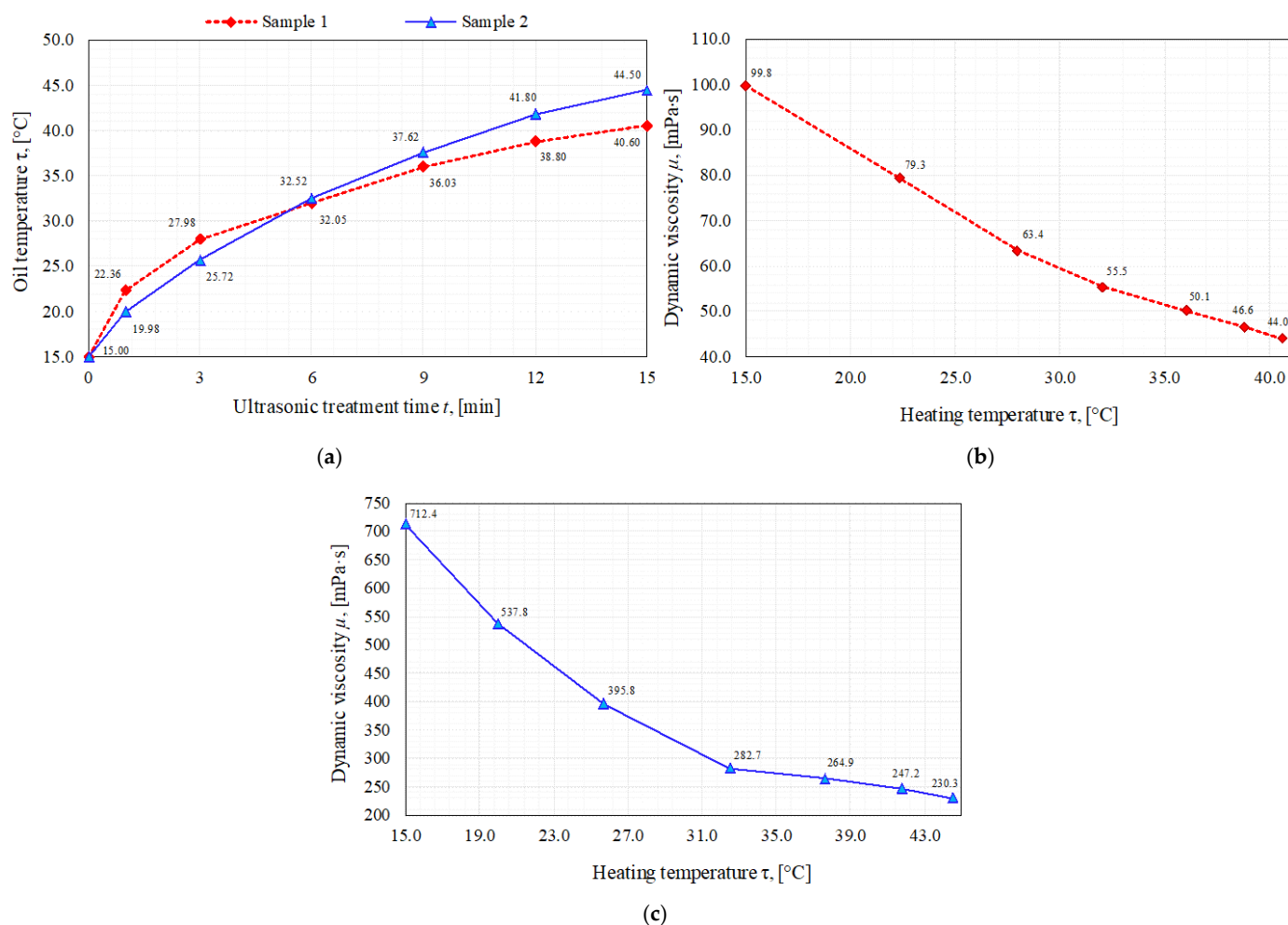


Figure 2. Results of the second stage of the experiment: (a) $\tau(t)$ of the samples 1 and 2; (b) $\mu(\tau)$ of the sample 1; (c) $\mu(\tau)$ of the sample 2 (created by the authors).

The sample 2 shows a continuous rise in temperature during the US treatment, with the heating rate gradually decreasing over time. From 0 to 6 min, the cumulative increase in temperature indicates an active interaction between the US effect and the heterogeneous oil medium.

Initially, the high-viscosity and concentration of asphaltenes, resins, and paraffins form a stable network that limits the movement of the medium and inhibits the propagation of sound waves. As the sample is heated, these structures partially soften and break down, reducing viscosity and dissipative losses. This allows the temperature to continue rising, but at a slower rate. After 6 min of treatment, the rate of temperature increase becomes more gradual, which may be attributed to partial depletion of the potential for structural transformation and transition of the system into a state where further heating is primarily determined by changes in the US absorption coefficient of the medium.

Thus, the observed temperature behavior is related to the composition and structural organization of the oil. The sample 2 has a more pronounced asphaltene–resinous structural network than sample 1, and the initial treatment period corresponds to the stage of partial destruction of this framework. At the later stage of the US treatment, the heating behavior of the sample 2 becomes closer to that of the sample 1, which is reflected in a similar tendency toward a decreasing interval heating rate.

It should also be noted that, in modern studies of the US oil treatment, the ambiguity of the influence of acoustic effects on the viscous properties of the medium has been noted [42–44]. A number of authors have recorded an effect of increasing viscosity during

intensification of treatment regimes, which is associated with processes of radical polymerization or secondary flocculation of asphaltenes due to the insufficient stability of dispersed systems. In contrast, results from the obtained characteristics $\mu(\tau)$ of the samples 1 and 2, shown in Figure 2b,c, demonstrate the effectiveness of selected US treatment mode in reducing viscosity.

3.2. The Results of the IR Analysis

During the second stage of the experiment, a comparative study was carried out on two methods of preparing viscous oil samples: continuous US treatment and isothermal heating without acoustic exposure. Both methods were implemented in identical temperature ranges: (15.00–40.60 °C) and (15–44.5 °C), respectively, for the samples 1 and 2.

3.2.1. Initial State of the Samples

The analysis of the spectra revealed a difference in the structural organization of the oils. The sample 1 has a low heterogeneous structure, with no absorption bands in the regions of 1620–1680 cm^{-1} and 3200–3600 cm^{-1} , corresponding to water fluctuations. It also has a low level of light scattering. The sample 2, on the other hand, shows a high degree of waterlogging, with increased scattering levels, indicating the presence of well-developed supramolecular asphaltene–resinous systems and emulsified water.

3.2.2. The IR Spectroscopy Results for the Sample 1

The results of the analysis of the sample 1, presented in Table 3, demonstrate high chemical stability of the hydrocarbon composition. The structural indices I_{foc} , $I_{\text{CH}_3/\text{CH}_2}$, I_{par} and I_{arom} remain constant throughout the entire 15 min cycle, which is confirmed by finding values within confidence intervals. The dehydration of the sample is confirmed by the absence of index $I_{\text{H}_2\text{O}}$ variability.

Table 3. Analysis of the IR spectrogram of the sample 1 (created by the authors).

Index	0 min 15.00 °C	1 min 22.36 °C	3 min 27.98 °C	6 min 32.05 °C	9 min 36.03 °C	12 min 38.80 °C	15 min 40.60 °C	SD	RSD, [%]	CI _{95%}
$I_{\text{H}_2\text{O}}$	0.0721	0.0680 0.0718	0.0685 0.0714	0.0720 0.0677	0.0677 0.0681	0.0682 0.0694	0.0685 0.0688	0.00191 0.00184	2.76 2.63	[0.0675;0.0711] [0.0682;0.0716]
I_{par}	0.1580	0.1588 0.1574	0.1568 0.1566	0.1593 0.1560	0.1575 0.1604	0.1571 0.1596	0.1571 0.1575	0.00095 0.00157	0.60 1.00	[0.1569;0.1587] [0.1565;0.1594]
I_{arom}	0.0461	0.0459 0.0458	0.0477 0.0465	0.0456 0.0427	0.0474 0.0446	0.0474 0.0458	0.0472 0.0466	0.00086 0.00138	1.84 3.03	[0.0460;0.0476] [0.0442;0.0467]
I_{gas}	0.0149	0.1030 0.0184	0.4225 0.1029	0.0000 0.1039	0.0000 0.0385	0.0000 0.0368	0.0000 0.0000	—	—	Completed Completed
I_{foc}	0.5980	0.5949 0.6004	0.5955 0.6010	0.5970 0.5991	0.5991 0.5959	0.5982 0.5959	0.5985 0.5955	0.00159 0.00227	0.27 0.38	[0.5958;0.5988] [0.5959;0.6001]
I_{trs}	0.3204	0.2830 0.3548	0.2302 0.3941	0.1910 0.2361	0.1858 0.2094	0.1833 0.1971	0.1845 0.1902	—42.01% —34.64% (changes 0→9 min)	—	—42.42% —40.64% (changes 0→15 min)
$I_{\text{CH}_3/\text{CH}_2}$	0.4547	0.4518 0.4540	0.4526 0.4503	0.4509 0.4529	0.4474 0.4501	0.4551 0.4522	0.4512 0.4517	0.0026 0.0017	0.58 0.38	[0.4496;0.4544] [0.4507;0.4539]
$I_{\text{C=O}}$	0.04132	0.04104 0.04000	0.04030 0.03927	0.04049 0.04177	0.04099 0.03964	0.04013 0.04070	0.03824 0.03958	0.00103 0.00095	2.55 2.37	[0.03941;0.04131] [0.03944;0.04121]

The data in Table 3 is presented in the following format: numerator—US treatment; denominator—isothermal heating.

The dynamics of the indicators I_{trs} and I_{gas} also indicate that the US exposure is a highly effective tool for physical modification, providing intensive degassing and reducing the heterogeneity of the medium. Comparison with isothermal control shows that the US

treatment surpasses heating in terms of the depth of structural changes and the rate of degassing, reaching the maximum degree of dispersion by the ninth minute.

The observed low variability of the index $I_{C=O}$ confirms the absence of thermal oxidative degradation. The data obtained proves that US energy is spent solely on physical restructuring of the supramolecular structure and degassing, without initiating chemical oxidation reactions.

In Figure 3, the decrease in intensity in the range of $400\text{--}650\text{ cm}^{-1}$ observed at the 9th minute of the US treatment is due to a decrease in the contribution of light scattering caused by the effective destruction of large supramolecular aggregates. Fluctuations in intensity were observed in the range of $3600\text{--}4000\text{ cm}^{-1}$ at 9 min, and they are related both to limited sensitivity of detector in high-frequency range and dynamic optical effects from intense Brownian motion of ultrafine particles formed during treatment [56]. However, this effect does not impact the quality of the decoding of the IR results, as this area is not sufficiently informative. After 6 min of treatment, fluctuations were also observed, but none were seen during isothermal heating.

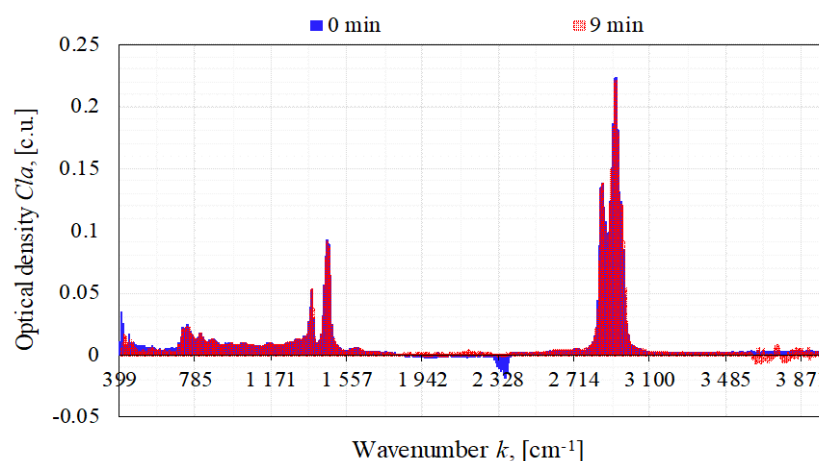


Figure 3. The IR spectra of the oil sample 1 before and after 9 min of the US treatment at sampling points 1 and 2 (created by the authors).

3.2.3. The IR Spectroscopy Results for the Sample 2

According to the processing results presented in Table 4, it can be concluded that the optimal time for the US preparation of the oil sample 2 for the IR analysis is 9 min. The IR spectrograms of the sample 2 before and after 9 min of the US treatment are shown in Figure 4. Unlike the sample 1, this sample demonstrates high dynamism in structural transformations, which is confirmed by significant variability in spectral indices, as reflected in Table 4.

By the 9th minute of the US treatment, the scattering index decreased by 92.83%. This is interpreted as a significant decrease in the level of structural heterogeneity of the medium. The dynamics of this index correlate with the processes of disaggregation of inhomogeneities into micro-sized particles. After 9 min of the US treatment, regular interference oscillations are observed in the high frequency range of $3500\text{--}4000\text{ cm}^{-1}$. According to physical scattering models, the transition from large supramolecular aggregates to ultrafine microparticles leads to changes in the nature of interaction between the IR radiation and the sample. Even minor fluctuations in density and intense Brownian motion cause optical interference, recorded as baseline oscillations in the high-frequency region.

Comparative analysis shows that isothermal heating at an identical temperature provides a decrease in the index by only 49.04%. This is due to thermal decrease in viscosity without destroying the structure of associates. At the same time, the US cavitation caused

by shock waves and microjets leads to irreversible mechanical destruction of asphaltenes, resins and paraffins, providing the most effective reduction in structural heterogeneity in the oil sample.

Table 4. Analysis of the IR spectrogram of the sample 2 (created by the authors).

Index	0 min 15.00 °C	1 min 19.98 °C	3 min 25.72 °C	6 min 32.52 °C	9 min 37.62 °C	12 min 41.80 °C	15 min 44.50 °C	Changes 0 → 9 min 15 → 37.62 °C	Changes 0 → 15 min 15 → 44.50 °C
I_{H_2O}	0.5119	$\frac{0.5363}{0.5633}$	$\frac{0.4388}{0.6110}$	$\frac{0.3322}{0.5583}$	$\frac{0.0697}{0.2102}$	$\frac{0.0702}{0.1502}$	$\frac{0.0692}{0.1252}$	$\frac{-86.38\%}{-58.94\%}$	$\frac{-86.48\%}{-75.54\%}$
I_{par}	0.8458	$\frac{0.8082}{0.8890}$	$\frac{0.8348}{0.9577}$	$\frac{0.5947}{0.9110}$	$\frac{0.1581}{0.6216}$	$\frac{0.1577}{0.4416}$	$\frac{0.1622}{0.3144}$	$\frac{-81.31\%}{-26.51\%}$	$\frac{-80.82\%}{-62.83\%}$
I_{arom}	0.1575	$\frac{0.1633}{0.1695}$	$\frac{0.1416}{0.1797}$	$\frac{0.1158}{0.1674}$	$\frac{0.0687}{0.1258}$	$\frac{0.0693}{0.1011}$	$\frac{0.0684}{0.0955}$	$\frac{-56.38\%}{-20.13\%}$	$\frac{-56.57\%}{-39.37\%}$
I_{gas}	0.0000	$\frac{0.3269}{0.0084}$	$\frac{0.2937}{0.0911}$	$\frac{0.0586}{0.2896}$	$\frac{0.0000}{0.0896}$	$\frac{0.0000}{0.0506}$	$\frac{0.1244}{0.0416}$	Completed Not completed	New cycle Not completed
I_{foc}	0.7446	$\frac{0.7468}{0.7415}$	$\frac{0.7238}{0.7515}$	$\frac{0.7187}{0.7465}$	$\frac{0.7122}{0.7290}$	$\frac{0.7144}{0.7210}$	$\frac{0.7138}{0.7192}$	$\frac{-4.35\%}{-2.10\%}$	$\frac{-4.14\%}{-2.10\%}$
I_{trs}	8.0422	$\frac{8.1512}{8.3211}$	$\frac{7.5939}{9.1290}$	$\frac{5.5415}{8.7428}$	$\frac{0.5769}{4.0983}$	$\frac{0.5739}{2.2888}$	$\frac{0.5855}{1.4925}$	$\frac{-92.83\%}{-49.04\%}$	$\frac{-92.72\%}{-81.44\%}$
I_{CH_3/CH_2}	0.4970	$\frac{0.5011}{0.4955}$	$\frac{0.5045}{0.5014}$	$\frac{0.4977}{0.5033}$	$\frac{0.4969}{0.4961}$	$\frac{0.5059}{0.5022}$	$\frac{0.5182}{0.4998}$	$\frac{[0.4953;0.5035]}{[0.4944;0.5030]}$	$\frac{[0.4960;0.5100]}{[0.4964;0.5022]}$
$I_{C=O}$	—	—	—	—	$\frac{0.04518}{-}$	$\frac{0.04525}{-}$	$\frac{0.04771}{-}$	SD = 0.0014, RSD = 3.13%, CI = [0.04524;0.04696]	

The data in Table 4 is presented in the following format: numerator—US treatment; denominator—isothermal heating.

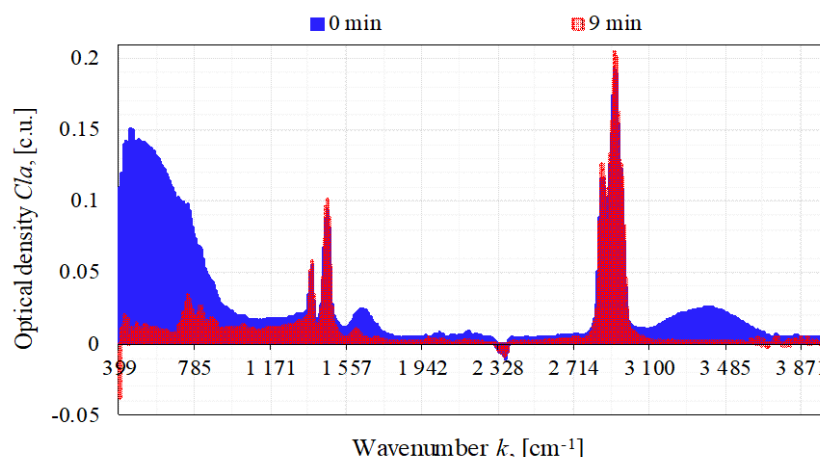


Figure 4. The IR spectra of the oil sample 2 before and after 9 min of the US treatment at sampling points 1 and 2 (created by the authors).

The mechanism of disaggregation of supramolecular structures is most clearly illustrated by the dynamics of indicators I_{par} and I_{arom} . The initial high values of these indices indicate that a significant part of aliphatic and aromatic fragments are present in the composition of supramolecules or are masked by an aqueous emulsion phase. A decrease in I_{par} by 81.31% and I_{arom} by 56.38% during the US treatment indicates the unmasking of the components. The physico-chemical mechanism of this phenomenon consists of cavitation overcoming the intermolecular Van der Waals forces that hold the components together and sedimentation of water. As a result, the effect of masking analytical bands is eliminated and the actual intensity of absorption by these groups can be registered. Thus, a decrease in indices by 9–15 min during processing reflects the transition to a state where the measured values correspond to the true chemical composition of oil, not distorted by supramolecular structures.

The dynamics of the index I_{gas} , with an increase at the first minute and a subsequent decrease to zero by the sixth minute, confirms the effectiveness of cavitation degassing. When cavitation bubbles collapse, dissolved CO_2 passes into the gas phase, coalescing and being removed from the sample volume. With isothermal heating, the degassing process proceeds monotonically and much more slowly, not reaching completion by the end of the experiment.

The 86.38% decrease in the index $I_{\text{H}_2\text{O}}$ is due to the destruction of adsorption–solvate layers of asphaltenes and resins, which form strong shells around water droplets. The US cavitation generates sufficient shear stresses to destroy these shells, promoting coalescence and sedimentation of the aqueous phase. A slight increase in the US treatment in the first minute is probably due to the initial release of water droplets from their encapsulated state into larger aggregates, which increases their concentration in the measuring area. Under isothermal conditions, the value of $I_{\text{H}_2\text{O}}$ is higher because there is less effective coalescence of the water droplets due to the absence of acoustic microflows. This effect is confirmed by the results of aliquot analysis at sampling point 3, as shown in Figure 5, where there is an increase in free aqueous phase volume as the time of the US treatment increases.

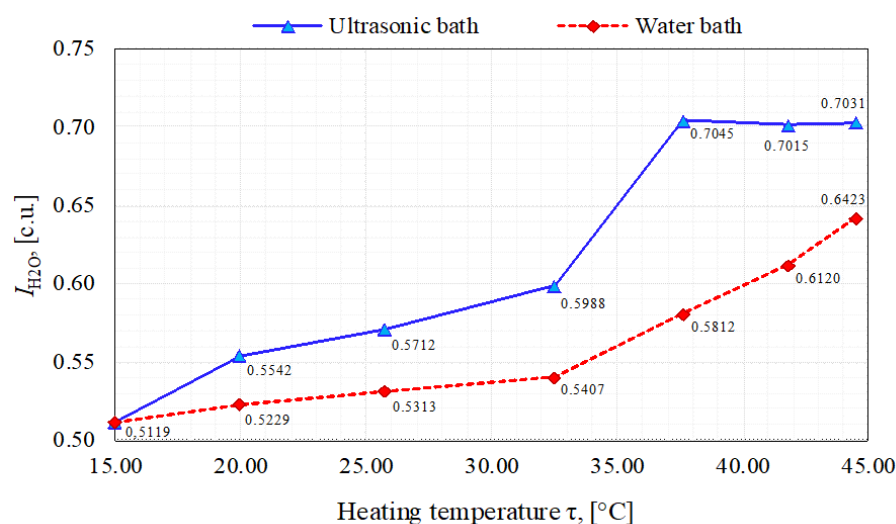


Figure 5. The graph of the dependence of $I_{\text{H}_2\text{O}}$ on the heating temperature τ at the sampling point 3 under the US and isothermal conditions for the sample 2 (created by the authors).

3.2.4. The Main Causes of Noise and Their Elimination Mechanisms

The main causes of noise include:

1. The effect of the sample heterogeneity on the spectral pattern. The presence of water and supramolecular aggregates leads to intense light scattering, distorting the baseline. As a result, there is an overestimation of the intensity of the bands in the areas 695, 720, 744, 812, 1600, and 3030 cm^{-1} , and signal suppression in areas 2852, 2922 and 2950 cm^{-1} , as well as a mixed effect in areas of 1375 and 1456 cm^{-1} . The distortion of spectral density in these ranges makes it difficult to accurately interpret the composition.

The dehydration process takes place in two stages: initial release of water within 1 min of treatment, followed by sedimentation, which intensifies by the 6th minute. Complete deposition of the aqueous phase in the US-treated sample is achieved by the 9th minute, as confirmed by a plateau in the dependence $I_{\text{H}_2\text{O}}(\tau)$ in the range 9–15 min (Figure 5 and Table 4). High positive correlation fundamentally proves that emulsified water is the main cause of optical heterogeneity in oil, rather than other components. Unlike US, isothermal heating does not completely remove water from sampling zones, confirming the superior

efficacy of acoustic exposure. The isothermal heating experiment was chosen as the primary control for this study, as the aim was to isolate the cavitation-induced effect of the US from any thermal effects.

2. Degassing. The dynamics of the index I_{gas} are characterized by a sharp increase in the first minute of the US treatment, reflecting the cavitation-induced release of dissolved CO_2 . Under conditions of the US exposure, the correlation between indices I_{gas} and I_{trs} reaches 0.864, which allows to conclude that the active degassing process is associated with destruction of structures. With isothermal heating, degassing proceeds slowly and chaotically, without correlation. As a result, there is no statistically significant relationship between indices I_{gas} and I_{trs} . Thus, bubbles contribute little to scattering, since water makes the main contribution, followed by aggregates.

To summarize, the main observed changes in the samples are due to three physical processes: dehydration, disaggregation of supramolecular structures, and degassing. The results of the Pearson correlation analysis presented in Table 5 confirm the proposed physical model and allow us to quantify the relationship between these processes.

Table 5. Pearson pair correlation coefficients for the indices of the sample 2 (created by the authors).

Correlation	US Treatment	Isothermal Heating
$r(I_{H_2O}, I_{trs})$	+0.995	+0.991
$r(I_{gas}, I_{trs})$	+0.864	+0.229
$r(I_{par}, I_{arom})$	+0.988	+0.992
$r(I_{H_2O}, I_{arom})$	+0.999	+0.986
$r(I_{H_2O}, I_{par})$	+0.998	+0.998

Figure 6 visualizes the structure of oil aliquots from the sample 2, taken from sampling points 1 and 2 before and after the US exposure.

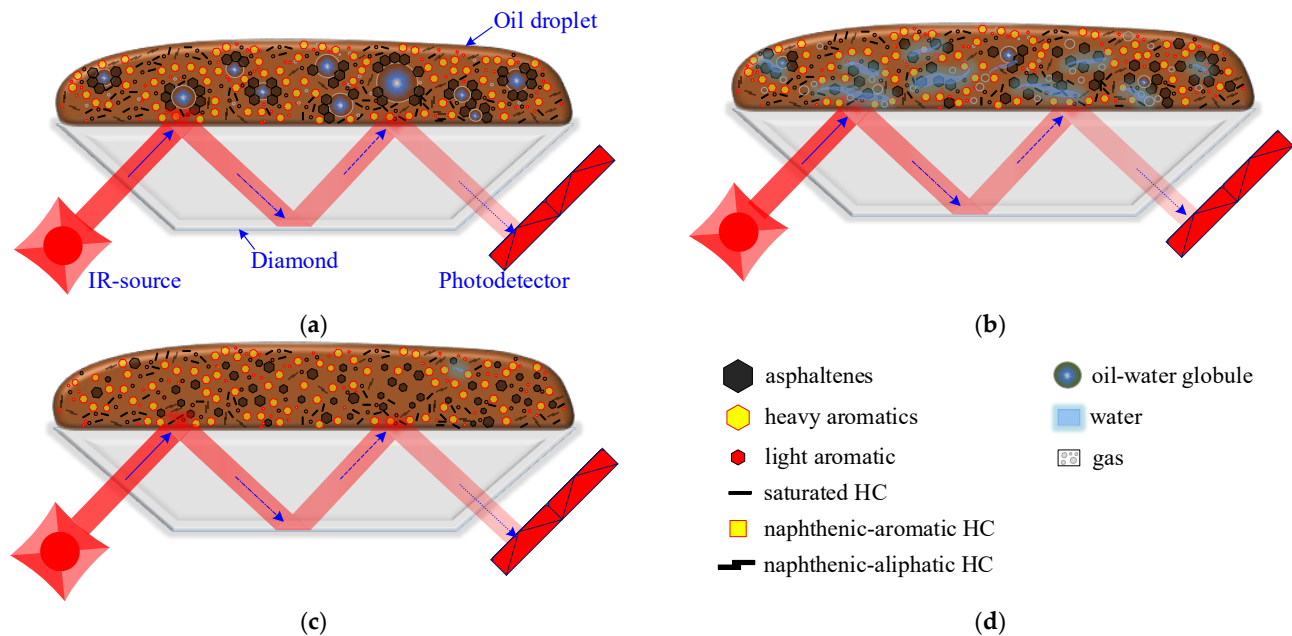


Figure 6. Visualization of the results of the IR spectroscopy of the oil sample 2, depending on the duration of the US sample preparation: (a) the initial sample; (b) after 1 min of the US exposure; (c) after 9 min of the US exposure; (d) decoding of symbols (created by the authors).

3.3. The Results of Microscopic Analysis of Oil Samples

Microscopic analysis was performed to visualize structural changes and verify the mechanisms of homogenization identified during spectral data processing. The results of the microscopic examination of the samples 1 and 2 before and after the US treatment are shown in Figure 7.

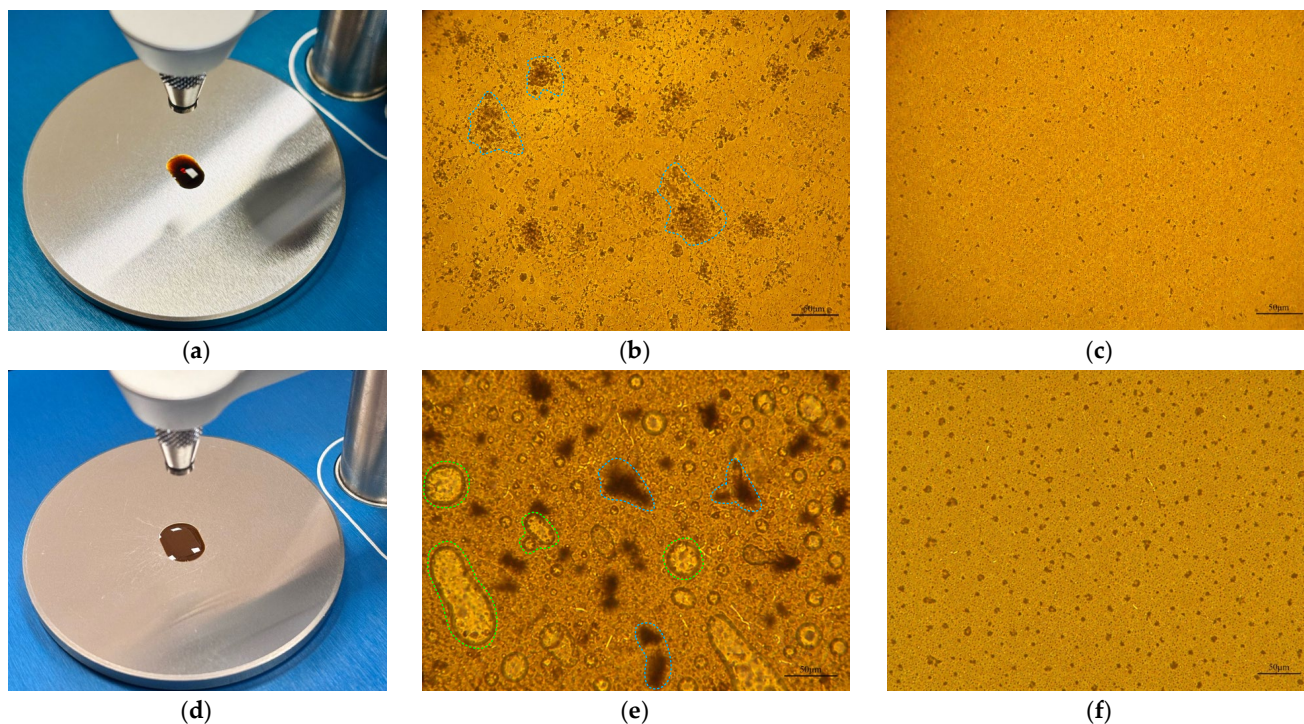


Figure 7. Microscopic analysis of the oil samples: (a,d) the appearance of the oil samples 1 and 2 on the Quest set-top box of the IR spectrometer, respectively; (b,e) the condition of the oil samples 1 and 2 before the US processing; (c,f) the condition of the oil samples 1 and 2 after 9 min of the US processing (created by the authors).

In Figure 7b, the oil sample 1 is characterized by moderate heterogeneity, expressed as a continuous oil medium with accumulations of loose asphaltene–resinous aggregates, outlined by a blue dashed line. In Figure 7e, the oil sample 2 has a significantly higher density of components before the US processing. In this sample, an emulsion is formed, where resin–asphaltene aggregates and droplets of the aqueous phase are outlined by blue and green dashed lines, respectively. These water aggregates form a stable system, which causes intense light scattering. This is recorded in the IR spectra as background noise. Due to the multiphase nature and significant difference in refractive indices between the components, it was difficult to focus simultaneously on asphaltenes and water droplets due to the limited depth of field of the microscope.

After 9 min of the US treatment, the observed changes indicate a deep structural restructuring. In Figure 7c, the sample 1 demonstrates the almost complete destruction of large bonding structures and the transition of oil to a state of highly dispersed suspension. In Figure 7f, after the US treatment, sample 2 also shows a decrease in the number of large tar–asphaltene spots, as well as the absence of water droplets. This is consistent with the data in Table 4 and the lack of extremes in the range $3100\text{--}3600\text{ cm}^{-1}$. However, unlike the sample 1, the background of the sample 2 retains a lower optical transparency, and the dispersed particles have slightly larger sizes. This effect is explained by the higher initial viscosity and saturation of the sample 2 with high-molecular components, which makes it

difficult to achieve the same degree of dispersion as in less viscous sample 1, despite the identical mode of the US exposure.

3.4. The Effect of the US on Changes in the Chemical Composition of the Oil Samples

To confirm the absence of destructive processes, an analysis of structural coefficients $I_{\text{CH}_3/\text{CH}_2}$, I_{foc} and $I_{\text{C=O}}$ was carried out.

Statistical processing of the sample 1 data (Table 3) demonstrates high precision of measurements. The coefficient values $I_{\text{CH}_3/\text{CH}_2}$ and I_{foc} lie within narrow confidence intervals at low values of *SD* and *RSD*. This indicates the structural stability of the hydrocarbon matrix. Chemical inertia of the process is confirmed by the absence of significant absorption bands in the areas 1700–1750 and 3200–3500 cm^{-1} , responsible for oxidation products. Moreover, the lack of a shift in the baseline and absorption bands in the central part of the 700–3000 cm^{-1} spectrum confirms that dispersion and degassing processes occur without any chemical transformation of the hydrocarbon skeleton. This correlates with high stability of calculated structural indices.

The sample 2 (Table 4), characterized by increased viscosity and emulsification, demonstrates a more dynamic response of spectral parameters compared to the sample 1. The index I_{foc} shows moderate variability—a decrease of 4.35%, which is not chemical but opto-physical in nature. This fact arises because this index represents the ratio of the intensities of the 1375 cm^{-1} and 1456 cm^{-1} bands. The 1375 cm^{-1} band exhibits increased sensitivity to baseline distortions caused by light scattering at micro-uniformities, whereas the 1455 cm^{-1} band has a higher intensity and remains more stable because it reflects all hydrocarbon fragments. Therefore, the observed variability is a consequence of optical instability of the sample within the range of 0–6 min of the US treatment, rather than destruction of the carbon skeleton.

Methodologically, it is important to emphasize that the high viscosity of the sample 2 provides a damping effect. The high viscosity limits the amplitude of cavitation microflows and prevents local overheating, which could initiate cracking or polymerization [57–59]. Since no changes in the indices were observed in reference the sample 1 during similar treatment, it can be argued that, in the sample 2, the probability of chemical modification of molecules is a priori excluded.

Starting from the 9th minute of processing, the index value I_{foc} of the sample 2 stabilized. This stabilization correlated with a sharp decrease in the scattering index and the completion of the sedimentation process of the aqueous phase, indicating the transition of the system to a more optically transparent state.

Of particular interest is the behavior of the system during the 15th minute of the US exposure. Reaching the temperature threshold of 44.5 °C demonstrates the beginning of most likely chemical modifications. This temperature threshold is accompanied by a new degassing cycle, which is confirmed by an increase in the index I_{gas} . At the same time, the change in the index $I_{\text{CH}_3/\text{CH}_2}$ reflects restructuring of aliphatic chain conformation, which may indicate deep structural restructuring. Thus, for the sample 2, the US treatment for 12–15 min is the limit for reducing US heterogeneity in the oil medium.

It is impossible to estimate the dynamics of the index $I_{\text{C=O}}$ of the sample 2 in the 0–9 min of the US treatment interval due to the high noise level caused by light scattering on water and supramolecular aggregates. The variability of the index $I_{\text{C=O}}$ stabilizes over a time interval of 9–12 min of processing and increases by the 15th minute. An increase in the index $I_{\text{C=O}}$ at 15 min of the US treatment may indicate processes associated with cavitation-induced cracking. However, this requires additional confirmation.

4. Discussion

A comprehensive analysis of the IR spectroscopic data obtained (Tables 3 and 4), in combination with microscopic studies (Figure 7), allows us to build a model for the transformation of the oil samples under the US treatment. It has been found that the US sample preparation is an effective tool for reducing oil heterogeneity, outperforming traditional isothermal heating method. The use of heat alone is not enough to effectively reduce structural heterogeneity in a highly viscous, water-saturated oil sample.

The analysis of the structural indices I_{foc} , I_{par} , I_{arom} and I_{trs} indicates that the US energy is consumed exclusively for the physical destruction of supramolecular asphaltene–paraffin associates, with a duration of the US treatment ranging from 0 to 15 min for the sample 1 and from 0 to 12 min for the sample 2. The stability of these indicators and the absence of an increase in the carbonyl group index $I_{\text{C=O}}$ confirms that the selected treatment mode, with the intensity of 0.12 W/mL, is below the threshold for chemical destruction of the hydrocarbon skeleton. High viscosity acts as a damping factor in this case, limiting the amplitude of cavitation microflows and preventing the development of polymerization or cracking reactions, which are often described in the literature as side effects of excess energy exposure to US.

The physical mechanism of reducing the heterogeneity of the sample 2 is confirmed by correlation analysis data (Table 5). The high degree of correlation between the indices $I_{\text{H}_2\text{O}}$ and I_{trs} proves that emulsified water and resin–asphaltene aggregates form a structurally complex system that acts as the main center of light scattering during the IR spectroscopy. The US cavitation disrupts the adsorption–solvation shells holding the aqueous phase, triggering a sequence of processes leading to water release, coalescence and sedimentation. Thus, the increase in spectral information content is manifested primarily in the unmasking of diagnostic absorption extremes that were previously distorted by water-related absorption and scattering from large aggregates.

Visual microscopic analysis data (Figure 7) provides direct evidence of spectral patterns. The transition of the sample 2 from a heterogeneous emulsion state to a highly dispersed suspension correlates with a decrease in the indices $I_{\text{H}_2\text{O}}$ and I_{trs} , as well as the stabilization of the spectrum baseline. Thus, eliminating optical heterogeneity in the medium by mechanically destroying the emulsion structure of oil is a crucial condition for improving the reliability of interpreting the IR spectrograms.

The results obtained allow us to conclude that the US sample preparation effectively eliminates spectral distortions and the effects of masking analytical bands caused by the multiphase nature of the sample. This creates a technological basis for the introduction of the IR spectroscopy methods into the practice of operational oil quality control directly at the wellhead. The optimal time for the US treatment with an intensity of 0.12 W/mL for the samples 1 and 2 was 9 min.

The limitations of the proposed method include the risk of gravitational segregation of heavy asphaltene aggregates. Intensive decrease in viscosity initiated by US in the first minutes of the treatment contributes to disaggregation and release of asphaltenes complexes from the oil's structural framework. Due to significant difference in densities of these complexes and oil matrix, along with concomitant sedimentation of aqueous phase, heavy components tend to concentrate at bottom layers of the sample. This may lead to decrease in representativeness of selected aliquot. The second aspect is the stochastic nature of cavitation. The behavior of cavitation bubbles is characterized by high randomness [60], which makes it difficult to maintain a stable exposure regime throughout the entire treatment cycle. A promising solution to this problem is hybrid system control of both oil properties and the sample preparation process based on machine learning methods [61]. In particular, the use of neural network algorithms for optical image analysis will allow real-time tracking

of bubble size distribution and frequency of their generation [62], providing feedback to maintain optimal power of the US transducers.

4.1. Practical Implementation and Significance of the Results

The proposed method of the US sample preparation in combination with the IR spectroscopy makes it possible to implement dynamic, express control of the physico-chemical properties of highly viscous oil directly at production facilities. Dissimilar existing laboratory methods, which often require the use of toxic organochlorine and organosulfide solvents [63,64], the US dispersion technique is more environmentally friendly and preserves the chemical integrity of hydrocarbons. Introducing this technology into portable analytical systems eliminates logistical delays common in remote areas and brings oil quality management to real-time operational monitoring.

4.1.1. Practical Significance

The proposed approach makes it possible to solve a wide range of geological and technological problems.

1. Geological and technological support for field development. Operational monitoring of the physical and chemical properties of oil at the wellhead allows refining the geological structure and filter capacity parameters of production facilities. It also assists with assessing current reserves of remaining oil and continuously monitors the effectiveness of current geological and technical measures.
2. Technological safety during transportation. The use of the IR analysis with preliminary US sample preparation provides reliable monitoring of critical parameters such as paraffin content, water content, nitrogen and sulfur content. This allows for timely selection of transportation methods and dosage of depressant additives to minimize the risks of gel formation, paraffin deposition, and corrosion.
3. Analysis of multiphase flows. This method is promising for estimating the oil–water–gas ratio in the production of highly watered wells. Since the US exposure provides forced separation of the three-phase flow, this opens up the possibility of creating automated control systems for controlling the oil/water/gas ratios.

4.1.2. Portable IR Spectrometer with the US Pretreatment for the Oil Analysis

To implement the proposed rapid analysis method, a mobile system was designed to provide automated sampling, the US preparation, and the IR spectroscopic monitoring of oil directly at production facilities. The design of the device and the technological schemes for its interface with oil and gas equipment are shown in Figure 8.

The principle of operation of the mobile system is based on automated sampling and subsequent US processing aimed at degassing, dehydrating and disaggregating asphaltene–paraffin associations. A key element of the technological cycle is the mode of multiple sample recirculation through the US bath, which allows for increasing the cumulative dose of the US exposure. For highly viscous oils, a single treatment may not be sufficient to completely disaggregate. The recirculating unit creates the necessary conditions for the destruction of the mechanically strong supramolecular shells and the effective coalescence of the emulsified water.

The US exposure, minimizing light scattering, ensures the transition of the system to a state with increased optical transparency, which creates conditions for high-precision photometric measurements in a flow cell made of lyophobic material with adjustable wall gap. The hardware and software complex automatically control the cycles of measurement, data collection, sample recycling, and final cleaning of the system. This architecture ensures

autonomous operation and high reproducibility of analytical results during operation directly at the wellhead or during pumping through a pipeline.

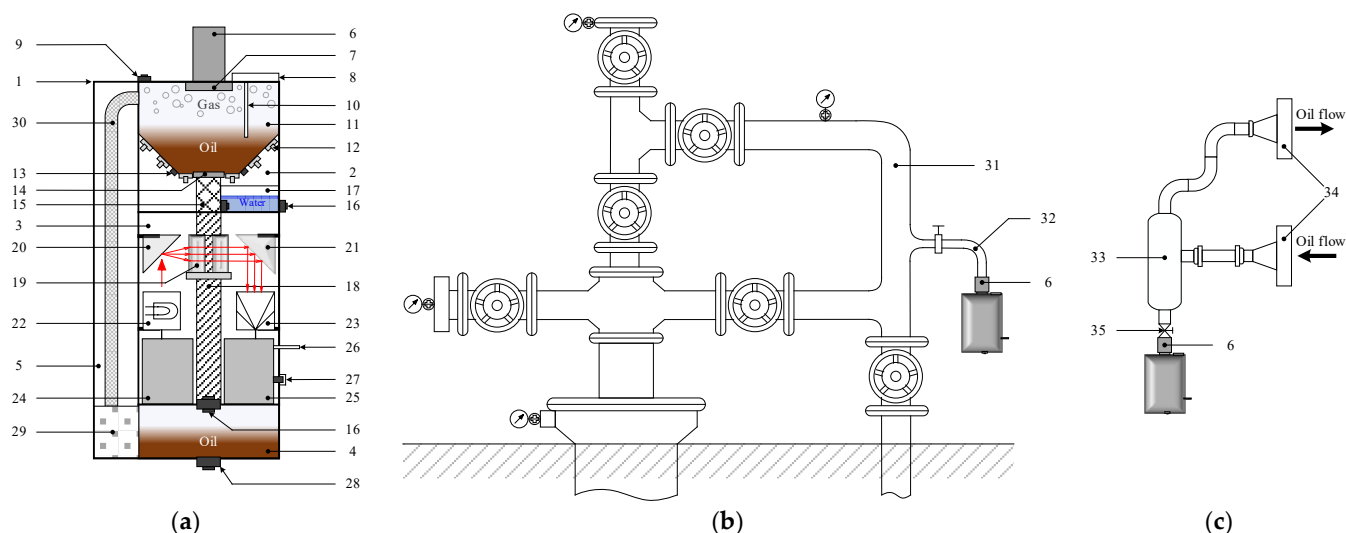


Figure 8. Design and connection diagrams for the mobile system: (a) internal device; (b) connection diagram to fountain fittings; (c) connection diagram to the pipeline. 1—case, 2—receiving unit, 3—measuring unit, 4—drain unit, 5—recirculation unit, 6—clutch, 7—ball valve, 8—control module, 9—gas valve, 10—level gauge, 11—bath, 12—US transducer (6 pcs), 13—temperature control sensor (2 pcs), 14—disk shutter, 15—water absorber, 16—valve assembly (3 pcs), 17—water chamber, 18—oil drain tube, 19—mechanically driven sample holder, 20—monochromator, 21—prism, 22—IR radiation source, 23—photometric sensor, 24—power source, 25—hardware and software module, 26—antenna, 27—charging port with cap, 28—drain valve, 29—pump, 30—flow channel, 31—fountain fittings, 32—sampling outlet, 33—sampling unit, 34—flange, 35—valve (created by the authors).

5. Conclusions

This study demonstrates that integrating a low-energy physical pretreatment step into IR spectroscopic analysis is an effective method for reducing optical heterogeneity in complex multiphase hydrocarbon systems. The paper substantiates and implements an approach for the preparation of the samples of high-viscosity oils for field IR spectroscopic analysis based on the use of US cavitation. It has been established that the US sample preparation is a necessary technological step that makes it possible to transform heterogeneous water–oil emulsions into more optically homogeneous media suitable for rapid analysis in the field conditions. Dissimilar traditional methods, the proposed method provides destruction of supramolecular associates and degassing without the risk of chemical destruction of the hydrocarbon skeleton, which is confirmed by high stability of structural spectral indices.

Although high-energy US may theoretically induce radical reactions, the regime used in this study was moderate: 40 kHz, 0.12 W/mL, and 9 min. No increase in the C=O index or instability of degradation-sensitive structural indices was observed; therefore, within the sensitivity of ATR-IR spectroscopy, no evidence of chemical degradation was detected. Trace radical effects below the IR detection limit may be considered in future studies. In addition, GC analysis may also be carried out.

The practical significance of the developed method is the increase in the information content and reliability of monitoring chemical properties of extracted products at wellheads. The integration of the US sample preparation unit into field analytical complexes will eliminate logistical distortions typical of laboratory analysis and create a reliable database for solving field development management tasks. In combination with chemometric algorithms for spectrum processing, the proposed technique forms the basis for intelligent

oil quality control systems capable of predicting the risks of paraffin deposition, selecting optimal modes of transportation and dosing of reagents in real time. This approach is a cost-effective solution that minimizes the risks of complications during oil production and transportation in hard-to-reach Arctic regions, ensuring industrial safety and operational control. It translates the process of assessing fluid properties from periodic laboratory audits to continuous analytical monitoring of field development. More generally, the proposed approach can be considered as a paradigm for combining physical field sample pretreatment with in situ spectral monitoring of optically heterogeneous fluids.

Further work will be focused on the expansion of the experimental base due to other types of oil—more highly paraffinic as well as bitumen. Combining the proposed approach with existing chemometric methods, neural network technologies and machine learning will create a reliable basis for predictive analysis and decision-making. This expands the potential application of the method beyond heavy oil analysis toward real-time process control of other heterogeneous liquid systems, including water–oil emulsions, drilling fluids, and industrial suspensions.

6. Patents

Mobile system for determining physico-chemical properties of oil. Available online: https://new.fips.ru/registers-doc-view/fips_servlet?DB=RUPAT&DocNumber=2858410&TypeFile=html (accessed on 25 April 2026).

Author Contributions: Conceptualization, V.F. and I.R.; methodology, V.F.; formal analysis, V.F.; validation, I.R. and V.F.; investigation, V.F. and F.C.; data curation, V.F.; writing—original draft preparation, V.F., I.R. and F.C.; supervision, I.R. and F.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

Acknowledgments: The authors express their gratitude to the V.P. Vologdin Center for Induction Technologies and New Materials for technical support during the research.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

IR	Infrared
GC	Gas chromatography
US	Ultrasound, ultrasonic

Nomenclature

The symbols used in the equations, formulas, indexes, parameters, and variables, are summarized in the following table:

Symbols	Description	Unit
CI	Confidence interval	c.u.
Cl_a	Optical density	c.u.
f	Ultrasound frequency	kHz

I_{arom}	Aromaticity index	c.u.
$I_{\text{CH}_3/\text{CH}_2}$	Methyl/methylene ratio index	c.u.
$I_{\text{C=O}}$	Carbonyl index	c.u.
I_{foc}	Structural degradation index	c.u.
I_{gas}	Gas saturation index	c.u.
$I_{\text{H}_2\text{O}}$	Water content index	c.u.
I_{par}	Paraffin index	c.u.
I_{trs}	Light scattering index	c.u.
$\overline{I}_x$	Mean value of the index	c.u.
k	Wavenumber	cm^{-1}
n	Sample size	–
P	Ultrasound power	W
r	Pearson linear correlation coefficient	–
RSD	Relative standard deviation	%
$S_{[x;y]}$	Peak area in the range of x – y	$\text{c.u.} \cdot \text{cm}^{-1}$
SD	Standard deviation	c.u.
SNR	Signal-to-noise ratio	–
t	Duration of ultrasonic treatment	min
$t_{0.05;n}$	Critical Student's t -value	–
V	Volume	mL
μ	Dynamic viscosity	$\text{mPa} \cdot \text{s}$
ρ	Oil density	g/cm^3
σ	Measurement error of device	%
τ	Heating temperature	$^{\circ}\text{C}$

References

1. Litvinenko, V.S.; Dvoynikov, M.V.; Trushko, V.L. Elaboration of a conceptual solution for the development of the Arctic shelf from seasonally flooded coastal areas. *Int. J. Min. Sci. Technol.* **2022**, *32*, 113–119. [[CrossRef](#)]
2. Nikolaev, A.; Goluntsov, A.; Plotnikova, K. A physically based rheological model for predicting the flow behavior of non-newtonian crude oil mixtures under cold climate conditions. *Front. Chem. Eng.* **2026**, *8*, 1736520. [[CrossRef](#)]
3. Cherepovitsyn, A.; Strelchenko, K. Prospects for the revitalization and strategic development of the Russian mica industry: A focus on the Arctic. *North Mark.* **2025**, *3*, 53–68. [[CrossRef](#)]
4. Korobov, G.; Rogachev, M.; Krylov, V. Mechanisms of Asphaltene–Resin–Paraffin Deposit Formation and Prevention in Oil Production: From Physicochemical Processes to Inhibition and Delivery Strategies. *Eng* **2026**, *7*, 116. [[CrossRef](#)]
5. Chen, P. Advancements and future outlook of safety monitoring, inspection and assessment technologies for oil and gas pipeline networks. *J. Pipeline Sci. Eng.* **2025**, *5*, 100267. [[CrossRef](#)]
6. Bēben, D.; Steliga, T. Monitoring and Preventing Failures of Transmission Pipelines at Oil and Natural Gas Plants. *Energies* **2023**, *16*, 6640. [[CrossRef](#)]
7. Raupov, I.; Rogachev, M.; Shevaldin, E. Review of Formation Mechanisms, Localization Methods, and Enhanced Oil Recovery Technologies for Residual Oil in Terrigenous Reservoirs. *Energies* **2025**, *18*, 5649. [[CrossRef](#)]
8. Iktissanov, V.; Bernatov, M. Impact of Effective Pressure Variations on Reservoir Rock Porosity and Compressibility. *Int. J. Eng.* **2026**, *39*, 2521–2528. [[CrossRef](#)]
9. Mohammadpour, M.; Malayeri, M.; Kazemzadeh, Y.; Riazi, M. On the impact of oil compounds on emulsion behavior under different thermodynamic conditions. *Sci. Rep.* **2023**, *13*, 15727. [[CrossRef](#)] [[PubMed](#)]
10. Muravyev, A.V. Gas Condensate Wells: Challenges of Sampling, Testing and Production Optimization. *Energies* **2022**, *15*, 5419. [[CrossRef](#)]
11. Wang, D.; Zhang, S.; Lv, Y.; Wu, Z.; Li, Y.; Hui, L.; Li, D. Research on the structure of oil content in-situ detection probe combining infrared absorption spectroscopy and fluorescence spectroscopy. *Spectrochim. Acta Part A* **2026**, *357*, 127830. [[CrossRef](#)] [[PubMed](#)]
12. Tang, L.; Wang, T.; Liu, Y.; Zhou, H. Methane Interface Desorption Mechanism in Geological Reservoirs After Natural Gas Hydrate Decomposition. *Reserv. Sci.* **2026**, *2*, 172–188. [[CrossRef](#)]

13. Li, Q.; Li, Q.; Wu, J.; He, K.; Xia, Y.; Liu, J.; Wang, F.; Cheng, Y. Wellhead Stability During Development Process of Hydrate Reservoir in the Northern South China Sea: Sensitivity Analysis. *Processes* **2025**, *13*, 1630. [\[CrossRef\]](#)
14. Li, Q.; Li, Q.; Wang, F.; Wu, J.; Wang, Y.; Jin, J. Effects of Geological and Fluid Characteristics on the Injection Filtration of Hydraulic Fracturing Fluid in the Wellbores of Shale Reservoirs: Numerical Analysis and Mechanism Determination. *Processes* **2025**, *13*, 1747. [\[CrossRef\]](#)
15. Raupov, I.; Burkhanov, R.; Lutfullin, A.; Maksyutin, A.; Lebedev, A.; Safiullina, E. Experience in the Application of Hydrocarbon Optical Studies in Oil Field Development. *Energies* **2022**, *15*, 3626. [\[CrossRef\]](#)
16. Al Madan, A.; Hussein, A.; Akhtar, S. A review on internal corrosion of pipelines in the oil and gas industry due to hydrogen sulfide and the role of coatings as a solution. *Corros. Rev.* **2025**, *43*, 189–208. [\[CrossRef\]](#)
17. Pshenin, V.V.; Zakirova, G.S. Improving the efficiency of oil vapor recovery units in the commodity transport operations at oil terminals. *J. Min. Inst.* **2024**, *265*, 121–128. [\[CrossRef\]](#)
18. Foulk, S.J.; Lerud, R. Automated near infrared analyzer validation (ASTM D6122) for the oil and gas industry. *NIR News* **2019**, *30*, 39–41. [\[CrossRef\]](#)
19. Rastvorova, I.; Filatov, V.; Vilkov, S. Reduction of Optical Density in Highly Viscous Oils through Ultrasonic Treatment within The Infrared Wavelength Range. *Int. J. Eng.* **2026**, *39*, 1865–1877. [\[CrossRef\]](#)
20. Wang, W.; Hu, S.; Ke, Y. Status Quo and Prospect of Oil-Water Two-phase Flow Detection Technology in Petrochemical Pipeline Network. *Crimson* **2023**, *5*, 4. [\[CrossRef\]](#)
21. Filatov, V.M.; Rastvorova, I.I.; Zhurba, E.D. Review of radio-electronic wave techniques and devices for oil diagnostics and monitoring. *Bull. Tomsk. Polytech. Univ. Geo Assets Eng.* **2025**, *336*, 164–181. [\[CrossRef\]](#)
22. Earnshaw, M.; Bolle, C.; Kopf, R.; Cappuzzo, M.; Tate, A.; Hu, T. Compact, efficient ultra-wide tunable laser with reduced thermal crosstalk. *Opt. Express* **2024**, *32*, 33283–33293. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Rasool, H.N.; Zeb, M. Neural Network based Portable Spectrometer for Fluid Classification. *Int. J. Eng. Work.* **2026**, *13*, 1–6. [\[CrossRef\]](#)
24. Sarafdokht, H.; Rabbani, A.R.; Asemani, M. A novel multidisciplinary approach for crude oil classification based on structural characteristics of asphaltenes. *Sci. Rep.* **2026**, *16*, 4250. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Mishra, P.; Passos, D.; Roger, J.-M.; Marini, F.; Biancolillo, A.; Rutledge, D.; Gowen, A.; Amigo, J.; Jansen, J. Deep learning for near-infrared spectral data modelling: Hypes and benefits. *TrAC-Trends Anal. Chem.* **2022**, *157*, 116804. [\[CrossRef\]](#)
26. Yang, S.-B.; Moreira, J.; Li, Z. Predicting Crude Oil Properties Using Fourier-Transform Infrared Spectroscopy (FTIR) and Data-Driven Methods. *Digit. Chem. Eng.* **2022**, *3*, 100031. [\[CrossRef\]](#)
27. Moro, M.; Castro, E.; Romão, W.; Filgueiras, P. Data fusion applied in near and mid infrared spectroscopy for crude oil classification. *Fuel* **2023**, *340*, 127580. [\[CrossRef\]](#)
28. Xu, S.; Xu, Z.; Zheng, J.; Lin, H.; Zou, L.; Lei, M. Where does the crude oil originate? The role of near-infrared spectroscopy in accurate source detection. *Memetic Comput.* **2024**, *16*, 429–443. [\[CrossRef\]](#)
29. Wan Jusoh, W.N.L.; Omar, M.B.; Sami, A.; Bingi, K.; Ibrahim, R. Crude Oil Yield Estimation: Recent Advances and Technological Progress in the Oil Refining Industry. *Sensors* **2025**, *25*, 5511. [\[CrossRef\]](#) [\[PubMed\]](#)
30. Dengaev, A.; Kayumov, A.; Getalov, A.; Aliev, F.; Baimukhametov, G.; Sargin, B.; Maksimenko, A.; Vakhin, A. Chemical Viscosity Reduction of Heavy Oil by Multi-Frequency Ultrasonic Waves with the Main Harmonics of 20–60 kHz. *Fluids* **2023**, *8*, 136. [\[CrossRef\]](#)
31. Gao, J.; Wu, P.; Li, C.; Xu, D.; Wang, X. Influence and Mechanism Study of Ultrasonic Electric Power Input on Heavy Oil Viscosity. *Energies* **2023**, *16*, 79. [\[CrossRef\]](#)
32. Chen, W.; Chen, Z.; Chang, J.; Chen, C.; Zeng, Y. Ultrasound-assisted desalination of crude oil: The influence of mixing extent, crude oil species, chemical demulsifier and operation variables. *Ultrason. Sonochemistry* **2022**, *83*, 105947. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Aleksandrova, T.N.; Lyublyanova, V.A. Enhancing copper recovery from copper minerals via sulfuric acid leaching. *Obogashchenie Rud* **2025**, *6*, 16–21. [\[CrossRef\]](#)
34. Liu, J.; Yang, F.; Xia, J.; Wu, F.; Pu, C. Mechanism of Ultrasonic Physical-Chemical Viscosity Reduction for Different Heavy Oils. *ACS Omega* **2021**, *13*, 2276–2283. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Mierez, J.; AlTammar, M.; Alruwaili, K.; Alfaraj, R. Recent advances of ultrasound applications in the oil and gas industry. *Ultrason. Sonochemistry* **2024**, *103*, 106767. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Kadyirov, A.; Karaeva, J. Ultrasonic and Heat Treatment of Crude Oils. *Energies* **2019**, *12*, 3084. [\[CrossRef\]](#)
37. Olaya-Escobar, D.-R.; Quintana-Jiménez, L.-A.; González-Jiménez, E.-E.; Olaya-Escobar, E.-S. Ultrasound Applied in the Reduction of Viscosity of Heavy Crude Oil. *Rev. Fac. Ing. Univ. Ant.* **2020**, *29*, e11528. [\[CrossRef\]](#)
38. Shi, Z.; Wang, Z.; Yang, B.; Liu, L. Insights into cavitation enhancement: Numerical simulation and spectrum analysis of a novel dual-frequency octagonal ultrasonic reactor. *Ultrason. Sonochemistry* **2025**, *112*, 107197. [\[CrossRef\]](#) [\[PubMed\]](#)

39. GOST ISO 5024-2013; Petroleum Liquids and Liquefied Petroleum Gases. Measurement. Standard Reference Conditions. Standartinform: Moscow, Russia, 2019.
40. Shi, J.; Tong, L.; Sun, L.; Jiang, T.; Yu, X.; Yu, K.; Lu, S.; Xu, W. Molecular Dynamics Simulation on the Process of Ultrasonic Viscosity Reduction. *Processes* **2024**, *12*, 2803. [[CrossRef](#)]
41. Hua, Q. Experimental Studies on Viscosity Reduction of Heavy Crude Oil by Ultrasonic Irradiation. *Acoust. Phys.* **2020**, *66*, 495–500. [[CrossRef](#)]
42. Kadyirov, A.; Karaeva, J.; Barskaya, E.; Vachagina, E. Features of rheological behavior of crude oil after ultrasonic treatment. *Braz. J. Chem. Eng.* **2023**, *40*, 159–168. [[CrossRef](#)]
43. Marfin, E.A.; Galimzyanova, A.R.; Gataullin, R.N.; Natfullin, R.A. Effect of ultrasonic treatment on rheological properties of paraffinic oil. *Nauka Tehnol. Trubopr.* **2024**, *14*, 352–361.
44. Volkova, G.; Zubarev, D.; Kadychagov, P. Effect of Ultrasonic Treatment on the Properties and Composition of High-Wax Crude Oil and Its Precipitates. *Pet. Chem.* **2024**, *64*, 540–547. [[CrossRef](#)]
45. Shammazov, I.A.; Zhurba, E.D.; Filatov, V. The Dynamics of Thermophysical Properties of Heavy Oil under Ultrasonic Treatment: A Mathematical Model and an Experimental Evaluation of the Process Time. *Int. J. Eng.* **2026**, *39*, 3170–3180. [[CrossRef](#)]
46. Ye, L.; Chuai, S.; Zhu, X.; Wang, D. Experimental Study on Ultrasonic Cavitation Intensity Based on Fluorescence Analysis. *Chin. J. Mech. Eng.* **2023**, *36*, 103. [[CrossRef](#)]
47. Gong, T.; Zhu, X.; Ye, L.; Fu, Y. Numerical study of cavitation shock wave emission in the thin liquid layer by power ultrasonic vibratory machining. *Sci. Rep.* **2024**, *14*, 16956. [[CrossRef](#)] [[PubMed](#)]
48. Razavifar, M.; Yunusov, T.; Mukhametdinova, A.; Bakulin, D.; Qajar, J.; Cheremisin, A.; Riazi, M. Improving oil recovery with ultrasound: Mitigating asphaltene-induced formation damage. *J. Pet. Explor. Prod. Technol.* **2025**, *15*, 78. [[CrossRef](#)]
49. Oshina, I.; Spigulis, J. Beer-Lambert law for optical tissue diagnostics: Current state of the art and the main limitations. *J. Biomed. Opt.* **2021**, *26*, 100901. [[CrossRef](#)] [[PubMed](#)]
50. Hou, J.K.; Wang, R.L.; Zhu, G.Y.; Li, J.; Zhu, Z.G.; Ai, Y.F. Geochemical heterogeneity of ultra-deep oil pyrolysis: Nanoscale infrared spectroscopy insights. *Pet. Sci.* **2025**. [[CrossRef](#)]
51. Ok, S.; Rajasekaran, N.; Sabti, M.A.; Joseph, G.A. Spectroscopic analysis of crude oil asphaltenes at molecular level. *Pet. Chem.* **2020**, *60*, 802–809. [[CrossRef](#)]
52. Chen, X.; Cheng, Y.; Matsuba, M.; Wang, X.; Han, S.; Jordan, M.; Zhu, Q. In situ monitoring of heterogeneous hydrosilylation reactions using infrared and Raman spectroscopy: Normalization using phase-specific internal standards. *Appl. Spectrosc.* **2019**, *73*, 1299–1307. [[CrossRef](#)] [[PubMed](#)]
53. Tanykova, N.; Petrova, Y.; Kostina, J.; Kozlova, E.; Leushina, E.; Spasennykh, M. Study of Organic Matter of Unconventional Reservoirs by IR Spectroscopy and IR Microscopy. *Geosciences* **2021**, *11*, 277. [[CrossRef](#)]
54. Wu, M.; Qin, Y.; Qin, Y.; Xu, N.; Feng, L. The Effect of Temperature on Molecular Structure of Medium-Rank Coal via Fourier Transform Infrared Spectroscopy. *Materials* **2023**, *16*, 6746. [[CrossRef](#)] [[PubMed](#)]
55. Fernández-González, V.; Andrade, J.M.; Ferreira, B.; López-Mahía, P.; Muniategui-Lorenzo, S. Monitorization of polyamide microplastics weathering using attenuated total reflectance and microreflectance infrared spectrometry. *Spectrochim. Acta Part A* **2021**, *263*, 120162. [[CrossRef](#)] [[PubMed](#)]
56. Falke, S.; Betzel, C. Dynamic Light Scattering (DLS): Principles, Perspectives, Applications to Biological Samples. In *Radiation in Bioanalysis: Spectroscopic Techniques and Theoretical Methods*; Springer International Publishing: Cham, Switzerland, 2019; Volume 29, pp. 173–193. [[CrossRef](#)]
57. Ilyushin, Y.; Martirosyan, A.V.; Asadulagi, M.-A.; Kukharova, T. Modeling and Optimization of an Automatic Temperature Control System for the Catalytic Cracking Process. *Modelling* **2026**, *7*, 68. [[CrossRef](#)]
58. Carpenter, J.; Pinjari, D.V.; Kumar Saharan, V.; Pandit, A.B. Critical review on hydrodynamic cavitation as an intensifying homogenizing technique for oil-in-water emulsification: Theoretical insight, current status, and future perspectives. *Ind. Eng. Chem. Res.* **2022**, *61*, 10587–10602. [[CrossRef](#)]
59. Kuimov, D.; Minkin, M.; Yurov, A.; Lukyanov, A. Current State of Research on the Mechanism of Cavitation Effects in the Treatment of Liquid Petroleum Products—Review and Proposals for Further Research. *Fluids* **2023**, *8*, 172. [[CrossRef](#)]
60. Vesipa, R.; Paissoni, E.; Manes, C.; Ridolfi, L. Dynamics of bubbles under stochastic pressure forcing. *Phys. Rev. D* **2021**, *103*, 023108. [[CrossRef](#)] [[PubMed](#)]
61. Nazarychev, A.; Iliev, I.; Manukian, D.; Beloev, H.; Suslov, K.; Beloev, I. Methodology for Developing a Maintenance Action Program for Power Units of Captive Power Plants Based on an Integrated Priority Indicator. *Energies* **2026**, *19*, 1584. [[CrossRef](#)]
62. Aleksandrova, T.; Gatiatullin, B.; Kuznetsov, V.; Nikita, S. Evaluation Methods for Aeration Parameters in Flotation Separation Modelling with Neural Network Applications. *Processes* **2026**, *14*, 728. [[CrossRef](#)]

63. Huminiiovych, R.; Stadnik, V.; Sozanskyi, M.; Shapoval, P.; Pidlisnyuk, V.; Poliuzhyn, I.; Kochubei, V.; Hrynychuk, Y.; Korchak, B. Sample preparation method for IR analysis of petroleum-contaminated soil: An innovative technology for ecological remediation using *Miscanthus x giganteus*. *Heliyon* **2024**, *10*, e40713. [[CrossRef](#)] [[PubMed](#)]
64. Farrahova, G.R.; Tanykova, N.G.; Kolosova, E.M.; Petrova, Y.Y.; Bajbulatov, R.Y.; Sutormin, O.S. Reducing the Gap Between Chemical and Biological Assessment of Petroleum-Contaminated Soils: An FTIR-Based Method Using Aqueous Dimethyl Sulfoxide Extraction. *Environments* **2026**, *13*, 140. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.