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Physicochemical and Rheological Properties of Viscous Paraffin Oils

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Abstract

The physicochemical properties of hard-to-recover viscous oil with high paraffin content were evaluated relying on the analysis of information from oil characteristics database, compiled at the Institute of Petroleum Chemistry SB RAS. It is established that Russia is distinguished by the largest reserves of viscous paraffin oil (VPO) on the territory of Eurasia, where almost three quarters of the reserves are concentrated in the Volga-Ural oil and gas basin. The characteristics of properties of these oils under various conditions of their occurrence have been analysed. It is shown that VPO is more confined to terrigenous rocks, in which the reserves are 4.6 times greater than those in carbonate formations. The physicochemical properties of VPO in productive formations differing from each other in permeability and porosity are considered. It is established that in the case of high permeability of formations, the density of VPO increases (oil becomes heavier), coking ability, sulphur and resin content grow, the content of paraffins and the gas factor decrease. Viscous paraffin oils in reservoirs with different permeabilities have a positive pour point and are characterised by low gas content. In medium- and highly porous formations, VPOs are heavy, sulphurous, medium-resinous and medium-asphaltene, with low gas content. It is shown that in highly permeable and highly porous reservoirs, the content of paraffins in VPO is minimal and quite contrary the content of paraffins in oil is the greatest in low-permeable and low-porous reservoirs. The properties of high-hardening VPOs are revealed, which significantly differ from the properties of oils with negative pour point. High-setting VPOs differ from low-setting oils by medium density (low-setting oils are heavy), but very high viscosity; higher content of paraffins and oxygen, but lower content of resins, asphaltenes, sulphur (almost 2 times) and nitrogen; the gas factor is higher by 81 %.

Keywords: viscous paraffin oil, physicochemical properties, carbonate and terrigenous reservoir, porosity, permeability

INTRODUCTION

One of the most important trends in the oil producing industry is the necessity to pass on the development of hard-to-recover oil resources because of the decreased extraction of medium- and low-viscous oil. The widespread kinds of hard-to-recover oils are viscous, high-paraffin and viscous-paraffin oils [1–4]. Oilfields with viscous oil or with the increased content of paraffin in oil are widespread over the world [5–7]. However, the resources of viscous paraffin oil (VPO) are concentrated mainly in Eurasia, and Russia possesses the absolute majority of these resources. The problems concerning the development of oilfields with VPO are highly relevant for our country, especially for the regions in which hydrocarbons are extracted from already depleted oilfields, and the new centres of oil production. Oil production in Russia is shifting to the regions that are under complicated geographical (Eastern Siberia, Far East, sea shelf), climatic (the Arctic zone of the Russian Federation) and geological (small reserves, deep occurrence, etc.) conditions [8–13], or to the regions in which several factors are combined, for example, hydrocarbon extraction from the shelf of the Arctic Ocean [8, 10]. The listed regions possess enormous resources of hard-to-recover oil [9, 11]. In addition, these regions are extremely unstable from an ecological viewpoint, which may cause tremendous environmental hazard in the case of a technogenic accident [12–14]. All these factors combined together form elevated requirements for the studies of the physicochemical properties of extracted oil, the conditions of productive oil reservoir occurrence, and lithological and filtration reservoir characteristics, especially for hard-to-recover oil such as VPO.

The production and transportation of VPO are complicated due to many problems, in particular intense formation of asphaltene-resin-paraffin deposits in the borehole zones of productive reservoirs, oilwells and surface equipment [5, 15–17]. It is known that most VPO types are non-Newtonian fluids with respect to their rheological properties. In the Earth's interior, under high pressure and at high reservoir temperature, oil is close in its characteristics to Newtonian fluid, independent of the concentrations of paraffin, resins and asphaltenes. During extraction, oil temperature decreases while approaching the surface, and oil passes into the state with complicated rheological characteristics, which is accompanied by the deposition of paraffins onto the equipment [17]. Highly viscous oils possess complicated rheological characteristics directly in the productive reservoirs of oilfields.

Concerns related to the regularities of VPO characteristics changing under different reservoir conditions are insufficiently discussed in the literature. For this reason, the goal of the present work was to analyse the resources, occurrence conditions and physicochemical properties of VPO relying on the information from the Database (DB) of the Institute of Petroleum Chemistry SB RAS (IPC SB RAS, Tomsk) on the physicochemical properties of oil.

METHODS AND DATA CHARACTERISATION

The methodological basis of the investigation is formed by the statistical methods of information analysis: comparative and correlation-regression. The spatial distribution of VPO was studied using the geoinformation system (GIS) developed at the IPC SB RAS on the basis of ArcGis 10.8 "Hard-to-recover oils in the world", which is promising to study the spatial, temporal, geological, thermobaric, lithological and other regularities of changes in the physicochemical properties of hard-to-recover oils and the conditions of their occurrence at the territories over different scales, from continents to the regional level. The proposed GIS may reveal the regions of prevailing localization of hard-to-recover oils of different types and refine the forecast of their quality.

The studies were carried out on the basis of the information from the DB on the physicochemical characteristics of oils over the world [18, 19], which currently contains the informational descriptions of more than 40 750 oil samples from 6749 oilfields of 195 oil and gas bearing basins (OGB) over different continents. The object of investigation is viscous oil (with viscosity 35 mm^2/s and higher at 20 °C) with a high content of paraffins (more than 6 wt. %), which will be referred to as viscous paraffin oil (VPO) according to oil classification [18, 19].

To carry out the studies of the features of VPO properties on the basis of the information from the above-mentioned DB, an array of 244 VPO samples from 157 oilfields of 24 Eurasian OGB was formed.

The total number of oilfields with VPO in Russia is determined to be 93 (this is nearly 59 % of all Eurasian oilfields with VPO) from 7 OGB: the Volga-Ural, the Yenisei-Anabar, the West Siberian, the Lena-Siberian, the Lena-Tungus, the Precaspian (Russia), the North Caucasian (Russia), and the Timan-Pechora basins. The next position in the number of oilfields with VPO is occupied by Kazakhstan, where 17 oilfields related to the Precaspian and North Caucasian OGB are revealed. The number of VPO oilfields determined in Azerbaijan is 7, in Turkmenistan – 6, in Belarus and China – 5 oilfields in each of these countries, in Mongolia, Tajikistan and Uzbekistan – 4 oilfields in each of these countries, etc. Most of the oilfields with VPO in Russia are situated in the Volga-Ural OGB – 48 oilfields, located mostly in the central part of the basin. In the Timan-Pechora basin, there are 18 oilfields, located in the eastern part of the basin, and 15 of these oilfields relate to the Arctic. The number of oilfields determined in the West Siberian OGB is 17, and 14 of these oilfields are located in the Tomsk Region, the Novoportovskoye oilfield is in the Yamal-Nenets Autonomous District, the Severo-Varyeganskoye and Yuzhno-Tolumskoye oilfields are in the Khanty-Mansi Autonomous District. The distribution of oilfields with VPO over the basins and countries is presented in Table 1.

TABLE 1

Distribution of oilfields with viscous paraffin oil over the oil and gas bearing basins

Oil and gas bearing basin	Oil and gas bearing region	Number of oilfields (name)	Country
Amu-Darya	Murgab	1 (Sharapli)	Turkmenistan
	Bukhara	1 (West Tashly)	Uzbekistan
Afghan-Tadzhik	Surkhan-Vakhsh	2 (Beshtentyak, Shaambary)	Tadzhikistan
	Fergana	3 (Shorsu-IV, Northern Sokh, Sharikhan-Khodzhaabad)	Uzbekistan
	Fergana	2 (Ayritan, Ravat)	Tadzhikistan
	Fergana	3 (Maylisu-III, Kirgizskoye, Togap)	Kirghizia
Volga-Ural	Buzuluk	7	Russia
	Verkhnekamskaya	5	Russia
	Melekess-Abdulinskaya	12	Russia
	Nizhnevolzhskaya	1 (Stepnovskoye)	Russia
	Perm-Bashkir	6	Russia
	Srednevolzhskaya	5	Russia
	Tatar	11	Russia
	Ufa-Orenburg	1 (Urshakskoye)	Russia
East Gobi	–	2 (Zuunbayan, Tsagaan-Els)	Mongolia
Dnepr-Pripyat	Dnept-Donets	1 (Bugrevatovskoye)	Ukraine
	Pripyat	5	Belarus
Yenisei-Anabar	Yenisei-Khatanga	1 (Khabey)	Russia
Yellow Sea	–	1 (Kaoshe)	China
West Siberian	Vasyuganskaya	6	Russia
	Kaymysovskaya	8	Russia
	Nadym-Pur	1 (Severo-Varyeganskoye)	Russia
	Cis-Urals	1 (Yuzhno-Tolumskoye)	Russia
	Yamal	1 (Novoportovskoye)	Russia
Carpathian	Pre-Carpathian	1 (Orov-Ulichnyanskoye)	Ukraine
Lena-Tungus	Nepsko-Botuobinskaya	1 (Irelyakh)	Russia
Pannonian	–	2 (Bunyan, Mramor-Budo)	Croatia
Persian Gulf	–	1 (Al-Rayan)	Qatar
Pre-Nanshan	–	1 (Laozunmiao)	China
Precaspian	Astrakhan-Kalmyk	1 (Astrakhan)	Russia
	Volgograd-Karachaganak	2 (Daryinskoye, Karachaganak)	Kazakhstan
	Enbeksko-Zharkamysskaya	1 (Akzhar)	Kazakhstan
	Embinsko-Buzachinskaya	3 (Kalamkas, Kotyrtas Severnyi, Urtatau-Sarybulak)	Kazakhstan
	Southern Embinskaya	1 (Ravninnoye)	Kazakhstan
Rhine	–	1 (Landau)	Germany
North Caucasian	Eastern Pre-Caucassian	2 (Pravoberezhnoye, Yuzhno-Sukhokumskoye)	Russia
	Indolo-Kuban	2 (Abino-Ukrainskoye, Khadyzhenskoye)	Russia
	Tersk-Caspian	2 (Berikey, Malgobek-Gorskoye)	Russia
	Southern Mangyshlak	8	Kazakhstan
North Javan	–	1 (Sinta)	Indonesia
Sunlyuao	–	3 (Fularti, Muto, Khongand)	China
Tamtsag-Khaylar	–	2 (Tamsagbulag, Toson-Uul)	Mongolia
Tarim	–	1 (Yangner)	China
Timan-Pechora	Varandey-Adzvin	4	Russia
	Pechora-Kolva	4	Russia
	Khoreyver	10	Russia
Turan	Southern Turgay	2 (Ashchisay, Bektas)	Kazakhstan
Central European	–	1 (Ikring)	Great Britain
	–	1 (Emlichheim)	Germany
South Caspian	Apsheron-Prebalkhan	2	Azerbaijan
	Apsheron-Prebalkhan	5	Turkmenistan
	Kobystan-Kurin	5	Azerbaijan

The VPO resource potential of different Eurasian countries is considered. The distribution of VPO samples, oilfields and their reserves in the DB shows that the largest number of samples (58 %), oilfields (58 %) and VPO reserves (71 % of total VPO resources) are concentrated in Russia. The Russian oilfields that are unique in resources are the Romashkinskoye, Novo-Elkhovskoye, Arlanskoye in the Volga-Ural OGB, the Astrakhan in the Precaspian OGB (the Russian territory), the Usinkoye in the Timan-Pechora OGB, the Novoportovskoye in the West Siberian OGB. Kazakhstan possesses substantial VPO reserves (Fig. 1), and the oilfields unique in the reserves are the Karachaganak, Uzen, Kalamkas and Zhetybay.

The largest resources of VPO in Russia are concentrated at the territory of the Volga-Ural OGB (more than 73 % of all Russian resources, Fig. 2). There are 7 unique and large oilfields in the basin; the unique ones are indicated above, and large oilfields include Chutyr-Kiengop, Radaevskoye, Nurlatskoye and Yakushkinskoye. The major VPO resources of the Timan-Pechora OGB are concentrated on three oilfields: Usinsk, Kharyaginskoye and Khasyreyskoye. The oilfields distinguished in their resources in the West Siberian OGB are the Novoportovskoye (unique), and large oilfields – the Mayskoye and Festivalnoye (the Tomsk Region). A large Irelyakh oilfield may be distinguished in the Lena-Tungus OGB.

RESULTS AND DISCUSSION

The spatial distribution of viscous paraffin oils

Investigation of oil distribution in different stratigraphic complexes shows that VPO occur within a broad range, from the Silurian system of Paleozoic sediments to the Pliocene formations of the Cenozoic erathem [16]. Most VPO occurrences and their resources are concentrated in the Paleozoic sediments (53 and 76 %, respectively, Fig. 3, *a*). Most of the samples relate to Devonian and Carboniferous systems. Most of the Paleozoic VPO are concentrated in the Volga-Ural OGB – 37 samples, in the Dnepr-Prypat basin – 12 samples, and in the West Siberian and Timan-Pechora OGB there are 9 samples of Paleozoic VPO per each of these basins. The fraction of Russian VPO was 77 % of the total number of Paleozoic samples. The OGB distinguished in the number of Mesozoic VPO are the West Siberian OGB (13 samples) and the North Caucasian OGB (7 samples). The fraction of Russian Mesozoic VPO was almost 45 % of the whole set of samples from the Mesozoic sediments The largest number of Cenozoic VPO samples relate to the South Caspian (14 samples) and North Caucasian (5 samples) basins. Here, the fraction of Russian samples is low: a little more than 8 %.

One can see in Fig. 3, *a* that the resources in the Paleozoic sediments are the largest. The oilfields distinguished he amount of Paleozoic resources are the Karachaganak (the Precaspian OGB), Usinsk and Khasyreyskoye (the Timan-Pechora OGB), Radaevskoye and Yakushkinskoye (the Volga-Ural OGB), the Festivalnoye (the West Siberian OGB), Ostashkovichskoye (the Dnepr-Pripyat OGB) and the Irelyakh oilfield (the Lena-Tungus OGB). The reserves of the Mesozoic reservoirs with VPO are nearly 4 times smaller than the Paleozoic reserves; the large amounts of the Mesozoic VPO are concentrated in the Novoportovskoye, Festivalnoye and Mayskoye oilfields (the West Siberian OGB), Tamsag-

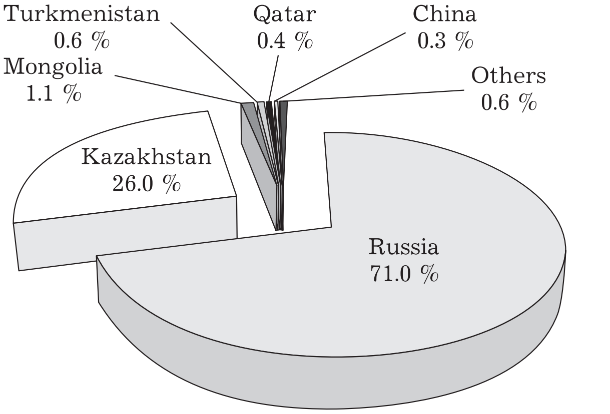

Fig. 1. Distribution of the resources of viscous paraffin oils over the countries of Eurasia.

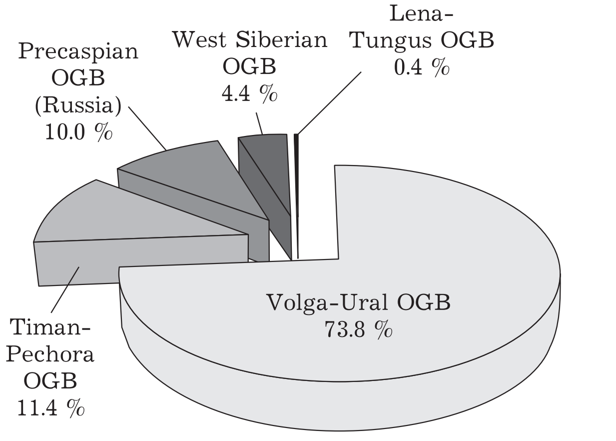

Fig. 2. Distribution of the resources of viscous paraffin oils over the oil and gas bearing basins in Russia.

bulak (Mongolia), and Zhetybay (the North Caucasian OGB). The reserves of Cenozoic sediments are the smallest: more than 10 times smaller than the Paleozoic reserves. Large oilfields are the Malgobek-Gorskoye in the North Caucasian basin and two in the South Caspian basin – the Nebit-Dag and the Kumdag (Turkmenistan).

The distribution of VPO samples over depth (see Fig. 3, *b*) shows that oil occurs over a wide range of reservoir depths, from 200 to 5500 m, with the largest number of samples at a depth of 1000–2000 m (34 % of all samples). It has been established that at a small depth (0–1000 m) the amount of Russian VPO is 23 %, within the medium depth range (1000–3000 m) the fraction of Russian VPO was more than 34 %, so that at a depth of 1000–2000 m, these are mainly oils from the Volga-Urals basin, while within the range of 2000–3000 m – oils from the West Siberian basin. At depths from 3000 to 4000 m, the fraction of Russian VPO accounts for 40 %, mostly in the West Siberian OGB. There are no samples of deep-seated (deeper than 4500 m) VPO in Russia, the samples from this depth come from the Precaspian (Kazakhstan) and South Caspian (Azerbaijan) OGB.

The maximal VPO resources have been revealed at a depth of 1000–2000 m (see Fig. 3, *b*), their fraction was 30 %, the oilfields distinguished by the largest amounts of resources are the Usinsk (the Timan-Pechora OGB), the Zhetybay (the North Caucasian basin) and the Radaevskoye (the Volga-Ural OGB). The oilfields distinguished by the amount of resources at a small depth are the Novoportovskoye (the West Siberian OGB), Irelyakh (the Lena-Tungus OGB) and Fularti (the Sunlyao basin). Large resources of deep-seated oil (deeper than 4000 m) were discovered in oilfields the Karachaganak and the Akzhar (the Precaspian OGB), the Sangachaly-more, the Duvannyi-more and Kyursangya (the South Caspian basin).

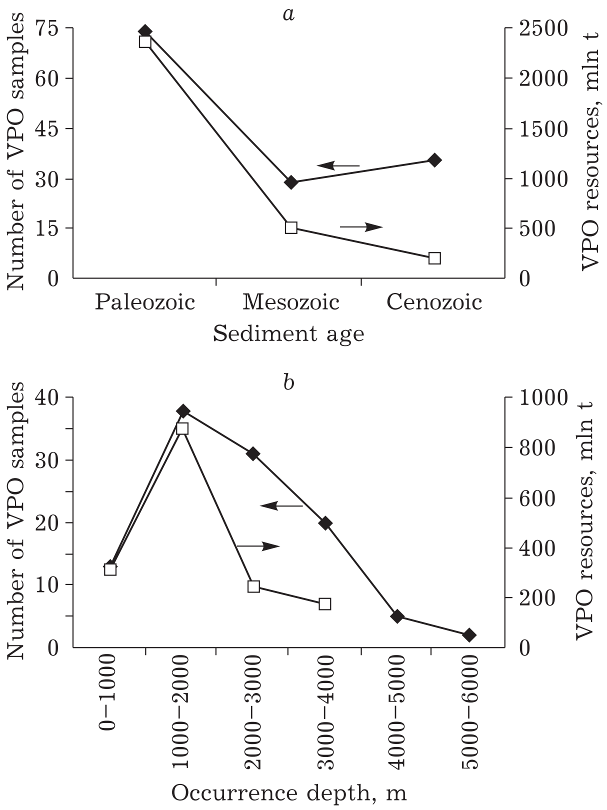

Fig. 3. Dependence of the number and resources of viscous paraffin oils (VPO) on sediment age (*a*) and occurrence depth (*b*).

Physicochemical properties of high- and low-setting viscous paraffin oils

Complications due to paraffinisation of interhole mining and transporting equipment are the strongest during the extraction of high-setting VPO. The occurrence of 66 oilfields in 17 basins with positive oil pour points and 26 oilfields in 11 OGB with negative oil pour points has been established. The VPO pour point from 25 to 40 °C is characteristic of high-setting oils from the deposits: Kaoshe (the Yellow Sea OGB), Zuunbayan and Tsaagan-Els (the East Gobi OGB), Kharyaginskoye (the Timan-Pechora OGB), Turkmenoy (the North Caucasian OGB), Sinta (the North Java OGB) and Festivalnoye (the West Siberian OGB).

The data on the reservoir characteristics and properties of VPO with negative and positive pour points are presented in Table 2. It is very important to know these characteristics if complications arise during VPO mining and transportation. One can see that high-setting VPO differ from low-setting oils by medium density but very high viscosity; higher paraffin content (higher by 9 %) and oxygen (higher by 30 %), but lower content of resins (lower by 15 %), asphaltenes (lower by 35 %), sulphur (lower almost by a factor of 2) and nitrogen (lower by 38 %); the gas factor is higher by almost 81 %; coking ability is lower by 38 %.

Physicochemical properties of viscous paraffin oils in carbonate and terrigenous reservoirs

The improvement and development of principally new highly efficient technologies of VPO mining require comprehensive analysis of the complicated mechanisms of intra-reservoir pro-

TABLE 2

Physicochemical properties of viscous paraffin oil with positive and negative pour point

Parameter	Positive pour point		Negative pour point	
	Average value	Number of samples	Average value	Number of samples
Occurrence conditions				
Reservoir temperature, °C	76.25	27	54.30	10
Reservoir pressure, MPa	28.88	26	18.08	11
Permeability, μm^2	0.83	10	0.16	6
Porosity, %	13.38	12	17.80	7
Physical parameters				
Density, g/cm^3	0.8669	98	0.8918	29
Viscosity at 20 °C, mm^2/s	891.77	100	334.78	29
Pour point, °C	14.66	100	−14.02	29
Chemical parameters				
Content, wt. %:				
paraffins	11.42	100	10.40	29
resins	9.52	80	11.14	26
asphaltenes	1.77	83	2.72	27
sulphur	0.71	68	1.35	25
hydrogen H	12.78	18	12.92	7
carbon C	85.90	18	85.56	7
oxygen O	0.43	13	0.33	6
nitrogen N	0.16	26	0.26	10
Gas content in oil, m^3/t	112.52	19	62.22	8
Coking ability, wt. %	2.80	33	4.53	17

cesses. It has been established on the basis of the information from the DB that VPO reserves from terrigenous reservoirs are 4.6 times higher than VPO reserves in carbonate reservoirs, which is in agreement with [16]. The physicochemical properties of VPO in reservoirs differing from each other in lithological characteristics are presented in Table 3.

According to the data obtained, terrigenous reservoirs differ from carbonate ones by lower temperature and pressure but higher permeability (3.5 times) and porosity (higher by 28 %), that is, terrigenous sediments are distinguished by the best collecting filtration characteristics. On average, the physicochemical properties of VPO (see Table 3) are as follows: oils in terrigenous reservoirs are lighter, less viscous, with lower resin (by 12 %), asphaltene (by 5 %) and paraffin content, which leads to lower intensity of asphaltene-resin-paraffin deposition in the borehole zones, intra-well and surface equipment. The content of fractions decreases by 4 % on average, the gas factor is smaller by 20 %, the pour point is positive on average, in terrigenous pools it is higher by 26 %, and sulphur content is also higher by almost 13 %.

Physicochemical properties of viscous paraffin oils with different occurrence conditions

The properties of VPO with different reservoir conditions were analysed. The most significant reservoir characteristics that are used to attribute oil resources to hard-to-recover reserves include the parameters directly connected with the filtration characteristics of adjacent formations and occurrence conditions: rock permeability and porosity, reservoir temperature and occurrence depth.

Permeability and porosity have direct influence on extraction mode and e technologies used to extract oil. With respect to permeability, the productive strata are divided into low-permeable (less than 0.05 μm^2), medium-permeable (from 0.05 to 0.5 μm^2) and high-permeable (above 0.5 μm^2). It has been established that most reservoirs with VPO (42.6 %) are related to medium-permeable ones, 34 % – to low-permeable, while 23.4 % are highly permeable reservoirs. According to the information from the DB, 16 VPO samples originate from low-permeable reservoirs, with the largest amounts of resources determined

TABLE 3

Physicochemical properties of viscous paraffin oil in carbonate and terrigenous reservoirs

Parameter	Carbonate reservoirs		Terrogenous reservoirs	
	Average value	Number of samples	Average value	Number of samples
Occurrence conditions				
Reservoir temperature, °C	56.81	24	53.30	24
Reservoir pressure, MPa	19.49	26	17.52	26
Permeaility, μm^2	0.14	17	0.50	11
Porosity, %	14.04	19	19.41	14
Physical parameters				
Density, g/cm^3	0.8826	38	0.8834	41
Viscosity at 20 °C, mm^2/s	74.97	38	66.13	41
Pour point, °C	1.29	14	1.63	16
Chemical parameters				
Content, wt. %:				
paraffins	9.12	38	8.83	41
resins	12.40	34	10.89	38
asphaltenes	3.39	34	3.22	39
sulphur	1.34	34	1.51	38
fraction i. b. p.–200 °C	18.67	10	17.11	14
fraction i. b. p.–300 °C	35.21	10	34.44	14
fraction i. b. p.–350 °C	46.16	5	45.97	11
Gas content in oil, m^3/t	63.11	24	50.65	19

Note. i. b. b. – initial boiling point.

in the oilfields: Usinsk (the Timan-Pechora OGB), Radaevskoye (the Volga-Ural OGB), Ostashkovichskoye (the Dnepr-Pripyat basin) and Mayskoye (the West Siberian OGB). The number of samples related to medium-permeable reservoirs is 20, with the largest resources in the Yakushkinskoye oilfield (the Volga-Ural OGB) and the Fularti (Synlyao). The smallest number of samples, only 11, relate to highly permeable collectors, and Mongolian oilfields Tamsagnulag and Tsagaan-Els, may be mentioned as those containing the largest amount of resources.

The data on the reservoir characteristics of oil-bearing rocks differing from each other in permeability are presented in Table 4. One can see that reservoir temperature and pressure decrease with an increase in reservoir porosity by 44 and 34 %, respectively. An increase in the porosity of strata in low-permeable reservoirs to reach the porosity of highly permeable reservoirs is more than 1.5 times, while permeability values of low-permeable and medium-permeable reservoirs differ from each other by an order of magnitude, while with respect to high-permeable reservoirs the difference reaches almost 163 times. It is now necessary to consider the features of oil properties depending on rock permeability and porosity.

Results of the analysis of VPO characteristics are shown in Table 5 for productive reservoirs differing in permeability.

In low-permeable reservoirs, VPO are characterised by lower density (see Table 5) and relate to the class of medium-density oils according to classification described in [18, 19], with lower content of sulphur (almost 2 times lower than sulphur content in oil from highly permeable reservoirs), asphaltenes (lower by almost 50 % compared with asphaltene content in VPO from reservoirs with medium permeability), coking ability (lower by 44 % in comparison with the coking ability of oil from highly permeable reservoirs), but with higher pour point, paraffin content (higher by almost 14 % compared with paraffin content in VPO from highly permeable reservoirs) and gas factor (4 times higher than petroleum gas content in oil from highly permeable reservoirs). Oil samples from reservoirs with medium permeability are distinguished by the lowest pour point, the highest viscosity and high asphaltene content. In highly permeable reservoirs, VPO is distinguished by low viscosity, the lowest paraffin content, high sulphur and resin content. In general, the following regularities may be outlined (see Table 5): with an increase in the permeability of oil-bearing rocks, the density of VPO

TABLE 4

Reservoir characteristics of the occurrence of viscous paraffin oil in low-, medium- and high-permeable productive beds

Reservoir characteristics	Low-permeable reservoir	Medium-permeable reservoir	High-permeable reservoir
Reservoir temperature, °C	60.79	38.44	34.11
Reservoir pressure, MPa	22.65	16.21	15.00
Permeability, μm^2	0.021	0.21	3.44
Porosity, %	12.84	16.23	21.06

TABLE 5

Physicochemical properties of viscous paraffin oils in low-, medium-, and high-permeable reservoirs

Parameters	Low-permeable reservoir	Medium-permeable reservoir	High-permeable reservoir
Density, g/cm^3	0.8760	0.8918	0.8917
Viscosity at 20 °C, mm^2/s	109.41	204.69	75.89
Pour point, °C	6.99	0.50	5.00
Content, wt. %:			
sulphur	1.26	1.84	2.33
paraffins	9.94	8.85	8.74
resins	12.34	12.25	14.48
asphaltenes	3.49	6.92	3.56
Gas content, m^3/e	70.75	36.82	17.62
Coking ability, wt. %	3.86	5.86	6.90

increases (oil from the reservoirs with medium and high permeability is heavy [18, 19]), so do also coking ability, sulphur and resin content, while the content of paraffin and petroleum gas decreases. Viscous paraffin oils in reservoirs differing from each other in permeability are characterised by positive pour point and low gas content (less than 200 m^3/t, [18, 19]).

Results of the analysis of VPO properties in oil-bearing rocks of the reservoirs differing from each other in porosity are presented. With respect to rock porosity, the efficient reservoir capacity may be small (with porosity less than 5 %), medium (with porosity 5 to 15 %) and large (more than 15 %). It has been determined that only 2 % of VPO samples are in low-porosity reservoirs (with porosity less than 5 %) – these are mainly VPO samples from the Vyshanskoye oilfield in the Dnepr-Pripyat OGB. More than 44 % of oil resources are in medium-porosity formations; the oilfields distinguished by the amount of resources are the Radaevskoye (the Volga-Ural OGB), Ostashkovichskoye (the Dnepr-Pripyat OGB) and Mayskoye (the West Siberian OGB). Most VPO (54 %) occur in highly porous formations with porosity more than 15 %; the oilfields with unique and large resources are the Usinsk (the Timan-Pechora OGB), Novoportovskoye (the West Siberian OGB), Radaevskoye and Yakushkinskoye (the Volga-Ural OGB).

The formation characteristics of reservoirs characterized by different porosity values are presented in Table 6. Note that medium- and high-porous reservoirs are at the same time medium-permeable ones. One can see that with an increase in reservoir porosity, the values of the reservoir temperature and pressure decrease by a factor of 1.5 and 2.3, respectively. Reservoir porosity increases more than 6 times when passing from low-porous to high-porous reservoirs. At the same time, the permeability of low-porous reservoirs is 5 times lower than the permeability of medium-porous reservoirs, and almost 58 times lower than the permeability of highly porous reservoirs.

Results of the analysis of VPO properties in the reservoirs with different porosity values are presented in Table 7. It has been established that VPO in low-porous reservoirs are characterised by medium density, medium sulphur and asphaltene content, and high resin content, and are related to the high-resin oil class according to the classification described in [18, 19]. These VPO samples are also characterized by higher petro-

TABLE 6

Formation characteristics of productive beds with different porosity for viscous paraffin oils

Reservoir characteristics	Low-permeable reservoir	Medium-permeable reservoir	High-permeable reservoir
Reservoir temperature, °C	58.00	50.27	37.82
Reservoir pressure, MPa	33.70	22.01	14.67
Permeability, μm^2	0.016	0.09	0.93
Porosity, %	3.20	11.10	21.22

TABLE 7

Physicochemical properties of viscous paraffin oils in the productive reservoirs with different porosity

Parameter	Low-permeable reservoir	Medium-permeable reservoir	High-permeable reservoir
Density, g/cm^3	0.8651	0.8836	0.8893
Viscosity at 20 °C, mm^2/s	94.22	67.26	125.20
Pour point, °C	12	7.32	−1.33
Content, wt. %:			
sulphur	0.68	1.76	1.67
paraffins	8.19	8.72	7.96
resins	15.00	12.67	12.02
asphaltenes	3.43	4.53	4.12
Gas content, m^3/t	93.50	55.84	37.49
Coking ability, wt. %	5.78	5.53	4.22

leum gas content and higher coking ability. In reservoirs with medium porosity, VPO samples are characterised by the lowest oil viscosity, along with the highest paraffin and asphaltene content. Highly porous formations contain the heaviest and the most viscous oils, distinguished by the negative pour point values, the lowest paraffin and resin content, and the lowest gas content and coking ability. In general, VPO in medium- and high-porous formations are heavy, sulphurous (sulphur content 1–3 %), with medium resin and asphaltene content, and with low gas content.

The possibility to extract hard-to-recover VPO in some oilfields is also complicated by other occurrence factors. For instance, reservoir temperature below 20 °C was determined for two oilfields with terrigenous reservoirs: the Yakushkinskoye (the Volga-Ural OGB) and Fularti (Sunlyao). High reservoir temperatures (above 100 °C) were detected for four oilfields: the Kaoshe (the Yellow Sea OGB) and Gerasimovskoye, Mayskoye, Severo-Kalinovoye, Urmanskoye from the West Siberian OGB in terrigenous and carbonate reservoirs. Low porosity (less than 5 %) was detected only for carbonate reservoirs; low-permeable reservoirs (permeability less than 0.05 μm^2) were revealed at 15 oilfields. In the Arctic zone of Russia, 18 oilfields with VPO were determined, which even enhances the difficulties in recovering these oils. Most of these oilfields are located in the Timan-Pechora OGB, two oilfields (the Novoportovskoye and Severo-Varyeganskoye) are in the West Siberian OGB, and the Khabeyskoye oilfield is in the Yenisei-Anabar OGB. All VPO oilfields are situated on the continent, and none were discovered in the offshore zones of the Arctic seas.

Broad variations in the reservoir thermobaric characteristics of VPO occurrence have been revealed. For instance, reservoir pressure varies within the range from 2.5 MPa (the Shorsu oilfield, the Afghan-Tadzhik OGB) to anomalously high value, 57 MPa (the Karachaganak oilfield in the Precaspian OGB). However, no direct connection was revealed between the reservoir pressure and changes in the physicochemical properties of oil. It is shown in Fig. 4, *a*, *b* that oil characteristics are closely related to reservoir temperatures, which vary also within a broad range: from 18 °C (the Fularti oilfield, Sunlyao) to 128 °C (the Mayskoye oilfield, the West Siberian OGB). On average, oil viscosity decreases in the hot beds; inverse dependence is typical for paraffins: with an increase in reservoir temperature, paraffin concentration increases. These trends are confirmed

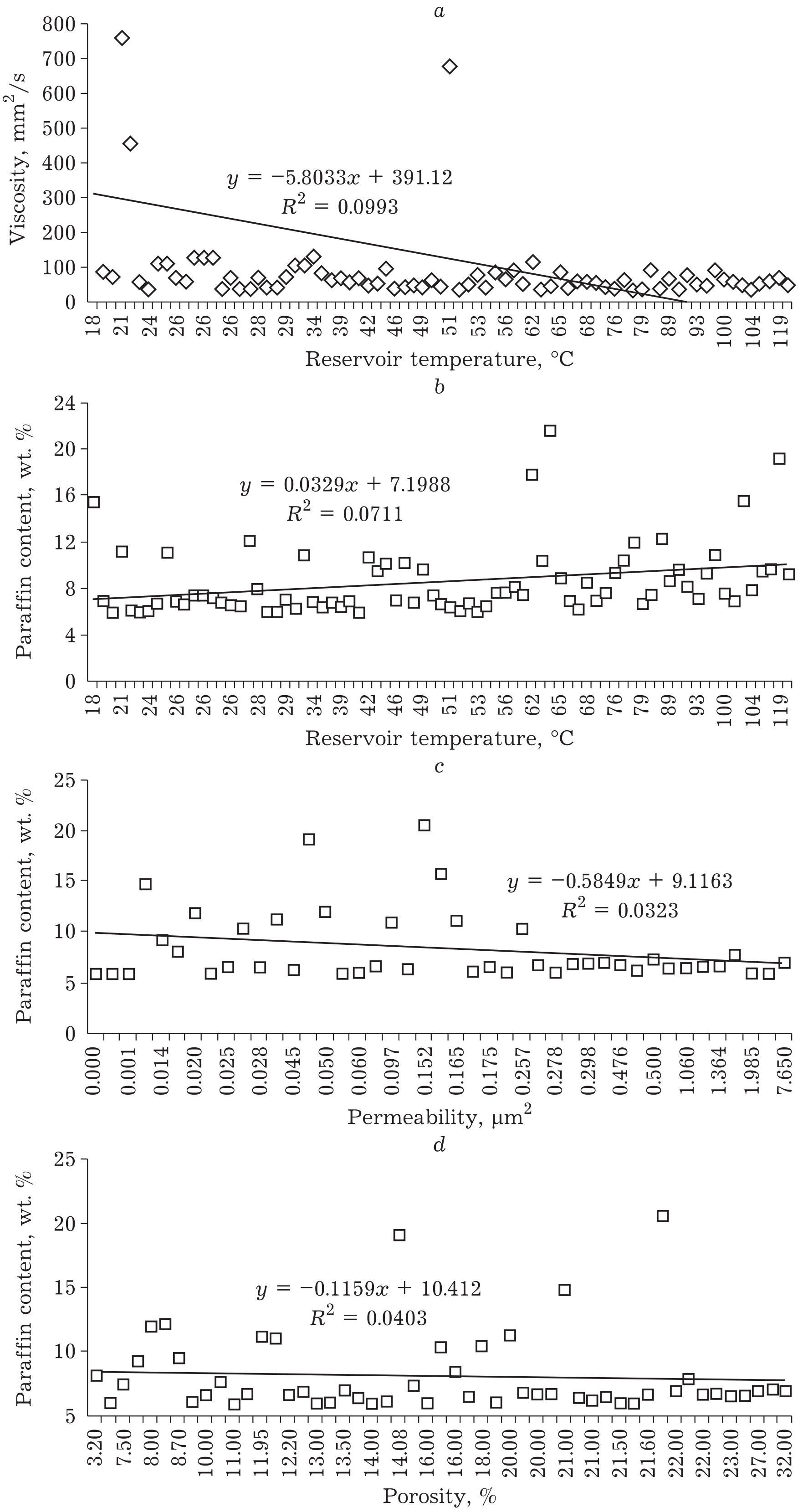

Fig. 4. Effect of reservoir conditions on the characteristics of viscous paraffin oils: dependence of viscosity (*a*) and paraffin content in oil (*b*) on reservoir temperature; changes in paraffin content in reservoirs with different permeabilities (*c*) and porosities (*d*).

by the results presented in Tables 2 and 3. The indicated relationships are only weakly pronounced statistically, for example, the correlation coefficient between reservoir temperature and paraffin content was determined to be 0.32 (see Fig. 4, *b*). The inverse dependences between a decrease in paraffin content in VPO and an increase in reservoir permeability and porosity manifests itself only weakly in the plots (see Fig. 4, *c* and *d*, respectively), however, these trends are confirmed by the data shorn in Tables 5 and 7 – the content of paraffins in VPO is minimal in highly permeable and highly porous reservoirs, and quite contrary, paraffin content in oil is the highest in low-permeable and low-porous reservoirs. No trends of this kind were revealed for oil viscosity.

CONCLUSION

An array of VPO samples with description of physicochemical properties and rheological-filtration characteristics of oil-bearing rocks from 157 oilfields in 24 Eurasian OGB was compiled from the DB of the IPC SB RAS. The largest number of samples (58 %), oilfields (58 %), and VPO resources (71 % of the total amount of VPO resources) are concentrated in Russia. In Russia, 90 oilfields from 7 OGB have been determined; the largest resources are concentrated in the Volga-Ural basin, 18 oilfields from the Yenisei-Anabar, West Siberian, and Timan-Pechora basins are situated in the Arctic zone. Most VPO samples were determined to be characterised by high pour points (14 °C on average). Almost half of the VPO samples occurred in reservoirs with medium and high porosity. The largest VPO reserves (76 %) are concentrated on Paleozoic formations at a medium depth (1000–2000 m). It is demonstrated that VPO are mostly confined to terrigenous rocks with medium porosity and permeability, where the amount of resources is 4.6 times larger than in carbonate formations.

The influence of high paraffin content on the physicochemical and rheological characteristics of viscous oil was studied, comparative analysis of physicochemical properties under different occurrence conditions was carried out for VPO in Eurasia. It has been determined that, depending on rheological characteristics, VPO samples substantially differ from each other in the physicochemical properties: in comparison with low pout point VPO, high pour point ones are characterised by medium density (oils with low pour point are heavy) but very high viscosity. Oils with high pour point contain higher concentrations of paraffins and oxygen, petroleum gas (higher by 81 %) but lower content of resins (lower by 15 %), asphaltenes (lower by 35 %), sulphur (two times lower) and nitrogen (lower by 38 %).

The current studies are of practical significance because VPO extraction and transportation are accompanied by substantial complications. The results presented here may cause interest for the development of special technologies of extraction, transportation and treatment of oils of this kind for the purpose of reducing the intensity of asphaltene-resin-paraffin deposition, for prediction of the quality and properties of VPO from new production centres.

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