Tonkie Khimicheskie Tekhnologii = Fine Chemical Technologies.
2025;20(5):483–496 ISSN 2686-7575 (Online)

UDC 665.6
https://doi.org/10.32362/2410-6593-2025-20-5-483-496
EDN MLHKXX

RESEARCH ARTICLE

Effect of cavitation on the structural characteristics of oil asphaltenes

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Abstract

Objectives. To investigate the influence of hydrodynamic cavitation on the group hydrocarbon composition of straight-run fuel oil and the structural characteristics of its asphaltenes.

Methods. The cavitation treatment of fuel oil was carried out in hydrodynamic mode using a Donor-2 device. The pressure drop in the working part was 50 MPa, while the number of treatment cycles varied from 1 to 10. In some cases, to intensify the process, the fuel oil was compounded with low-boiling hydrocarbons (propane-butane fraction, decalin). The determination of the group hydrocarbon composition of the sample was based on the different solubility of hydrocarbons in polar and nonpolar solvents; asphaltenes were studied by diffractometry and Raman spectroscopy.

Results. It is shown that the group hydrocarbon composition of the sample changes as a result of the cavitation effect: the content of resins and asphaltenes decreases, the amount of the oil fraction increases, and its group hydrocarbon composition is altered. It was found that cavitation exposure also changes the structural characteristics of asphaltenes: they decrease the L_a and L_c crystallite parameters that characterize their dimensions in plane and height, as well as increase the distance between alkyl substituents and the degree of plasticity of asphaltenes. The processing of Raman spectra by various methods demonstrated consistent results: in all cases, an increase in the intensity of exposure led to an increase in the structural disorder of asphaltenes. In the case of preliminary compounding of the sample with low-boiling hydrocarbons, the effect of cavitation was enhanced.

Conclusions. The results obtained may indicate the localization of cavitation bubbles at the boundaries of complex structural units of the dispersed petroleum system formed by asphalt-resinous substances and a dispersion medium. For this reason, it is resins and asphaltenes that are most exposed to the thermal effects that occur when cavitation bubbles collapse. The destruction of resins and asphaltenes leads to a decrease in the size of complex structural units and consequent decrease in the viscosity of the petroleum dispersed system, while the oil fraction is enriched with saturated hydrocarbons.

Keywords

hydrodynamic cavitation, petroleum and petroleum products, straight-run fuel oil, asphaltenes, a complex structural unit, group composition, viscosity

Submitted: 09.12.2024
Revised: 27.01.2025
Accepted: 05.09.2025

For citation

Nikishin D.V., Peshnev B.V., Nikolaev A.I. Effect of cavitation on the structural characteristics of oil asphaltenes. *Tonk. Khim. Tekhnol.* = *Fine Chem. Technol.* 2025;20(5):483–496. https://doi.org/10.32362/2410-6593-2025-20-5-483-496

НАУЧНАЯ СТАТЬЯ

Влияние кавитационного воздействия на структурные характеристики асфальтенов нефти

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Аннотация

Цели. Рассмотреть влияние гидродинамической кавитации на групповой углеводородный состав прямогонного мазута и структурные характеристики его асфальтенов.

Методы. Кавитационную обработку мазута проводили в гидродинамическом режиме с использованием аппарата «Донор-2». Перепад давления в рабочей части составлял 50 МПа, число циклов обработки варьировали от 1 до 10. В ряде случаев, для интенсификации процесса, мазут компаундировали с низкокипящими углеводородами (пропан-бутановой фракцией, декалином). Определение группового углеводородного состава образца основывалось на различной растворимости углеводородов в полярных и неполярных растворителях, асфальтены исследовались методами дифрактометрии и спектроскопии комбинационного рассеяния (рамановской спектроскопии).

Результаты. Показано, что в результате кавитационного воздействия изменяется групповой углеводородный состав образца, в нем снижается содержание смол и асфальтенов, возрастает доля масляной фракции и при этом изменяется ее групповой углеводородный состав. Кроме этого установлено, что при кавитационном воздействии изменяются структурные характеристики асфальтенов: у них снижаются параметры кристаллитов L_a и L_c, характеризующие их размеры в плоскости и по высоте, увеличиваются расстояние между алкильными заместителями и степень ароматичности асфальтенов. Обработка спектров комбинационного рассеяния различными методами показала принципиальную схожесть результатов: увеличение интенсивности воздействия приводило к увеличению структурной разупорядоченности асфальтенов. В случае предварительного компаундирования образца с низкокипящими углеводородами эффект от кавитационной обработки усиливался.

Выводы. Полученные результаты могут свидетельствовать о локализации пузырьков кавитации на границах сложных структурных единиц нефтяной дисперсной системы, сформированных асфальто-смолистыми веществами и дисперсионной средой. В связи с этим, именно смолы и асфальтены подвергаются наибольшему термическому воздействию, возникающему при схлопывании кавитационных пузырьков. Деструкция смол и асфальтенов приводит к уменьшению размеров сложных структурных единиц и, соответственно, снижению вязкости нефтяной дисперсной системы, а масляная фракция при этом обогащается насыщенными углеводородами.

Ключевые слова

гидродинамическая кавитация, нефть и нефтепродукты, прямогонный мазут, асфальтены, сложная структурная единица, групповой состав, вязкость

Поступила: 09.12.2024
Доработана: 27.01.2025
Принята в печать: 05.09.2025

Для цитирования

Никишин Д.В., Пешнев Б.В., Николаев А.И. Влияние кавитационного воздействия на структурные характеристики асфальтенов нефти. *Тонкие химические технологии*. 2025;20(5):483–496. https://doi.org/10.32362/2410-6593-2025-20-5-483-496

INTRODUCTION

One of the current priorities of the oil refining industry is to increase the depth of oil processing, which is achieved by improving the efficiency and technological sophistication of the processing of raw materials arriving at oil refineries. However, the search for solutions to such problems is complicated by the trend towards the extraction of heavier crude oil fractions. Therefore, the development of methods and technologies aimed at increasing the yield of light petroleum products becomes a significant and relevant task.

The scientific literature discusses several options for increasing the depth of oil processing through physical methods: using ultrasonic, hydrodynamic, magnetic, electrohydraulic and other treatment methods [1–5]. With each passing year, interest in the application of such pre-treatment methods in oil refining continues to grow. One of the most effective processing approaches is based on the use of cavitation phenomena [2].

Cavitation treatment involves creating conditions under which cavitation bubble nuclei form, grow, and subsequently collapse [6]. The result of the collapse of an individual bubble is the emergence of extreme pressures up to 1000 MPa and temperatures up to 5000 K in a localized area to release energy of about $2.5 \cdot 10^{-5}$ J [7, 8]. As confirmed by experimental studies, cavitation treatment of oil dispersion systems (ODS) can lead to changes in their properties and hydrocarbon composition [9–11]. However, the observed changes described in the literature [10, 12–15] are not always unambiguous: for example, in the study [13], it is indicated that cavitation treatment led to a decrease in the density of the raw material, while in the study [12], it led to an increase. The viscosity of the oil system after such treatment decreases [3, 5, 9, 16, 17], but then, over time, it returns to values close to the initial ones, although not reaching them [16, 17]. Such a change in viscosity may indicate the destruction of the ODS structure due to the disruption of intermolecular interactions (2–10 kJ/mol), Van der Waals forces (10–20 kJ/mol), and hydrogen bonds (20–160 kJ/mol) of asphaltenes and resins, representing the least stable and most high-molecular-weight components of the oil system, to form supramolecular complex structural units (CSU) [18, 19].

The CSU core consists of asphaltenes and resins surrounded by a solvate shell of compounds whose molecular weight decreases from the center to the periphery to form a dispersed phase of the system that has an interface with the dispersion medium. The presence of resins and asphaltenes in oil and petroleum products is an important factor that must be taken into account in the processes of extraction, transportation, and refining. At the extraction stage, they form asphaltene-resin-paraffin deposits in collectors and pipelines resulting in reduced throughput. Increased viscosity of the oil as a result of resin and asphaltene content increases transportation costs, while their presence in high-temperature processes leads to increased coking.

In studies [20, 21], the formation of cavitation bubble nuclei is shown to be promoted by the presence of a phase boundary. In the case of ODS, such a boundary is formed between the dispersed phase, which is composed of resins and asphaltenes, and the dispersion medium. It can be assumed that the cavitation bubbles are localized precisely at this boundary. Therefore, as a result of bubble collapse, the hydrocarbons forming the phase boundary—including resins with asphaltenes—should be subjected to the most intense thermal processing.

In this study, the structural changes of fuel oil asphaltenes under the influence of hydrodynamic cavitation are examined. The samples were studied using methods of Raman spectroscopy and powder X-ray diffraction.

EXPERIMENTAL

The object of the study is a sample of straight-run vacuum residue obtained at the ELOU-AVT-6 unit of the *Gazpromneft-MNPZ* plant (Moscow, Russia). Cavitation treatment of the fuel oil was conducted in hydrodynamic mode on the Donor-2 apparatus (*Experimental Plant of Scientific Instrumentation of the Russian Academy of Sciences*, Russia) [16] at a temperature of 50°C. The pressure drop in the working part of the device was 50 MPa; the number of processing cycles varied from 1 to 10. In several publications, the addition of gaseous or liquid components into the treated system is proposed as a means to enhance the efficiency of cavitation processing [18, 22–25]. In the current study, propane-butane fraction (PBF) was used as such intensifying components with the following composition (in vol %): C_2H_6 ~ 15, C_3H_8 ~ 65, C_4H_{10} ~ 20, and a decalin-containing additive (hereinafter referred to as decalin) with the following composition (in wt %): decahydronaphthalene ($C_{10}H_{18}$) ~ 83.0, bicyclopentyl ($C_{10}H_{18}$) ~ 5.5, bicyclo[5.3.0]decane ($C_{10}H_{18}$) ~ 5.2. Identification was carried out using gas chromatography-mass spectrometry analysis. PBF was added by gas bubbling through the sample layer with a gas flow rate of 75 and 225 cm³/min for 30 min immediately before treatment.

Viscosity was determined using viscometers for opaque liquids (*EKROSKHIM*, Russia) according to

GOST 33-2016[1]. The group composition of the samples was determined using the method described in study [26]. When precipitating asphaltenes, the mass ratio of the sample to the solvent was taken to be 1 : 40. Asphaltenes were precipitated for 24 h. The resulting solution was filtered using a decolorized paper filter of the Blue Ribbon brand (*Melior XXI*, Russia). The isolated asphaltenes were washed from co-precipitated paraffins and resins in a Soxhlet apparatus for 2 h with petroleum ether 40–70°C (pure, *EKOS-1*, Russia) and dried in a laboratory vacuum oven for 1 h. As an adsorbent in the column, silica gel of the ASCG grade[2] (*ChromLab*, Russia) with a fraction of 0.25–0.50 mm was used. Petroleum ether, toluene (chemically pure, *Base No. 1 for Chemical Reagents*, Russia), and isopropyl alcohol (chemically pure, *Base No. 1 for Chemical Reagents*, Russia) were used as solvents. For the precipitation and washing of asphaltenes, as well as for the isolation of saturated hydrocarbons, petroleum ether was used; for the isolation of aromatic hydrocarbons—toluene; for the isolation of resins—a mixture of toluene and isopropyl alcohol in a 30 to 70 ratio. The volumetric ratio of silica gel to sample was 100 : 1.

The asphaltenes extracted from the samples of fuel oil were studied using powder diffractometry and Raman spectroscopy. The following sample numbering is used in the study: (1) asphaltenes extracted from the original fuel oil; (2) asphaltenes extracted from the fuel oil after cavitation treatment; (3) asphaltenes extracted from the fuel oil after treatment (the fuel oil was purged with PBF immediately before the treatment at a flow rate of 225 cm³/min); (4) asphaltenes extracted from a fuel oil compound with decalin (at a concentration of 2 wt %) after its treatment. In all cases, five cycles of treatment were carried out.

The diffraction patterns of the isolated asphaltenes were recorded at room temperature using an X-ray diffractometer XRD 6000 (CuK_α radiation, wavelength $\lambda = 0.1542$ nm, *Shimadzu Corporation*, Japan) at angles $2\theta = 10°–80°$. The speed of the goniometer rotation was 0.02°/s. The obtained diffractograms were processed in the Origin software. For separating the obtained peaks, Gaussian functions were used.

The Raman spectra of asphaltenes were obtained at room temperature (20°C) using a Confotec Uno confocal Raman microscope (*SOL Instruments*®, Belarus) in the shift range from 400 to 4000 cm^{-1}. At a radiation power 10% of the maximum possible value (50 mW), the wavelength of the radiation was 532 nm; the test duration was 50 s. The obtained spectra were processed in the Origin software. To separate the obtained spectra into peaks D1–D4 and G, Gaussian, Lorentzian, and Voigt functions were applied (method 1) [27]. The separation of the obtained spectra into their constituent peaks was carried out using the method described in study [28], in which the G peak (approximately at the maximum position ~1580 cm^{-1}) corresponds to the presence of an ideal graphite structure (the response is formed by the vibrations of carbon atoms with sp^2 hybridization, forming the planes of condensed aromatic layers), while the D peak (~1350–1370 cm^{-1}) corresponds to defects in the lattice of the ideal graphite structure and its edges (method 2). While the assignment of peaks SL (~1230 cm^{-1}), VR (~1380 cm^{-1}), VL (~1460 cm^{-1}), GR (~1540 cm^{-1}), G2 (~1600 cm^{-1}) to various structural fragments is revealed in studies [28–30], it was only possible to reliably interpret the ratio of the integral intensities of the D and G peaks.

The structural parameters of asphaltenes were determined based on the results of X-ray structural analysis using formulas (1)–(8) [31, 32].

The distance between aromatic layers d_m was calculated using the Bragg–Wulf formula (1):

$$d_m = \frac{\lambda}{2\sin\theta_{002}}, \quad (1)$$

where λ is the wavelength of X-ray radiation, Å; θ_{002} is the angle corresponding to the maximum of the 002 peak, degrees.

The distances between aliphatic chains or cycles d_γ were calculated using formula (2):

$$d_\gamma = \frac{\lambda}{2\sin\theta_\gamma}. \quad (2)$$

The average diameter of the aromatic layers L_a was calculated using formula (3):

$$L_a = \frac{0.92}{FWHM_{10}}, \quad (3)$$

where $FWHM_{10}$ (full width at half maximum) is the full width of the halo at half its maximum height, measured in units of $(\sin\theta)/\lambda$, degrees.

The average height of the stack of aromatic layers L_c (crystallite size) was calculated using formula (4):

$$L_c = \frac{0.45}{FWHM_{002}}, \quad (4)$$

where $FWHM_{002}$ is the full width at half maximum of halo 002, measured in units of $(\sin\theta)/\lambda$, degrees.

[1] GOST 33-2016. Interstate Standard. Petroleum and petroleum products. Transparent and opaque liquids. Determination of kinematic and dynamic viscosity. Moscow: Standartinform; 2017.

[2] Activated silica gel, coarse-pored, granulated.

The average number of carbon atoms in the aromatic layer C_{au} (au stands for atomic units) was estimated using formula (5):

$$C_{au} = \frac{L_a + 1.23}{0.65}. \quad (5)$$

The average number of aromatic rings NO_a in the layer was estimated using formula (6):

$$NO_a = \frac{L_a}{2.667}. \quad (6)$$

The average number of aromatic layers in the pack M was estimated using formula (7):

$$M = \frac{L_c}{d_m} + 1. \quad (7)$$

The degree of aromaticity of asphaltenes f_a was determined using formula (8):

$$f_a = \frac{A_{002}}{A_{002} + A_\gamma}, \quad (8)$$

where A_{002} and A_γ are the areas of the 002 and γ-band peaks.

Based on the results of processing the Raman spectra of asphaltenes, the parameters R_1 and R_2 were calculated using formulas (9) and (10) [33] to assess the disorder of their structure:

$$R_1 = \frac{I_{D1}}{I_G}, \quad (9)$$

$$R_2 = \frac{I_{D1}}{I_G + I_{D1}}, \quad (10)$$

where I_{D1} and I_G are the areas (integral intensities) of the D1 and G peaks.

The evaluation of the aromatic layer diameter based on the results of Raman spectroscopy (RS) L_a^{RS} (nm) was conducted using formula (11) [27, 34]:

$$L_a^{RS} = 4.4 \frac{A_G}{A_{D1}}. \quad (11)$$

The average number of aromatic rings in the layer NO_a based on the results of Raman spectroscopy was estimated using formula (12) [27]:

$$NO_a = \frac{L_a^{RS} \cdot 10}{2.667}. \quad (12)$$

RESULTS AND DISCUSSION

Figure 1 shows the results confirming the information about the reduction in the viscosity of the ODS due to cavitation effects. The results demonstrate that the number of processing cycles has a significant influence on the rheological characteristics of the system. The subsequent increase in viscosity aligns with previously obtained results. As previously mentioned, the reduction in the viscosity of petroleum products as a result of cavitation treatment is associated with the destruction of weak intermolecular CSU bonds. Over time, these bonds are restored to increase CSU sizes, resulting in an increase in viscosity. More importantly, the viscosity does not return to its original values, which can be seen as evidence of deeper changes in the CSU as a result of cavitation, including intramolecular transformations of resins and asphaltenes.

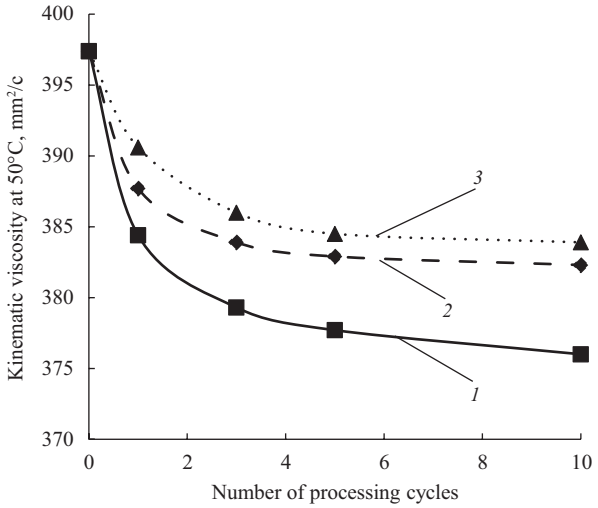

Fig. 1. Effect of hydrodynamic treatment conditions on the viscosity of straight–run fuel oil: (*1*) immediately after treatment; (*2*) after 5 days; (*3*) after 20 days

The data given in Table 1 confirm the change in the group composition of the fuel oil. It is evident that after cavitation treatment, the content of asphaltenes and resins in the sample decreased, while the amount of oil fractions increased. This effect, which can be increased by intensifying the cavitation process by saturating the feedstock before treatment with PBF or adding decalin, also increases the more PBF is introduced into the system. A change in the composition of the oil fractions, i.e., the ratio of saturated to aromatic hydrocarbons, was noted. Following cavitation treatment in the presence of an initiating agent (PBF or decalin), the content of saturated structures in the oil fraction increased, while the concentration of arenes decreased. This cannot be explained by the introduction of saturated hydrocarbons (decalin) into the sample, since the share of arenes in the oil fraction decreased to 34.7–35.0 wt % following the preliminary saturation of the fuel oil with PBF. Such a change in the hydrocarbon composition of the object under study can be explained by the destruction of resins and asphaltenes during processing. For example, the cleavage of alkyl substituents from the polycyclic

core. One of the possible transformation mechanisms in the asphaltene–resin–oil chain is considered in the studies [35]. It is possible that the incomplete relaxation of the viscosity of the fuel oil to its initial values following treatment is related to the destruction of the molecules constituting the CSU.

To confirm the hypothesis about the destruction of resins and asphaltenes in oil under cavitation impact, the asphaltenes extracted from the samples were studied using powder diffraction and Raman spectroscopy methods. Table 2 provides information on the structural characteristics of asphaltenes.

When comparing the characteristics of asphaltenes extracted from the original sample of fuel oil (sample 1) with those of asphaltenes extracted from the fuel oil after cavitation treatment (samples 2–4), several changes can be noted. As a result of the treatment, the average height of the aromatic layer stack L_c decreased, i.e., the size of the asphaltenes (CSU cores) became smaller, and the degree of aromaticity f_a of the asphaltenes increased, thus confirming the assumption of the detachment of alkyl substituents from them. This also aligns with the data on the increase in the parameter d_γ, which characterizes the distance between alkyl substituents.

During cavitation treatment of fuel oil in the presence of additives (PBF, decalin), the aromaticity of asphaltenes (samples 3 and 4) increased even more, while the average diameter of the aromatic layer L_a decreased. It should be noted that for asphaltenes, it is more accurate to speak not of the size of the aromatic layer, but rather of the size of the polycyclic layer formed by condensed aromatic and naphthenic rings. It is likely that in the case of samples 3 and 4, not only did the cleavage of alkyl chains occur, but also the opening of boundary saturated cycles with the subsequent detachment of the formed alkyl substituents, i.e., a more profound destruction of the compounds. This is consistent with the observed changes in group composition (see Table 1). When processing fuel oil compounded with PBF or decalin, a more significant increase in oil content was observed compared to processing without additives.

The described changes in the structural characteristics of asphaltenes are confirmed by the results of Raman spectrometry (Fig. 2, Table 3, Table 4).

Regardless of the method of processing Raman spectra and the functions used, a general trend is observed for asphaltene samples: an increase in the intensity of processing the initial oil leads to a more

Table 1. Change in the group composition of the straight-run fuel oil sample after its cavitation treatment under various conditions

Fraction, wt %	Initial sample	Cavitation treatment conditions*			
		Without additives	With propane-butane fraction, mL/min		With decalin
			75	225	
Asphaltenes	4.4	3.7	2.1	0.5	1.5
Resins	13.3	12.0	9.6	7.6	12.0
Oils	82.3	84.3	88.3	91.9	86.5

* Five cycles of exposure.

Table 2. Changes in the structural characteristics of fuel oil asphaltenes after treatment under various conditions

Sample	d_m, Å	d_γ, Å	L_a, Å	L_c, Å	C_{au}	NO_a	M	f_a
1	3.63	4.87	19.97	14.66	32.61	7.49	5.03	0.38
2	3.64	4.93	21.44	12.92	34.88	8.04	4.55	0.40
3	3.65	4.91	18.91	13.72	30.98	7.09	4.76	0.42
4	3.63	4.88	18.73	13.49	30.71	7.02	4.71	0.44

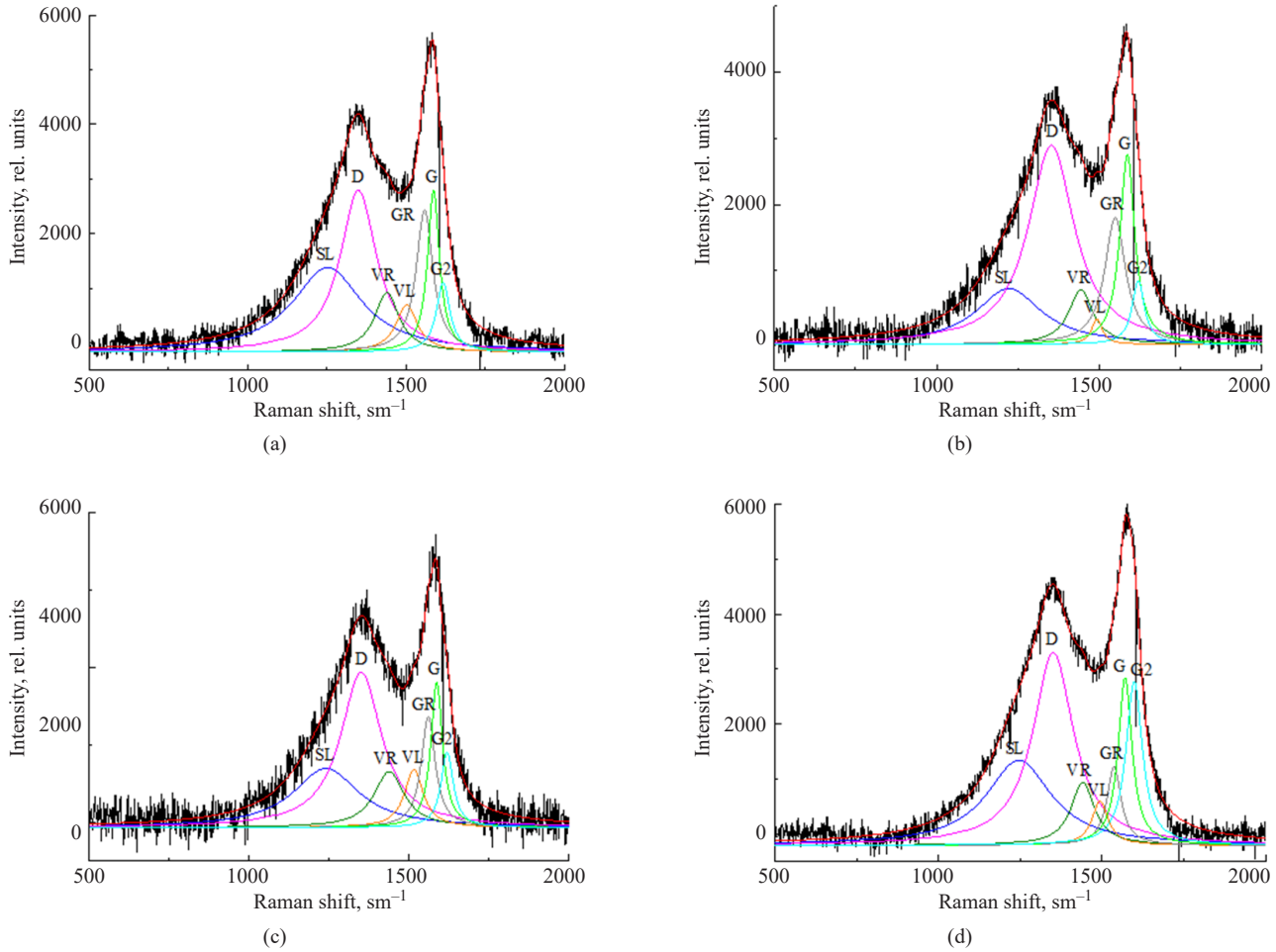

Fig. 2. Raman spectra of asphaltenes processed according to the method [28]:
(a) sample 1, (b) sample 2, (c) sample 3, (d) sample 4. The black line is the spectrum obtained experimentally; the red line is the curve describing the spectrum; the lines of the remaining colors are curves obtained by spectrum decomposition

pronounced increase in the disorder of the asphaltene structure, which is characterized by parameters R_1 and R_2. The increase in the values of parameters R_1 and R_2, as well as the intensity of peak D1 (see Table 4) relative to other peaks, indicates the emergence of additional defects in the structure of asphaltenes, which confirms the assumption of their destruction during cavitation processing.

It is significant that no significant changes in the parameters R_1 and R_2 were observed during the processing of fuel oil in the presence of decalin (sample 4, table 3). This may be due to the fact that decalin, having a higher boiling point compared to PBF (by 190–220°C), is less prone to the active formation of cavitation nuclei and the intensification of the process under cavitation treatment conditions.

Table 3. Results of processing Raman spectra (RS) by various methods and functions

Sample	R_1	R_2	L_a^{RS}, nm	NO_a
Method 1 [27]				
Gaussian function				
1	1.52	0.58	2.90	10.86
2	1.83	0.64	2.41	9.03
3	2.75	0.73	1.60	6.00
4	1.75	0.62	2.51	9.42

Table 3. Continued

Sample	R_1	R_2	L_a^{RS}, nm	NO_a
Lorentzian function				
1	1.13	0.53	3.89	14.58
2	1.22	0.55	3.62	13.58
3	1.65	0.62	2.66	9.98
4	1.22	0.55	3.60	13.50
Voigt function				
1	1.91	0.63	2.30	8.64
2	2.34	0.70	1.88	7.02
3	3.16	0.76	1.39	5.22
4	1.83	0.65	2.40	9.01
Method 2 [28]				
Lorentzian function				
1	3.11	0.76	1.42	5.31
2	3.29	0.77	1.34	5.01
3	3.79	0.79	1.16	4.35
4	3.39	0.77	1.30	4.87

Table 4. Analysis of the peaks of the first order of the Raman spectra of asphaltenes using various techniques and functions

Sample	Peak	Position, cm^{-1}	Intensity, rel. units	Width, cm^{-1}	Area, rel. units	Part, %
Method 1 [27]						
Gaussian function						
1	D4	1211	1242	271	357816	21.2
	D1	1362	3394	188	679850	40.5
	D3	1494	1471	99	155556	9.3
	G	1581	4953	85	447654	26.6
	D2	1665	665	57	40016	2.4
2	D4	1152	737	224	175558	12.7
	D1	1363	3225	216	740574	53.8
	D3	1478	492	68	35503	2.6
	G	1576	3761	101	405487	29.5
	D2	1674	372	47	18754	1.4
3	D4	1019	230	37	9116	0.9
	D1	1357	2337	290	722131	72.0
	D3	–	–	–	–	–
	G	1578	2529	98	262872	26.2
	D2	1674	204	42	9047	0.9

Table 4. Continued

Sample	Peak	Position, cm^{-1}	Intensity, rel. units	Width, cm^{-1}	Area, rel. units	Part, %
4	D4	1188	1117	257	305144	17.1
	D1	1360	3914	200	832291	46.7
	D3	1497	1420	94	142759	8.0
	G	1580	5199	86	475110	26.6
	D2	1664	585	44	27671	1.6
Lorentzian function						
1	D4	1236	1291	183	342872	18.9
	D1	1348	3213	135	643801	35.4
	D3	1471	1420	125	262639	14.4
	G	1579	4963	76	568910	31.3
	D2	–	–	–	–	–
2	D4	1229	914	200	262821	17.3
	D1	1351	2693	143	568004	37.4
	D3	1461	1107	136	221718	14.6
	G	1579	3951	79	467266	30.7
	D2	–	–	–	–	–
3	D4	1255	757	184	201775	18.0
	D1	1364	2122	161	498641	44.6
	D3	1510	757	103	116392	10.4
	G	1581	2824	71	301695	27.0
	D2	–	–	–	–	–
4	D4	1245	1472	178	379750	19.8
	D1	1353	3485	137	706699	36.8
	D3	1471	1427	121	255871	13.3
	G	1577	5210	74	578393	30.1
	D2	–	–	–	–	–
Voigt function						
1	D4	1180	1111	227	339072	19.5
	D1	1355	3663	192	758723	43.6
	D3	1505	1653	111	195718	11.3
	G	1583	4720	79	397212	22.9
	D2	1662	681	66	47894	2.8
2	D4	1153	518	246	138946	9.5
	D1	1363	3241	224	885906	60.6
	D3	1491	611	76	49185	3.4
	G	1581	3805	93	378077	25.9
	D2	1680	220	40	9378	0.6

Table 4. Continued

Sample	Peak	Position, cm^{-1}	Intensity, rel. units	Width, cm^{-1}	Area, rel. units	Part, %
3	D4	–	–	–	–	–
	D1	1361	2381	293	813860	76.0
	D3	–	–	–	–	–
	G	1580	2555	95	257397	24.0
	D2	–	–	–	–	–
4	D4	1115	597	183	116732	6.3
	D1	1353	4199	248	1109710	59.5
	D3	1496	497	61	32397	1.7
	G	1579	5268	93	605744	32.5
	D2	–	–	–	–	–
Method 2 [28]						
Lorentzian function						
1	SL	1252	1545	268	649719	28.6
	D	1350	2958	141	653498	30.5
	VR	1439	1089	94	161356	7.7
	VL	1502	864	83	112850	5.4
	GR	1559	2596	64	262344	12.6
	G	1587	2953	45	210196	10.2
	G2	1617	1274	52	104211	5.0
2	SL	1221	843	246	325267	17.0
	D	1352	3007	172	812491	44.0
	VR	1443	824	90	116626	6.5
	VL	1492	381	40	24135	1.4
	GR	1549	1916	78	233752	13.1
	G	1586	2864	55	246851	14.0
	G2	1619	958	47	69986	4.0
3	SL	1240	765	251	301243	21.6
	D	1350	2005	156	491390	36.8
	VR	1437	723	115	131168	10.0
	VL	1515	751	71	84750	6.5
	GR	1559	1433	53	119445	9.3
	G	1586	1872	44	129677	10.2
	G2	1619	970	47	71379	5.6
4	SL	1246	1546	242	588545	24.5
	D	1351	3508	151	830365	36.0
	VR	1441	1143	88	157084	7.0
	VL	1494	804	60	75508	3.4
	GR	1537	1431	53	118196	5.3
	G	1571	3048	51	245220	11.1
	G2	1599	2983	60	283111	12.7

CONCLUSIONS

The obtained results indirectly confirm the assumption about the formation of cavitation bubbles at the phase boundaries represented by CSU in oil and fuel oil products. In this regard, the destructive impact of the treatment is primarily directed at the components forming the CSU. As a result of the destruction of resins and asphaltenes, the group composition of the fuel oil changes (the share of resins and asphaltenes decreases, asphaltenes become more aromatic, and the oil fractions are enriched with saturated hydrocarbons) along with its rheological characteristics, which is reflected in the reduction of viscosity. The reduction in the size of the core forming the CSU means that the viscosity characteristics of the system do not return to their initial values even after the relaxation of intermolecular interactions between the core and the solvation layers. It is shown that the processes of CSU destruction under cavitation impact are intensified by the preliminary compounding of fuel oil with low-boiling hydrocarbons.

Acknowledgments

The work was carried out using the equipment of the Center for Collective Use at the RTU MIREA with the support of the Ministry of Science and Higher Education of the Russian Federation under agreement No. 075-15-2021-689 dated September 1, 2021. The authors thank the staff of the Department of Physics and Technical Mechanics of the Institute of Advanced Technologies and Industrial Programming at the RTU MIREA, A.D. Maksimov and N.A. Sanzharovskiy, for recording the Raman spectra of the provided samples.

Authors' contributions

D.V. Nikishin—identification of research objects, conducting experiments, analysis and processing of experimental data obtained and analysis of literary sources, writing and editing the text of the article.

B.V. Peshnev—formulation of the purpose and objectives of the research, analysis of literary sources, writing and editing the text of the article, development of methodology and analysis of the results obtained.

A.I. Nikolaev—consulting on the instrument base, methodology issues, editing the text of the article.

The authors declare no conflicts of interest.

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Translated from Russian into English by H. Moshkov
Edited for English language and spelling by Thomas A. Beavitt