DOI: 10.6060/ivkkt.20246704.6951

УДК: 622.276.4:622.276.6

ИССЛЕДОВАНИЕ РАСТВОРЯЮЩЕЙ СПОСОБНОСТИ ВОДНЫХ И УГЛЕВОДОРОДНЫХ РАСТВОРОВ НИЗШИХ СПИРТОВ И СЛОЖНЫХ ЭФИРОВ ПО ОТНОШЕНИЮ К ОРГАНИЧЕСКОМУ ВЕЩЕСТВУ ПОРОД БАЖЕНОВСКОЙ СВИТЫ

М.А. Силин, Л.А. Магадова, З.Р. Давлетов, Ю.Ж. Вагапова, Р.Н. Набиулина

Михаил Александрович Силин (ORCID 0000-0003-1170-8605), Любовь Абдулаевна Магадова (ORCID 0000-0001-5541-6896), Заур Растямович Давлетов (ORCID 0009-0000-2034-4490), Юлия Жановна Вагапова (ORCID 0000-0001-6958-2334)*, Рузалина Наиловна Набиулина (ORCID 0009-0006-0074-0035)

Кафедра технологии химических веществ для нефтяной и газовой промышленности, Факультет химической технологии и экологии, Российский государственный университет нефти и газа (НИУ) им. И.М. Губкина, Ленинский просп., 65, Москва, Российская Федерация, 119991
E-mail: silin.m@gubkin.ru, lubmag@gmail.com, zaurdavletov@mail.ru, juliatuesdays@yandex.ru*, nabiulina.ruzalina@mail.ru

Работа посвящена рассмотрению особенностей воздействия органическими соединениями (растворителями) на образцы породы баженовской свиты, в которой содержится большое количество непревращенного органического вещества (кероген, битумоиды). Данная статья содержит результаты изучения растворяющей способности индивидуальных низкомолекулярных спиртов и сложных эфиров, а также растворов указанных соединений в воде и в неполярном ароматическом растворителе (сольвент нефтяной). Среди исследованных индивидуальных растворителей наибольшую растворяющую способность проявляют сложные эфиры уксусной кислоты, менее активны спирты. Сольвент нефтяной в незначительной степени растворяет органическое вещество породы и требует добавления более полярных органических соединений. Зависимости растворяющей способности углеводородных растворов спиртов от концентрации спирта имеют экстремальный характер при максимуме, составляющем 10 %мас. На основании полученных результатов дополнительно оценивалось взаимное влияние растворителей в углеводородной среде. Установлено, что растворы изопропанола и ароматического растворителя проявляют синергетический эффект по отношению к растворимости органического вещества породы в большей степени, чем углеводородные растворы сложных эфиров. Для составов, показавших наибольшую растворяющую способность, была проведена качественная и полуколичественная оценка изменения составов образцов пород после экстракции с помощью рентгеновской дифрактометрии и ИК-Фурье-спектроскопии. Показано, что смеси полярного и неполярного растворителей обеспечивают более равномерное извлечение алифатических и ароматических компонентов органического вещества породы. Определено, что химические системы, содержащие сольвент нефтяной, изопропанол и изопропилацетат, могут стать основой для разработки технологических жидкостей, направленных на повышение нефтеотдачи в керогеносодержащих коллекторах.

Ключевые слова: органическое вещество, растворители, низкомолекулярные спирты, сложные эфиры, химические способы воздействия, нефтеизвлечение, кероген, экстракция, нетрадиционная нефть

Для цитирования:
Силин М.А., Магадова Л.А., Давлетов З.Р., Вагапова Ю.Ж., Набиулина Р.Н. Исследование растворяющей способности водных и углеводородных растворов низших спиртов и сложных эфиров по отношению к органическому веществу пород баженовской свиты. *Изв. вузов. Химия и хим. технология*. 2024. Т. 67. Вып. 4. С. 115–125. DOI: 10.6060/ivkkt.20246704.6951.

For citation:
Silin M.A., Magadova L.A., Davletov Z.R., Vagapova Yu.Zh., Nabiulina R.N. Analysis of dissolving ability of lower alcohols and esters aqueous and hydrocarbon solutions to organic matter of bazhenov formation rocks. *ChemChemTech [Izv. Vyssh. Uchebn. Zaved. Khim. Khim. Tekhnol.]*. 2024. V. 67. N 4. P. 115–125. DOI: 10.6060/ivkkt.20246704.6951.

ANALYSIS OF DISSOLVING ABILITY OF LOWER ALCOHOLS AND ESTERS AQUEOUS AND HYDROCARBON SOLUTIONS TO ORGANIC MATTER OF BAZHENOV FORMATION ROCKS

M.A. Silin, L.A. Magadova, Z.R. Davletov, Yu.Zh. Vagapova, R.N. Nabiulina

Mikhail A. Silin (ORCID 0000-0003-1170-8605), Lyubov A. Magadova (ORCID 0000-0001-5541-6896), Zaur R. Davletov (ORCID 0009-0000-2034-4490), Yuliya Zh. Vagapova (ORCID 0000-0001-6958-2334)*, Ruzalina N. Nabiulina (ORCID 0009-0006-0074-0035)

Department of Technology of Chemicals for Oil and Gas Industry, Faculty of Chemical and Environmental Engineering of Gubkin University, Leninsky ave., 65, Moscow, 119991, Russia
E-mail: silin.m@gubkin.ru, lubmag@gmail.com, zaurdavletov@mail.ru, juliatuesdays@yandex.ru*, nabiulina.ruzalina@mail.ru

This work is devoted to studying the characteristics of treatments with organic solvents on bazhenov formation rock samples, which contains a large amount of unconverted organic matter (kerogen, bitumen). This article contains the results of studying the dissolving abilities of individual low-molecular alcohols and esters, and solutions of these compounds in water and in a non-polar aromatic solvent (petroleum solvent). Among the individual solvents studied, esters of acetic acid showed the greatest dissolving ability; alcohols are less active. Petroleum solvent slightly dissolves the rock's organic matter and needs the addition of more polar organic compounds. The dependences of dissolving ability of alcohols' hydrocarbon solutions on alcohol concentration is extreme, with a maximum of 10 wt.%. Based on the obtained results, the mutual influence of solvents in the hydrocarbon fluid was additionally evaluated. It has been established that solutions of isopropanol and aromatic solvent show a synergistic effect to the dissolution of rock organic matter more than hydrocarbon solutions of esters. For the compositions that showed the greatest dissolving ability, a qualitative and semi-quantitative analysis was made for establishing changes in the composition of rock samples after extraction using X-Ray diffraction and Fourier-transform infrared spectroscopy. It is shown that mixtures of polar and non-polar solvents provide a more regular extraction of aliphatic and aromatic components of rock organic matter. Systems containing petroleum solvent, isopropanol and isopropyl acetate have been identified as the basis for the development of process fluids for increasing oil recovery in organic-rich reservoirs.

Key words: organic matter, solvents, lower alcohols, esters, chemical treatments, oil recovery, kerogen, extraction, unconventional oil

INTRODUCTION

Production of unconventional oil is actual all over the world. The researchers are paying close attention to development of effective technologies of shale oil recovery. Bazhenov formation is considered as the main potential source of hard-to-recover and unconventional oil in Russia. Difficulties in its development and the inapplicability of traditional technologies are driven by several features as multicomponent composition of rocks, which is complicated by high content of organic matter, high reservoir temperatures and pressures, low porosity and permeability, heterogeneous rocks' composition and properties. Thus, despite the long history of studying and developing bazhenov formation, nowadays, there are a lot of number important technological problems. Mainly, they include the creation of effective stimulation methods and technologies to ensure stable well productivity [1-3].

A key feature of bazhenov formation is the high content of organic matter. It is represented not only by potentially recoverable hydrocarbons, but also by kerogen, which has excellent potential for generating gaseous and liquid hydrocarbons. Under these high-carbon formation conditions, kerogen is occurred as a rock-forming component and in common with silicates builds up organo-mineral complexes. It determines the predominantly hydrophobic nature of surface wettability in the void space [4-6].

Irregularity of organic matter spread is noted for the rocks of bazhenov formation. Generated hydrocarbons not only migrate along the sections, but accumulate in the oil source rock mass due to low reservoir properties of these rocks [7]. Hydrocarbons and heteroatomic oil compounds can exist in a free state, or can be adsorbed on the surface of kerogen and minerals. Using existing technologies, light, medium and heavy oils are produced from bazhenov formation reservoirs, their density can be 770-910 kg/m^3 [8-9]. The observed difference is explained by the decrease of asphaltene-resin substances amount because of their adsorption on the surface of aluminosilicates during migration of hydrocarbons. Aggregates of asphaltenes and resins can be formed in the liquid hydrocarbons volume and block mobile hydrocarbons, so closed pores can occur [10].

The irregularity of organic matter spread is complicated by the presence of an isolated void space, and hydrocarbons can be extracted only when the rock matrix is broken. Many research results indicate difference in the composition and correlations of hydrocarbon amounts in open and closed parts of the void space [11]. Type and degree of organic matter maturity, migration processes, mineralogy, etc., have a significant impact [12]. In bazhenov formation rocks the presence of kerogen or organic porosity is also observed, it is formed as a result of thermal catalytic transformations of organic compounds [13].

The practice of bazhenov formation exploitation in pressure depletion indicates a rapid decrease in production rate in the first few years and low oil recovery factor. It is connected with a significant decrease in reservoir pressure and small well drainage area. Nowadays, there were proposed and tested different technologies of creating an extra filtration volume in rocks, thermal methods for maturing of organic matter, and using of chemical reagents [14].

According to the literature data, using of water-based technological fluids can lead to negative consequences in bazhenov formation – changes in surface wettability, swelling of clay minerals, formation of water blockades, colmatation of the pore space with water phase globules [15-17].

By the reason of these problems, development of hydrocarbon-based process fluids to improve the efficiency of oil recovery is of practical interest. Under bazhenov formation conditions, it is expected that solvents will desorb hydrocarbons from kerogen and minerals surface, provide the mobility of dispersed oil, and promote the unblocking of mobile hydrocarbons from closed pores by dissolution of asphaltene-resin aggregates.

The numerous research results have shown that solvents are mainly used for bitumoids extraction from bazhenov formation rocks for studying of organic matter composition. Thus, treatments with hexane allow to extract light hydrocarbons and oil components from rocks. Alcohol-benzene blend provides additional extraction of hydrocarbon components and asphaltene-resin compounds [10]. Chloroform is considered as a widely used extractant and an effective solvent for the neutral part of bitumoids [18]. Using of chloroform enables the dissolution up to 97% of light hydrocarbons content. At this time, it is noted that extraction from bazhenov formation rocks can significantly exceed 3 days caused by gradual extraction of hydrocarbons backed up by kerogen [19]. For a more complete extraction of organic matter components, step extraction using solvents of different polarity is proposed [20]. Also, to extract hydrocarbons from bazhenov formation rocks, it is effective to use mixtures of polar and non-polar solvents, for example, a mixture of n-hexane and chloroform (80:20% vol.) [21].

Solvents' impact on rocks of other high-carbon formations – shale oil deposits also is described in many scientific publications. Important characteristics that affect the dissolving ability are the polarity and the solubility parameter. It was shown in [22] with an example of methanol, toluene, cyclohexane, dichloromethane. Reaction time also affects the result: a decrease of saturated hydrocarbons content, an increase of polyaromatic compounds yield, and desorption of polar components of organic matter in the presence of dichloromethane are noted with an increase of extraction time from shale rocks [23]. In general, polar solvents (dichloromethane, chloroform, tetrahydrofuran, acetone) allow to extract more hydrocarbon compounds, but mixtures of polar and non-polar solvents significantly increase the extraction yield (for example, systems like tetrahydrofuran/toluene) [24].

Due to the facts mentioned above, the aim of this work is to analyse the effect of solvents with different polarity and their mixtures on bazhenov formation rock for the development of hydrocarbon-based process fluids directed to improving the efficiency of oil recovery.

MATERIALS AND METHODS

When choosing solvents, the presence of field experience in their use, their relative availability and the prohibition of organochlorine compounds use in oilfield chemistry were regarded [25, 26].

As a non-polar aromatic solvent (hydrocarbon base), petroleum solvent (nefras A-130/150), represented by a mixture of aromatic hydrocarbons of the benzene series, was used. According to chromatographic analysis, chosen non-polar solvent contains (% wt.): arenes – 89.2 (including C_7 – 33.6; C_8 – 39.7; C_9 – 10.1; C_{10} – 3.5; C_{11} – 2.0); paraffin-naphthenes – 8.6; olefins – 1.3; the rest is 0.9.

The polar reagents in this work were low molecular weight alcohols (methanol, ethanol, isopropanol) and acetic acid esters (methyl acetate, ethyl acetate, isopropyl acetate). In addition to studying individuals effect of reagents, the influence of low molecular weight alcohols and esters was evaluated in mixtures with non-polar solvent and in aqueous solutions. Ethyl acetate and isopropyl acetate were used only in mixture with aromatic solvent because of their limited solubility in water.

For carrying out this work, core samples from Palyanovskoye field related to bazhenov formation were taken. The mineralogical composition was analyzed using a Thermo Scientific ARL X'TRA X-Ray diffractometer. Emitting source is an X-Ray tube with a copper anode, the range of angles for taking diffractograms – 2-60° 2θ. Based on the analysis results of qualitative and quantitative mineralogical composition, an average sample was prepared for further research. According to this analysis, the average rock sample has the following mineralogical composition: quartz – 53.1%, albite – 12.2%, muscovite – 12.8%, illite – 11.7%, pyrite – 6.6%, kaolinite – 3.6%.

The impact of water-based and hydrocarbon-based systems was assessed by gravimetric method using disintegrated rock. Experiments were carried out at 70 °C under static conditions, the masses of the samples were analyzed at the reaction time of rock with solvent ½, 1, 2 and 3 h.

The mutual influence of the solvent mixture components was evaluated by deviation from the expected additive effect with calculation the corresponding coefficient:

$$K = {}^{P_{sol}}\!/_{(x_1 * P_1 + x_2 * P_2)}, \qquad (1)$$

where P_{sol} – amount of the dissolved organic matter by solvent's mixture, x_1, x_2 – concentration of components 1 and 2 in mixtures, respectively, P_1, P_2 – amount of the dissolved organic matter in individual components 1 and 2, respectively. At K > 1 synergism of components was observed in a mixture of solvents, K = = 1 – additivity, K < 1 – antagonism.

A semiquantitative analysis of rock samples' compositional change was carried out by determining crystallinity of the samples before and after treatment with solvents. This parameter was calculated from X-ray diffractograms using the Crystallinity software.

IR spectroscopy is a well-known method for studying rocks mineralogy, especially, in case of working with rocks of high-carbon formations as bazhenov formation in connection with the possibility of analyzing the characteristics of organic matter [27-30]. Effect of solvents on the organic matter components was determined using a Bruker TENSOR II Fourier-transform IR-spectrometer. The spectral range was 4000...500 cm^{-1}. Definition of changes in the organic matter structural-group composition was carried out using spectral coefficients calculated from the intensity of the absorption peaks [31, 32]:

$$C_1(aromaticity) = \frac{I_{1630}}{I_{2850}}, \qquad (2)$$

$$C_2(branching) = \frac{I_{1380}}{I_{1450}}, \qquad (3)$$

$$C_3(aliphaticity) = \frac{(I_{2850}+I_{1380})}{I_{1630}}. \qquad (4)$$

RESULTS AND DISCUSSION

Table 1 shows the dissolving ability of individual solvents after exposure to the rock samples for 3 h and characteristics of the solvent's polarity, their dipole moment, relative permittivity [33] and boiling point values.

Table 1

Dissolving ability of solvents to organic matter of the rock samples and physico-chemical properties of solvents

Таблица 1. **Растворяющая способность растворителей по отношению к органическому веществу породы и физико-химические характеристики растворителей**

Solvent	Amount of dissolved rock (A), % wt.	Dipole moment, D	Relative permittivity	Boiling point, °C
Water	-	1.82	80.1	100
Petroleum solvent	2.39	0.62 / 0.37*	2.57 / 2.38*	130-150**
Methanol	9.14	1.70	32.7	64.7
Ethanol	2.10	1.69	24.5	78.4
Isopropanol	6.22	1.66	17.9	82.4
Methyl acetate	10.51	1.72	7.0	57.1
Ethyl acetate	9.33	1.81	6.0	77.1
Isopropyl acetate	11.34	1.85	5.6	89

Notes: * The data are given for the components present in the largest amounts (o-xylene and toluene, respectively)
** Initial boiling point is not lower than 130 °C; boiling point of 90%, volume recovered is not higher than 150 °C
Примечания: * Данные приведены для компонентов, присутствующих в наибольших количествах (о-ксилол и толуол, соответственно)
** Температура начала перегонки – не ниже 130 °C; температура перегонки 90% от состава сольвента – не выше 150 °C

According to Table 1, esters of acetic acid show the highest dissolving ability among the studied individual solvents, alcohols are less active. This parameter for individual oxygen-containing solvents depends on the length of the hydrocarbon radical, which is determined by the polarity ratio and the affinity of solvent molecules with the components of rock's organic matter. Petroleum solvent slightly dissolves organic components, so it indicates necessity for adding more polar organic compounds to aromatic hydrocarbons contained in chosen solvent. Hence, the dissolving abilities of hydrocarbon and aqueous solutions of alcohols to organic matter of bazhenov formation rock were further determined (Fig. 1).

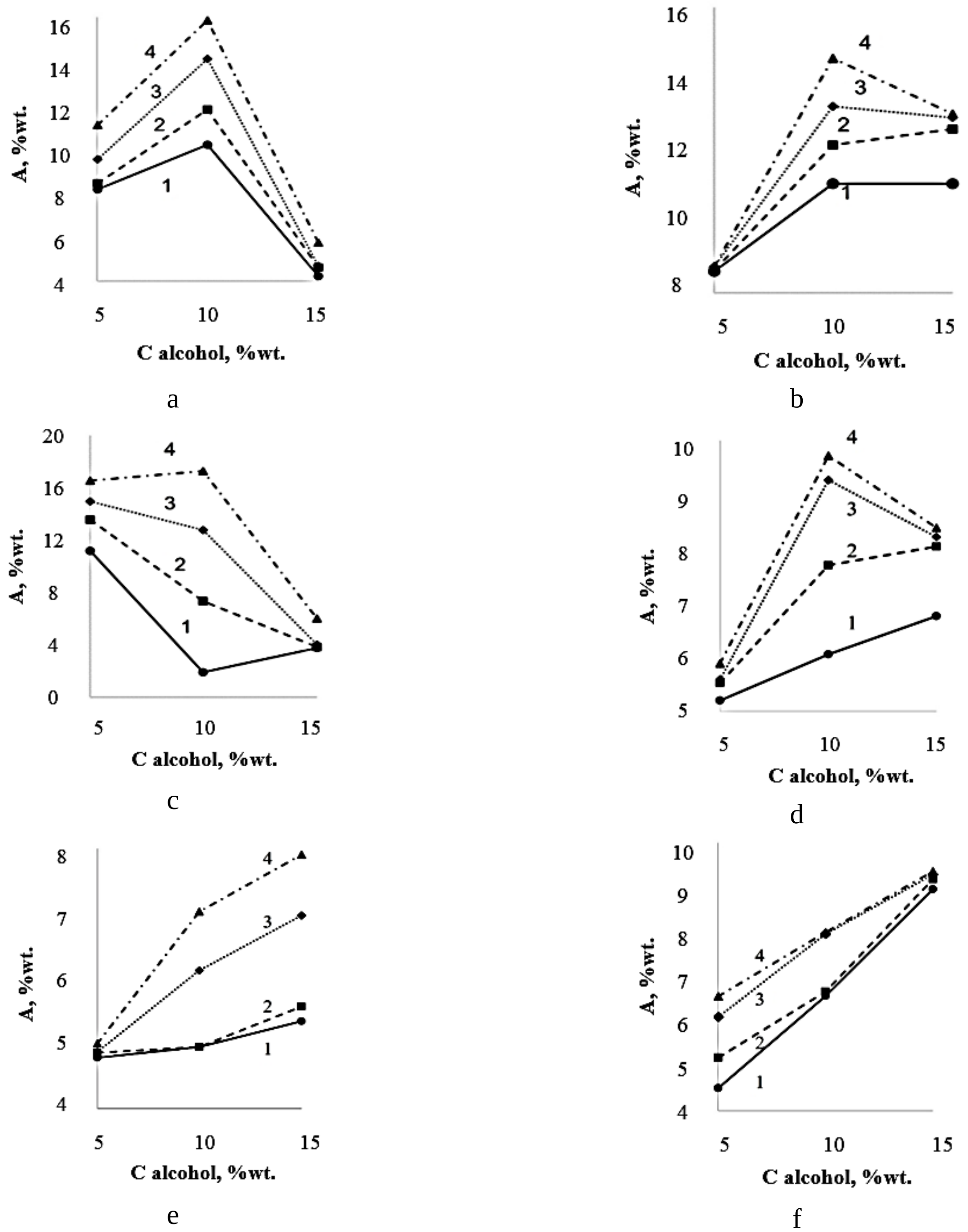

Fig. 1. Dependence of amount of dissolved rock's organic matter on alcohol concentration in hydrocarbon (**a-c**) and aqueous (**d-f**) solutions and reaction time: (**a**, **d**) – methanol; (**b**, **e**) – ethanol; (**c**, **f**) – isopropanol; 1- 0,5 h; 2 - 1 h; 3 - 2 h; 4 - 3 h

Рис. 1. Зависимости количества растворенного органического вещества породы от концентрации спирта в углеводородных(**a-c**) и водных(d-f) растворах и времени контакта: (**a**, **d**) – метанол; (**b**, **e**) – этанол; (**c**, **f**) – изопропанол; 1- 0,5 ч; 2 - 1 ч; 3 - 2 ч; 4 - 3 ч

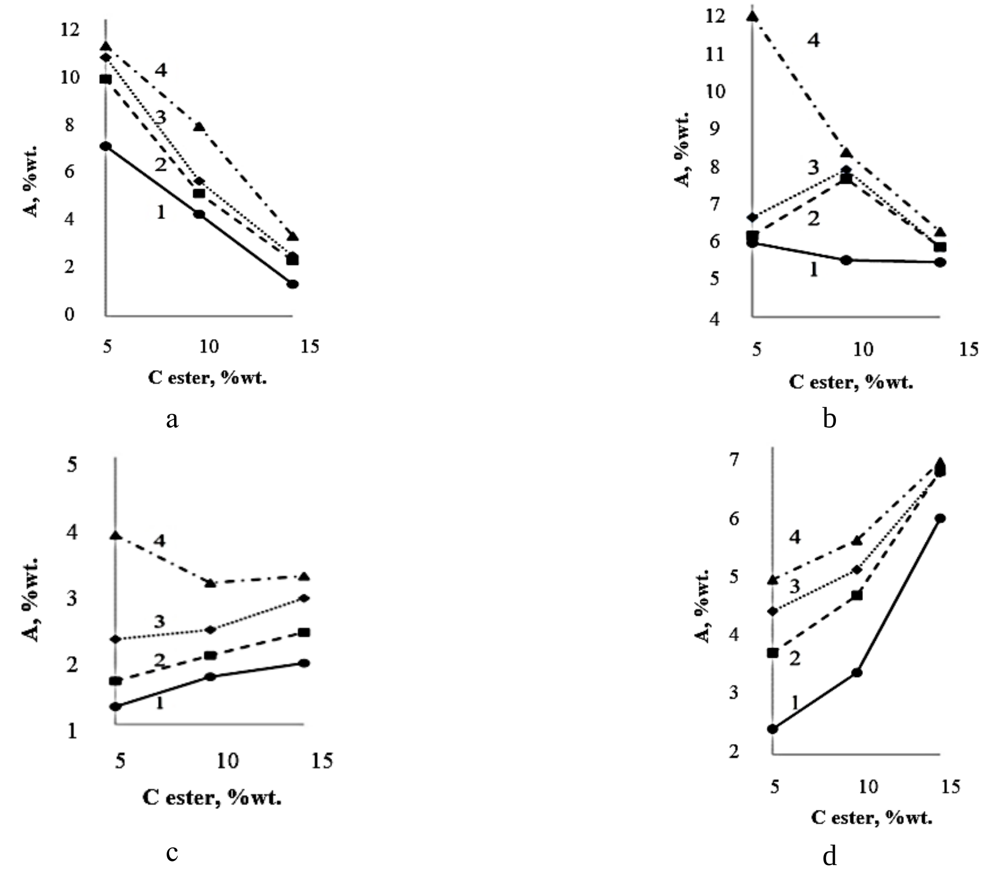

Fig. 2. Dependence of amount of dissolved rock's organic matter on ester concentration ((**a**, **b**) - methyl acetate; (**c**) - ethyl acetate; (**d**) - isopropyl acetate) in hydrocarbon (**a**, **c**, **d**) and aqueous (**b**) solutions and reaction time: 1- 0,5 h; 2 - 1 h; 3 - 2 h; 4 - 3 h

Рис. 2. Зависимости количества растворенного органического вещества породы от концентрации сложного эфира ((**a**, **b**) –метилацетат; (**c**) – этилацетат; (**d**)–изопропилацетат) в углеводородных (**a**, **c**, **d**) и водных(**b**) растворах и времени контакта 1- 0,5 ч; 2 - 1 ч; 3 - 2 ч; 4 - 3 ч

From the results obtained (Fig. 1), addition of alcohols provides an increase in the dissolving ability of systems containing aromatic solvent. In case of long-term experiments, hydrocarbon solutions of methanol and isopropanol at concentration 5-10% wt. and ethanol solutions at all concentrations have a bigger dissolving activity compared to individual alcohols. Increasing the interaction time of alcohol solutions and rock samples drives up the amount of dissolved rock. It is connected with incremental dissolution and desorption of organic matter components from the surface of minerals and kerogen.

During prolonged reaction with described core samples, an increase in the alcohols concentration up to 10% wt. in hydrocarbon solutions results in growth of the organic matter solubility, when alcohol amount becomes equal to 15% wt., there is a decrease in the solubility. These findings can be explained by an increase in the polarity of hydrocarbon solutions based on building up the concentration of more polar oxygen-containing solvent and the polarizability of arenes. This is also influenced by the change in ratio of orientation, induction and dispersion van der Waals forces. Polarity growth of hydrocarbon alcohol solutions leads to a better dissolution of polarizable aromatic hydrocarbons, polar heteroatomic compounds and asphaltene-resin compounds. Additionally, following build-up of the alcohols' concentration enhances their behavior as an antisolvent and reduces solubility of paraffin-naphthenic hydrocarbons, which are mainly dissolved under dispersion forces of intermolecular interaction.

Described principles of changes in the dissolving activity of hydrocarbon solutions among «methanol – ethanol – isopropanol» is associated with a decrease in polarities of individual alcohols and with an increase of the alkyl radical of their molecules. This affects the intermolecular interactions of solvent with various components of organic matter. For example, it was found in [34] that with an increase in length of hydrocarbon radical of alcohols, agglomeration of asphaltene particles is observed, that leads to precipitation of resin and asphaltene components by aliphatic alcohols.

Aqueous solutions of alcohols are characterized by significantly lower dissolution abilities of rocks' organic matter (Fig. 1). At the same time, prolonged contact of the rock with an increase in CH_3OH concentration in aqueous solutions leads to obtaining results similar to hydrocarbon solutions. However, organic compounds are dissolved weaker in aqueous solutions of methanol, than in individual alcohols. Also, an increase of the ethanol and isopropanol content in water (up to 15% wt.) brings to the slow dissolution of organic compounds from the core samples. It happened because of the solution polarity reducing which remains significantly higher than in the case of hydrocarbon solutions. Solvent can interact with polar asphaltene-resin compounds, which provides greater dispersion of organic components. Dissolution abilities of ethanol and isopropanol in water solutions are bigger than the effectiveness of their individual compounds.

Fig. 2 shows the results of esters' hydrocarbon solutions analysis and aqueous solutions of methyl acetate at the same conditions.

Esters in a mixture with aromatic solvent and water have smaller dissolution ability to organic compounds of the rock samples than their individual form. Length of the hydrocarbon radical affects the molecules polarity and esters affinity for organic components. The structure of esters also determines type of curves obtained depending on their concentration in hydrocarbon solutions: elevating methyl acetate amount reduces the dissolution process. At the same time, the dissolution ability of isopropyl acetate proportionally increases with the concentration growth. For ethyl acetate solutions, the amount of dissolved components slightly depends on the ester concentration and is characterized by low values. Long-term interaction of hydrocarbon and aqueous solutions of methyl acetate with the rock samples (for 3 h) involves their similar behavior, which indicates the absence of solvent's nature influence.

To compare the effect of studied oxygen-containing organic solvents, the mutual influence of the solvent mixture components was evaluated. The calculation results are presented in Table 2.

According to Table 2, for hydrocarbon solutions of alcohols and esters, a synergistic effect is observed within organic compounds dissolution. This can be explained by the polarizability of arenes in the hydrocarbon solvent in the presence of polar oxygen-containing compounds. Also, solvent mixtures provide a comprehensive effect on various organic components, including promoting desorption of hydrocarbons from kerogen surface. Mixtures containing alcohols show the greatest combined action. Esters have significantly reduced synergetic effect than alcohols, their combined action with aromatic solvent decreases in the following line: «methyl acetate – isopropyl acetate – ethyl acetate». Despite their reduced synergism, esters can be used in technologies that involve the delayed action in hydrocarbon-based chemical systems. At the same time, it is important to note the context of the investigated solvents application. Use of ethanol is restricted by government regulations, also methanol and methyl acetate have low boiling points that makes them difficult in treatments.

For a supplementary assessment of organic matter's dissolution ability, crystallinity of the rock samples was determined from X-ray diffractograms obtained using powder X-Ray diffraction method. The influence of individual solvents (petroleum solvent, isopropanol and isopropyl acetate) was analyzed. Hydrocarbon solutions of isopropanol (10% wt.) and isopropyl acetate (15% wt.), characterized by high dissolution abilities, were also studied. These results are shown in Table 3.

Table 2

Estimation of mutual influence of components in hydrocarbon solutions of alcohols and esters

Таблица 2. **Оценка взаимного влияния компонентов в углеводородных растворах спиртов и сложных эфиров**

Solvent	Mutual influence coefficient at the alcohol or ester concentration		
	5 % wt.	10 % wt.	15 % wt.
Methanol	4.1	5.2	1.7
Ethanol	3.7	6.2	5.6
Isopropanol	6.4	6.2	2.0
Methyl acetate	3.9	2.4	0.9
Ethyl acetate	1.4	1.0	0.9
Isopropyl acetate	1.7	1.7	1.8

Table 3

Crystallinity parameter of the rock samples of bazhenov formation

Таблица 3. **Степень кристалличности образцов породы баженовской свиты**

Solvent	Crystallinity, %
Before treatment	54
Petroleum solvent	68
Isopropanol	64
Isopropyl acetate	70
Isopropanol (10% wt.) + Petroleum solvent	65
Isopropyl acetate (15 % wt.) + Petroleum solvent	65

The initial rock samples from bazhenov formation is characterized by a low value of crystallinity and is established by the high content of organic matter referred by X-Ray analysis to an amorphous phase. Solvent extraction promotes an increase in crystallinity connected with the dissolution of bitumoids and light hydrocarbons in an isolated and sorbed state [35]. However, the evaluation of this parameter does not allow to establish features of individual solvents effect because of metod's low accuracy, irregular distribution of organic components in samples, interactions between solvent molecules and clay minerals causing volume growth of their aggregates and kerogen swelling [22, 36].

For a more detailed analysis of solvent's influence on changes in the structural-group composition of organic components, the rock samples were studied by FTIR-spectroscopy before and after treatments with solvents. Based on the FTIR-spectra, the spectral coefficients of aromaticity, branching and aliphaticity were calculated (Table 4).

Table 4

Characterization of changes in the structural-group composition of organic components after treatments with solvents using FTIR-spectroscopy method

Таблица 4. **Оценка изменений структурно-группового состава органического вещества пород при контакте с растворителями с помощью метода ИК-Фурье-спектроскопии**

Solvent	C_1	C_2	C_3
Before treatment	1.04	0.48	3.14
Petroleum solvent	0.75	0.60	6.80
Isopropanol	0.91	0.86	2.01
Isopropyl acetate	0.93	0.78	1.88
Isopropanol (10% wt.) + + Petroleum solvent	0.85	0.83	2.18
Isopropyl acetate (15% wt.) + + Petroleum solvent	0.92	0.87	2.16

As follows from the data in Table 4, petroleum solvent interacts to aromatic hydrocarbons of organic matter (the minimum value of aromaticity coefficient C_1 = 0.75) and reacts in smaller activity with paraffin-naphthenic hydrocarbons (the maximum value of aliphatic coefficient C_3 = 6.80). The effect on the rock samples by oxygen-containing organic compounds in an individual form and mixtures of esters and aromatic solvent, provides dissolution of all components (mostly aliphatic) that decreases the coefficients to C_1 = = 0.91-0.93 and C_3 = 1.88-2.16. Additionally, using of low molecular weight alcohol in solution with petroleum solvent significantly increases the dissolution ability to aromatic components (C_1 = 0.85).

CONCLUSION

Co-use of aromatic solvent (petroleum solvent) and lower alcohols allows to obtain systems with a high dissolving ability for treatments of organic matter containing in bazhenov formation rocks. These systems show synergism of solvents with different polarity because of the polarizability of arenes in nonpolar solvent. They more equally affect both aromatic and aliphatic components of organic matter, promote the dissolution of light hydrocarbons, heteroatomic petroleum compounds, asphaltene-resin components and provide desorption of hydrocarbons from the surface of kerogen and clay minerals.

Esters demonstrate weaker the mutual growth of dissolution in the presence of aromatic solvent in solutions than alcohols. Despite the poor synergism, esters can be used in technologies that involve the delayed action of hydrocarbon-based chemical systems. In oilfield practice, acid-generating compositions based on esters became widely used. Their application let to affect with them not only on organic components, but also to mineral matrix of rocks [37-39].

According to the results obtained, the dissolution intensity depends on reaction time of solvent with rock, concentration of oxygen-containing polar component, length of hydrocarbon group in molecule and nature of solvent (solution base).

Taking into account these results of dissolution abilities and some restrictions (for example, low boiling points and government regulation), solvent systems containing petroleum solvent, isopropanol and isopropyl acetate can be considered as process fluids for oil recovery under conditions of bazhenov formation.

ACKNOWLEDGMENTS

The research was supported by the Ministry of Science and Higher Education of the Russian Federation by the agreement № 075-15-2022-300, 18 April 2022, within the program of development of World Class Scientific Centers «Rational utilization of liquids reserves of the planet».

The authors declare the absence a conflict of interest warranting disclosure in this article.

Работа выполнена при поддержке Министерства науки и высшего образования Российской Федерации по соглашению № 075-15-2022-300 от 18.04.2022 г. в рамках программы развития НЦМУ «Рациональное освоение запасов жидких углеводородов планеты».

Авторы заявляют об отсутствии конфликта интересов, требующего раскрытия в данной статье.

ЛИТЕРАТУРА

1. **Конторович А.Э., Бурштейн Л.М., Лившиц В.Р., Рыжкова С.В.** Главные направления развития нефтяного комплекса России в первой половине XXI века. *Вестн. РАН.* 2019. Т. 89. Вып. 11. С. 1095-1104. DOI: 10.31857/S0869-587389111095-1104.
2. **Андреева Н.Н., Стрижнев К.В., Алексеев Ю.В.** Первые результаты работы над концепцией полигона общего доступа «Бажен». *Нефтяное хоз-во.* 2020. Вып. 3. С. 22-27. DOI: 10.24887/0028-2448-2020-3-22-27.
3. **Оксенойд Е.Е., Исаев В.И., Кузьменков С.Г., Новиков М.В., Печерин Т.Н.** Проблемы реализации нефтегазового потенциала баженовско-абалакского нефтегазоносного комплекса в Ханты-Мансийском автономном округе. *Георесурсы*. 2023. Т. 25. Вып. 1. С. 51-59. DOI: 10.18599/grs.2023.1.6.
4. **Topchii M.S., Kalmykov A.G., Kalmykov G.A., Fomina M., Ivanova D.** Evaluation of Hydrocarbon-Generating Potential of Bazhenov High-Carbon Formation: SPE Russian Petroleum Technology Conference. Moscow. 2020. SPE-201813-MS. DOI: 10.2118/201813-RU.
5. **Гончаров И.В., Фадеева С.В., Самойленко В.В., Обласов Н.В., Бахтина Е.С.** Генерационный потенциал органического вещества пород баженовской свиты юго-востока Западной Сибири (Томская область). *Нефтяное хоз-во.* 2014. Вып. 11. С. 12-16. DOI: 10.2118/171170-RU.
6. **Калмыков А.Г., Бычков А.Ю., Калмыков Г.А., Бугаев И.А., Козлова Е.В.** Генерационный потенциал керогена баженовской свиты и возможность его реализации. *Георесурсы*. 2017. Спецвып. Ч. 2. С. 165-172. DOI: 10.18599/grs.19.17.
7. **Миллер В.К., Иванова Л.В., Мансур Г., Уэртас-Будилова С.К., Кошелев В.Н., Примерова О.В.** Структурные особенности смоли и асфальтенов нефтей месторождений Удмуртии. *Изв. вузов. Химия и хим. технология.* 2021. Т. 64. Вып. 10. С. 113-118. DOI: 10.6060/ivkkt.20216410.6370.
8. **Ященко И.Г.** Пластовые условия залегания трудноизвлекаемых нефтей баженовской свиты и их физико-химические свойства. *Изв. вузов. Химия и хим. технология.* 2023. Т. 66. Вып. 11. С. 6-17. DOI: 10.6060/ivkkt.20236611.9t.
9. **Соболева Е.В.** Формирование состава нефтей пласта Ю0 Баженовской свиты Салымского месторождения. *Георесурсы*. 2017. Спецвып. Ч. 2. С. 144-154. DOI: 10.18599/grs.19.15.
10. **Костенко О.В.** Блокирующий характер распределения высокомолекулярных соединений битумоида в поровой системе баженовской свиты (Западно-Сибирский бассейн). *Нефтегаз. геология. Теория и практ.* 2014. Т. 9. Вып. 1. С. 1-13. DOI: 10.17353/2070-5379/12_2014.
11. **Конторович А.Э., Костырева Е.А., Родякин С.В., Сотнич И.С., Ян П.А.** Геохимия битумоидов баженовской свиты. *ГНГ*. 2018. Вып. 2. С. 79-88. DOI: 10.31087/0016-7894-2018-2-79-88.
12. **Колчина Г.Ю., Полетаева О.Ю., Леонтьев А.Ю., Мовсумзаде Э.М., Логинова М.Е., Колчин А.В.** Анализ состава и структуры тяжелых нефтей по данным ЯМР-спектроскопии. *Изв. вузов. Химия и хим. технология.* 2023. Т. 66. Вып. 6. С. 94-101. DOI: 10.6060/ivkkt.20236606.6783.
13. **Балушкина Н.С., Калмыков Г.А., Кирюхина Т.А., Коробова Н.И., Корост Д.В., Соболева Е.В., Ступакова А.В., Фадеева Н.П., Хамидуллин Р.А., Шарданова Т.А.** Закономерности строения баженовского горизонта и верхов абалакской свиты в связи с перспективами добычи нефти. *ГНГ*. 2013. Вып. 3. С. 48-61.
14. **Магадова Л.А., Давлетов З.Р., Вагапова Ю.Ж.** Обзор и анализ технологий, повышающих эффективность нефтеиз-

REFERENCES

1. **Kontorovich A.E., Burshtein L.M., Livshits V.R., Ryzhkova S.V.** Main directions of development of the oil complex of Russia in the first half of the twenty-first century. *Vest. RAN.* 2019. V.89. N 6. P. 1095-1104 (in Russian). DOI: 10.31857/S0869-587389111095-1104.
2. **Andreeva N.N., Strizhnev K.V., Alekseev Yu.V.** First results of work on concept of field test site with public access Bazhen. *Neftyanoe Khoz-vo.* 2020. N 3. P. 22-27 (in Russian). DOI: 10.24887/0028-2448-2020-3-22-27.
3. **Oksenoyd E.E., Isaev V.I., Kuzmenkov S.G., Novikov M.V., Pecherin T.N.** Problems of oil and gas potential realization in bazhenov-abalak play in Khanty-Mansi Autonomous *Okrug-Yugra. Georesursy.* 2023. V. 25. N 1. P. 51-59 (in Russian). DOI: 10.18599/grs.2023.1.6.
4. **Topchii M.S., Kalmykov A.G., Kalmykov G.A., Fomina M., Ivanova D.** Evaluation of Hydrocarbon-Generating Potential of Bazhenov High-Carbon Formation: SPE Russian Petroleum Technology Conference. Moscow. 2020. SPE-201813-MS. DOI: 10.2118/201813-RU.
5. **Goncharov I.V., Fadeeva S.V., Samoilenko V.V., Oblasov N.V., Bakhtina E.S.** Generation potential of organic matter Bazhenov Formation rocks in the south-east of West Siberia (Tomsk region).*Neftyanoe Khoz-vo.* 2014. N 11. P. 12-16 (in Russian). DOI: 10.2118/171170-RU.
6. **Kalmykov A.G., Bychkov A.Yu., Kalmykov G.A., Bugaev I.A., Kozlova E.V.** Generation potential of kerogen of the Bazhenov formation and possibility of its implementation. *Georesursy.* 2017. N S. P. 165-172 (in Russian). DOI: 10.18599/grs.19.17.
7. **Miller V.K., Ivanova L.V., Mansur G., Uertas-Budilova S.K., Koshelev V.N., Primerova O.V.** The structural features of resins and asphaltenes of crude oils from Udmurtia oilfields. *ChemChemTech [Izv. Vyssh. Uchebn. Zaved. Khim. Khim. Tekhnol.].* 2021. V. 64. N 10. P. 113-118. DOI: 10.6060/ivkkt.20216410.6370.
8. **Yashchenko I.G.** Formation conditions of occurrence of hard-to-recover oils of the bazhenov formation and their physico-chemical properties. *ChemChemTech [Izv. Vyssh. Uchebn. Zaved. Khim. Khim. Tekhnol.].* 2023. V. 66. N 11. P. 6-17. DOI: 10.6060/ivkkt.20236611.9t.
9. **Soboleva E.V.** Formation of the oil composition of the Yu0 Bazhenov formation, Salym oil field. *Georesursy.* 2017. N S. P. 144-154 (in Russian). DOI: 10.18599/grs.19.15.
10. **Kostenko O.V.** Blocking nature of distribution of high-molecular compounds of bitumoid in pore system of bazhenov formation (West Siberian basin). *Neftegaz. Geologiya. Teoriya Prakt.* 2014. V.9. N 1. P. 1-13. (in Russian). DOI: 10.17353/2070-5379/12_2014.
11. **Kontorovich A.E., Kostyreva E.A., Rodyakin S.V., Sotnich I.S., Yan P.A.** Geochemistry of the Bazhenov Formation bitumoids. *GNG.* 2018. N 2. P. 79-88 (in Russian). DOI: 10.31087/0016-7894-2018-2-79-88.
12. **Kolchina G.Yu., Poletaeva O.Yu., Leontev A.Yu., Movsumzade E.M., Loginova M.E., Kolchin A.V.**Analysis of the composition and structure of heavy oils according to NMR Spectroscopy. *ChemChemTech [Izv. Vyssh. Uchebn. Zaved. Khim. Khim. Tekhnol.].* 2023. V. 66. N 6. P. 94-101. DOI: 10.6060/ivkkt.20236606.6783.
13. **Balushkina N.S., Kalmykov G.A., Kiryukhina T.A., Korobova N.I., Korost D.V., Soboleva E.V., Stupakova A.V., Fadeyeva N.P., Khamidullin R.A., ShardanovaT.A.** Regularities of structure of bazhenov horizon and upper parts

влечения из пластов баженовской свиты. *Изв. Томск. политех. ун-та. Инж. георес.* 2023. Т. 334. Вып. 2. С. 206-216. DOI: 10.18799/24131830/2023/2/3854.

15. **Лопатин Н.В., Кос И.М., Емец Т.П.** Баженовская нефтяная система в зоне сочленения Сургутского и Нялинского сводов Западной Сибири. *Геология, геофизика и разр. нефт. и газ. мест-ий.* 2000. Вып. 1. С. 18-37.
16. **Вашкевич А.А., Стрижнев К.В., Жуков В.В.** Опыт компании «Газпром нефть» в разработке Баженовской свиты. Российская техническая нефтегазовая конференция и выставка SPE по разведке и добыче. 2014. SPE-171165-MS. DOI: 10.2118/171165-RU.
17. **Черемисин А.Н., Мухина Е.Д., Ушакова А.С., Прочухан К.Ю., Касьяненко А.А.** Химические, газовые и тепловые МУН для баженовской свиты. *Дел. журн. Neftegaz.RU.* 2022. Вып. 5-6 (125-126). С. 58-64.
18. **Нальгиева Х.В., Копытов М.А.** Характеристики продуктов деструкции смол и асфальтенов в сверхкритической воде. *Изв. вузов. Химия и хим. технология.* 2023. Т. 66. Вып. 11. С. 25-31. DOI: 10.6060/ivkkt.20236611.11t.
19. **Козлова Е.В., Фадеева Н.П., Калмыков Г.А., Балушкина Н.С., Пронина Н.В., Полудеткина Е.Н., Костенко О.В., Юрченко А.Ю., Борисов Р.С., Бычков А.Ю., Калмыков А.Г., Хамидуллин Р.А., Стрельцова Е.Д., Борисов М.В.** Технология исследования геохимических параметров органического вещества керогенонасыщенных отложений (на примере баженовской свиты, Западная Сибирь). *Вестн. Московск. ун-та. Сер. 4: Геология.* 2015. Вып. 5. С. 44-53.
20. **Тихонова М.С., Иванова Д.А., Калмыков А.Г., Борисов Р.С., Калмыков Г.А.** Методика ступенчатой экстракции пород высокоуглеродистых формаций для изучения компонентного распределения битумоидов и изменчивости их основных геохимических параметров. *Георесурсы*. 2019. Т. 21. Вып. 2. С. 172-182. DOI: 10.18599/grs.2019.2.172-182.
21. **Коржов Ю.В., Стариков А.И., Кузина М.Я., Романова Т.И.** Распределение ароматических углеводородов в нижнемеловых и юрских отложениях месторождения Боровое. *Бюлл. науки и практ.* 2022. Т. 8. Вып. 6. С. 95-115. DOI: 10.33619/2414-2948/79/12.
22. **DiStefano V.H., McFarlane J., Stack A.G., Perfect E., Mildner D.F.R., Bleuel M., Chipera S.J., Littrell K.C., Cheshire M.C., Manz K.E., Anovitz L.M.** Solvent-pore interactions in the Eagle Ford shale formation. *Fuel*. 2019. N 238. P. 298-311. DOI: 10.1016/j.fuel.2018.10.010.
23. **Mohnhoff D., Littke R., Krooss B.M., Weniger P.** Flow-through extraction of oil and gas shales under controlled stress using organic solvents: Implications for organic matter-related porosity and permeability changes with thermal maturity. *Int. J. Coal Geol*. 2016. V. 157. N 1. P. 84-99. DOI: 10.1016/j.coal.2015.09.010.
24. **Alnawafleh H.M., Fraige F.Y.** Shale Oil Solvent Extraction of Central Jordan El-Lajjun Oil Shale. *JASMI*. 2015. N 5. P. 35-43. DOI: 10.4236/jasmi.2015.53004.
25. **Козлов С.А., Фролов Д.А., Кузьмина Е.П., Кириллов А.С., Коновалов В.В., Склюев П.В., Алексеева Н.И.** Установление причин образования хлорорганических соединений в товарной нефти. *Нефтепром. дело.* 2019. Вып. 5 (605). С. 64-69. DOI: 10.30713/0207-2351-2019-5(605)-64-69.
26. **Татьянина О.С., Губайдулин Ф.Р., Судыкин С.Н., Жилина Е.В.** Исследование образования хлорорганических соединений в результате применения химических реагентов в нефтедобыче. *Нефтяное хоз-во*. 2022. Вып. 7. С. 55-57. DOI: 10.24887/0028-2448-2022-7-55-57.

of abalak suite in view of oil production prospects. *GNG*. 2013. N 3. P. 48-61 (in Russian).

14. **Magadova L.A., Davletov Z.R., Vagapova Yu.Zh.** Review and analysis of technologies increasing the efficiency of oil recovery from bazhenov formation reservoirs. *Izv. Tomsk. Politekh. Un-ta. Inzh. Geores.* 2023. V. 334. N 2. P. 206-216 (in Russian). DOI: 10.18799/24131830/2023/2/3854.
15. **Lopatin N.V., Kos I.M., Emets T.P.** Bazhenov oil system in the junction zone of the Surgut and Nyalin arches of Western Siberia. *Geologiya, Geofizika. Razr. Nefti Gaz. Mest-ii.* 2000. N 1. P. 18-37 (in Russian).
16. **Vashkevich A., Strizhnev K., Zhukov V.** GazpromNeft Experience of Bazhenov Suite Development: SPE Russian Oil and Gas Exploration & Production Technical Conference and Exhibition. 2014. SPE-171165-MS. (in Russian). DOI: 10.2118/171165-RU.
17. **Mukhina E.D., Cheremisin A.N., Ushakova A.S., Prochukhan K.Yu., Kasyanenko A.A.** Chemical, gas and thermal EOR for the bazhenov formation. *Del. Zhurn. Neftegaz. RU.* 2022. N 5-6 (125-126). P. 58-64 (in Russian).
18. **Nalgieva Kh.V., Kopytov M.A.** Characteristics of the degradation products of resins and asphaltenes in supercritical water. *ChemChemTech [Izv. Vyssh. Uchebn. Zaved. Khim. Khim. Tekhnol.]*. 2023. V. 66. N 11. P. 25-31. DOI: 10.6060/ivkkt.20236611.11t.
19. **Kozlova E.V., Fadeeva N.P., Kalmykov G.A., Balushkina N.S., Pronina N.V., Poludetkina E.N., Kostenko O.V., Yurchenko A.Yu., Borisov R.S., Bychkov A.Yu., Kalmykov A.G., Khamidullin R.A., Streltsova E.D.** Geochemical technique of organic matter research in deposits enriched in kerogen (the bazhenov formation, West Siberia). Vest. *Moscow Univ. Ser. 4. Geol.* 2015. N 5. P. 44-53 (in Russian).
20. **Tikhonova M.S., Ivanova D.A., Kalmykov A.G., Borisov R.S., Kalmykov G.A.** Methods of step extraction of rocks of high-carbon formations for the study of the component distribution of bitumen and variability of their basic geochemical parameters. *Georesursy.* 2019. V. 21. N 2. P. 172-182 (in Russian). DOI: 108599/grs.2019.2.172-182.
21. **Korzhov Yu., Starikov A., Kuzina M., Romanova T.** Vertical distribution of alkanes in the lower cretaceous and jurassic sediments of the Borovoye oil field. *Byull. Nauki Prakt.* 2022. V.8. N 6. P. 95-115 (in Russian). DOI: 10.33619/2414-2948/79/12.
22. **DiStefano V.H., McFarlane J., Stack A.G., Perfect E., Mildner D.F.R., Bleuel M., Chipera S.J., Littrell K.C., Cheshire M.C., Manz K.E., Anovitz L.M.** Solvent-pore interactions in the Eagle Ford shale formation. *Fuel*. 2019. N 238. P. 298-311. DOI: 10.1016/j.fuel.2018.10.010.
23. **Mohnhoff D., Littke R., Krooss B.M., Weniger P.** Flow-through extraction of oil and gas shales under controlled stress using organic solvents: Implications for organic matter-related porosity and permeability changes with thermal maturity. *Int. J. Coal Geol*. 2016. V. 157. N 1. P. 84-99. DOI: 10.1016/j.coal.2015.09.010.
24. **Alnawafleh H.M., Fraige F.Y.** Shale Oil Solvent Extraction of Central Jordan El-Lajjun Oil Shale. *JASMI*. 2015. N 5. P. 35-43. DOI: 10.4236/jasmi.2015.53004.
25. **Kozlov S.A., Frolov D.A., Kuzmina E.P., Kirillov A.S., Konovalov V.V., Sklyuev P.V., Alekseeva N.I.** Establishment of reasons for the formation of chloric-organic compounds in commodity oil. *Neftеprom. Delo.* 2019. N 5 (605). P. 64-69 (in Russian). DOI: 10.30713/0207-2351-2019-5(605)-64-69.
26. **Tatyanina O.S., Gubaidulin F.R., Sudykin S.N., Zhilina E.V.** Study of formation of organochlorine compounds due to application of oilfield chemicals. *Neftyanoe Khoz-vo.*

27. **Karlsson R., Isacsson U.** Laboratory studies of diffusion in bitumen using markers. *J. Mater. Sci.* 2003. V. 38. N 13. P. 2835-2844. DOI: 10.1023/A:1024476217060.
28. **Chen Y., Mastalerz M., Schimmelmann A.** Characterization of chemical functional groups in macerals across different coal ranks via micro-FTIR spectroscopy. *Int. J. Coal Geol.* 2012. V. 104. N 30. P. 22-33. DOI: 10.1016/j.coal.2012.09.001.
29. **Washburn K.E., Birdwell J.E., Foster M., Gutierrez F.** Detailed Description of Oil Shale Organic and Mineralogical Heterogeneity via Fourier Transform Infrared Microscopy. *Energy Fuels.* 2015. V. 29. N 7. P. 4264-4271. DOI: 10.1021/acs.energyfuels.5b00807.
30. **Петрова Ю.Ю., Таныкова Н.Г., Спасенных М.Ю., Козлова Е.В., Леушина Е.А., Костина Ю.В.** Комплексная оценка содержания органического вещества в породах методами ИК-спектроскопии, термического анализа и пиролиза. *Вести газ. науки.* 2022. Вып. 3 (52). С. 109-116.
31. **Lis G.P., Mastalerz M., Schimmelmann A., Lewan M.D., Stankiewicz B.A.** FTIR absorption indices for thermal maturity in comparison with vitrinite reflectance R0 in type-II kerogens from Devonian black shales.Org. *Geochem.* 2005. V. 36. N 11. P. 1533-1552. DOI: 10.1016/j.orggeochem. 2005.07.001.
32. **Петрова Ю.Ю., Таныкова Н.Г., Спасенных М.Ю., Козлова Е.В.** Возможности метода ИК-спектроскопии в оценке нефтегенерационного потенциала нефтяных сланцев. *Вестн. Московск. ун-та. Сер. 2. Химия.* 2020. Т. 61. Вып. 1. С. 34-42.
33. **Бокач Н.А., Болотин Д.С., Боярский В.П., Кинжалов М.А., Толстой П.М., Чулкова Т.Г.** Справочные таблицы по теоретическим основам органической химии и металлорганической химии переходных элементов. СПб.: Изд-во ВВМ. 2020. 58 с.
34. **Delgado-Linares J.G., Salmin D.C., Stoner H., Wu D.T., Zerpa L.E., Koh C.A., Mateen K., Scot B., Prince P., Teixeira A.** Effect of Alcohols on Asphaltene-Particle Size and Hydrate Non-Plugging Behavior of Crude Oils: Offshore Technology Conference. 2020. OTC-30916-MS. DOI: 10.4043/30916-MS.
35. **Калмыков Г.А., Балушкина Н.С., Белохин В.С., Билибин С.И., Дьяконова Т.Ф., Исакова Т.Г.** Пустотное пространство пород баженовской свиты и насыщающие его флюиды. *Недропользование XXI век.* 2015. Вып. 1 (51). С. 64-71.
36. **Zargari S., Canter K.L., Prasad M.** Porosity evolution in oil-prone source rocks. *Fuel*. 2015.V.153. P. 110-117. DOI: 10.1016/j.fuel.2015.02.072.
37. **Wang Y., Zhou C., Yi X., Li L., Zhou J., Han X., Gao Y.** Research and Evaluation of a New Autogenic Acid System Suitable for Acid Fracturing of a High-Temperature Reservoir. *ACS Omega.* 2020. V. 5. N 33. P. 20734–20738. DOI: 10.1021/acsomega.0c00336.
38. **Мухин М.М., Магадова Л.А., Пахомов М.Д., Цыганков В.А.** Эфиры уксусной кислоты в качестве основы интенсифицирующих составов для обработки низкопроницаемых карбонатных коллекторов с высокими пластовыми температурами. *Территория Нефтегаз.* 2012. Вып. 12. С. 64-69.
39. **Wang X., Smith K., Cutler J., Beall B.** Advancement in Acid-Precursor Chemistry for Removal of Drill-in Fluid Filter Cake: SPE Deepwater Drilling and Completions Conference. 2012. SPE-147480-MS. DOI: 10.2118/147480-MS.

2022. N 7. P. 55-57 (in Russian). DOI: 10.24887/0028-2448-2022-7-55-57.
27. **Karlsson R., Isacsson U.** Laboratory studies of diffusion in bitumen using markers. *J. Mater. Sci.* 2003. V. 38. N 13. P. 2835-2844. DOI: 10.1023/A:1024476217060.
28. **Chen Y., Mastalerz M., Schimmelmann A.** Characterization of chemical functional groups in macerals across different coal ranks via micro-FTIR spectroscopy. *Int. J. Coal Geol.* 2012. V. 104. N 30. P. 22-33. DOI: 10.1016/j.coal.2012.09.001.
29. **Washburn K.E., Birdwell J.E., Foster M., Gutierrez F.** Detailed Description of Oil Shale Organic and Mineralogical Heterogeneity via Fourier Transform Infrared Microscopy. *Energy Fuels.* 2015. V. 29. N 7. P. 4264-4271. DOI: 10.1021/acs.energyfuels.5b00807.
30. **Petrova Yu.Yu., Tanykova N.G., Spasennykh M.Yu., Kozlova E.V., Leushina E.A., Kostina J.V.** Comprehensive assessment of the organic matter content in source rocks by IR spectroscopy, thermal analysis and pyrolysis. *Vesti Gaz. Nauki.* 2022. N 3(52). P. 109-116 (in Russian).
31. **Lis G.P., Mastalerz M., Schimmelmann A., Lewan M.D., Stankiewicz B.A.** FTIR absorption indices for thermal maturity in comparison with vitrinite reflectance R0 in type-II kerogens from Devonian black shales.Org. *Geochem.* 2005. V. 36. N 11. P. 1533-1552. DOI: 10.1016/j.orggeochem.2005.07.001.
32. **Petrova Y.Y., Tanykova N.G., Spasennykh M.Y., Kozlova E.V.** The possibility of using IR spectroscopy in the estimation of the oil-generating potential of oil shales. *Vest. Moscow Univ. Ser. 2. Khimiya.* 2020. V. 75. N 1. P. 28-35 (in Russian). DOI: 10.3103/S0027131420010095.
33. **Bokach N.A., Bolotin D.S., Boyarsky V.P., Kinzhalov M.A., Tolstoy P.M., Chulkova T.G.** Reference tables on the theoretical foundations of organic chemistry and organometallic chemistry of transition elements. St. Petersburg: VVM publ. 2020. 58 p. (in Russian).
34. **Delgado-Linares J.G., Salmin D.C., Stoner H., Wu D.T., Zerpa L.E., Koh C.A., Mateen K., Scot B., Prince P., Teixeira A.** Effect of Alcohols on Asphaltene-Particle Size and Hydrate Non-Plugging Behavior of Crude Oils: Offshore Technology Conference. 2020. OTC-30916-MS. DOI: 10.4043/30916-MS.
35. **Kalmykov G.A., Balushkina N.S., Belokhin V.S., Bilibin S.I., Diyakonova T.F., Isakova T.G.** Voids rocks of the bazhenov formation and saturating its fluids. *Nedropolzovanie XXI vek.* 2015. N 1(51). P. 64-71 (in Russian).
36. **Zargari S., Canter K.L., Prasad M.** Porosity evolution in oil-prone source rocks. *Fuel*. 2015.V.153. P. 110-117. DOI: 10.1016/j.fuel.2015.02.072.
37. **Wang Y., Zhou C., Yi X., Li L., Zhou J., Han X., Gao Y.** Research and Evaluation of a New Autogenic Acid System Suitable for Acid Fracturing of a High-Temperature Reservoir. *ACS Omega.* 2020. V. 5. N 33. P. 20734–20738. DOI: 10.1021/acsomega.0c00336.
38. **Mukhin M.M., Magadova L.A., Pakhomov M.D., Tsygankov V.A.** Acetic acid esters as a basis for intensifying compositions for treatment of low permeability carbonate reservoirs with high formation temperatures. *Territoriya Neftegaz.* 2012. N 12. P. 64-69 (in Russian).
39. **Wang X., Smith K., Cutler J., Beall B.** Advancement in Acid-Precursor Chemistry for Removal of Drill-in Fluid Filter Cake: SPE Deepwater Drilling and Completions Conference. 2012. SPE-147480-MS. DOI: 10.2118/147480-MS.

Поступила в редакцию (Received) 21.08.2023
Принята к опубликованию (Accepted) 22.12.2023