Tonkie Khimicheskie Tekhnologii = Fine Chemical Technologies.
2024;19(6):485–496

ISSN 2686-7575 (Online)

UDC 519.87[665.761/532.13+661.666.4]*
https://doi.org/10.32362/2410-6593-2024-19-6-485-496
EDN JTDOHN

RESEARCH ARTICLE

A mathematical model of the dynamic viscosity dependence of motor oils on temperature, soot concentration, and its morphology

Anatoly V. Lesin[1, ✉], **Alexander V. Isaev**[1], **Boris P. Tonkonogov**[2], **Sergey V. Dunaev**[1], **Albert B. Kulikov**[1]
[1] *A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences, Moscow, 119991 Russia*
[2] *Gubkin University, Moscow, 119991 Russia*
✉ *Corresponding author, e-mail: lesinav@ips.ac.ru*

Abstract

Objectives. A quick cold start of emergency and auxiliary power units based on diesel engines should be possible at any time without problems and in the shortest possible time. The condition of the engine oil is one of the most important factors influencing the smooth start-up of power plants. During diesel engine operation, engine oil accumulates soot in its composition, negatively affecting its rheological properties. The aim of this research is to develop a mathematical model to describe changes in the dynamic viscosity of motor oils as a function of temperature. This model will account for the concentration of soot and its morphology, based on the results of experimental studies.

Methods. Standardly used motor oils for diesel engines M-14D$_2$SE and M-5z/14D$_2$SE were used as oil samples in the preparation of model mixtures. The dispersed phase of the suspensions comprised carbon black of the N110, N220, N330, and N220 grades, characterized by a dusty (nongranular) texture. The rheological properties of the samples were determined using a TA Instruments DHR-2 rotational rheometer. The experimental data was subjected to mathematical statistical processing, in order to obtain approximating dependencies.

Results. The paper presents an analysis of the various approaches to the description of the rheology of suspensions and the results of experimental studies of the viscosity-temperature characteristics (VTCs) of model samples of oils containing soot. The extant models of the dependence of the dynamic viscosity of suspensions on temperature, volume concentration of the dispersed phase, particle size and shape are demonstrated to be inadequate for the description of the VTCs of motor oils containing soot. A model of the rheological properties of soot-oil suspensions is proposed in the form of a mathematical dependence of their dynamic viscosity on temperature, mass concentration of soot, material density and size of soot particles, characteristics of the shape and structure of primary aggregates and the ratio of the sizes of aggregates and molecules of the dispersion medium.

Conclusions. It was demonstrated that a comprehensive description of the VTCs of engine oils containing soot necessitates the consideration of the structural characteristics of the primary aggregates of soot particles. A mathematical model of the VTCs of oils was developed. This model is based on the dependence of the dynamic viscosity of oils on temperature, mass concentration of soot, density of the particle material, degree of non-sphericity of aggregates, the ratio of the particle sizes of the dispersed phase (either aggregates or single particles of non-aggregated soot) and oil molecules, and on the structure of soot, characterized by adsorption of dibutyl phthalate.

Keywords
mathematical model, dynamic viscosity, engine oil, soot, structure of aggregates, rheological properties

Submitted: 20.08.2024
Revised: 16.09.2024
Accepted: 21.10.2024

For citation

Lesin A.V., Isaev A.V., Tonkonogov B.P., Dunaev S.V., Kulikov A.B. A mathematical model of the dynamic viscosity dependence of motor oils on temperature, soot concentration, and its morphology. *Tonk. Khim. Tekhnol. = Fine Chem. Technol.* 2024;19(6):485–496. https://doi.org/10.32362/2410-6593-2024-19-5-462-478

НАУЧНАЯ СТАТЬЯ

Математическая модель зависимости динамической вязкости моторных масел от температуры, концентрации сажи и ее морфологии

А.В. Лесин[1], ✉, А.В. Исаев[1], Б.П. Тонконогов[2], С.В. Дунаев[1], А.Б. Куликов[1]

[1] *Институт нефтехимического синтеза им. А.В. Топчиева, Российская академия наук, Москва, 119991 Россия*

[2] *Российский государственный университет нефти и газа (национальный исследовательский университет) им. И.М. Губкина, Москва, 119991 Россия*

✉ *Автор для переписки, e-mail: lesinav@ips.ac.ru*

Аннотация

Цели. Быстрый холодный пуск аварийных и вспомогательных энергетических установок на базе дизельных двигателей в любое время должен осуществляться без особых проблем и в кратчайшие сроки. Одним из основных факторов, влияющих на безаварийный пуск энергетических установок, является состояние моторного масла. В процессе работы дизельного двигателя моторное масло накапливает в своем составе сажу, что негативно влияет на его реологические свойства. Цель работы — разработка математической модели изменения динамической вязкости моторных масел в зависимости от температуры с учетом концентрации сажи и ее морфологии на основе результатов экспериментальных исследований.

Методы. В качестве образцов масел для приготовления модельных смесей использовались штатно применяемые моторные масла для дизельных двигателей М-14Д$_2$СЕ и М-5з/14Д$_2$СЕ. В качестве дисперсной фазы суспензий использовался технический углерод марок N110, N220, N330 и N220 пылящий (негранулированный). Реологические свойства образцов определялись на ротационном реометре TA Instruments DHR-2. Полученные экспериментальные данные обрабатывались методами математической статистики с получением аппроксимирующих зависимостей.

Результаты. В работе представлены анализ различных подходов к описанию реологии суспензий и результаты экспериментальных исследований вязкостно-температурных характеристик (ВТХ) модельных образцов масел, содержащих сажу. Показано, что существующие модели зависимости динамической вязкости суспензий от температуры, объемной концентрации дисперсной фазы, размеров и формы ее частиц не позволяют адекватно описать ВТХ моторных масел, содержащих сажу. Предложена модель реологических свойств саже-масляных суспензий в виде математической зависимости их динамической вязкости от температуры, массовой концентрации сажи, плотности материала и размеров сажевых частиц, от характеристик формы и структуры первичных агрегатов, а также от соотношения размеров агрегатов и молекул дисперсионной среды.

Выводы. Показано, что для адекватного описания ВТХ моторных масел, содержащих сажу, необходимо учитывать характеристики структуры первичных агрегатов сажевых частиц. Разработана математическая модель ВТХ масел в виде зависимости их динамической вязкости от температуры, массовой концентрации сажи, плотности материала частиц, степени несферичности агрегатов, соотношения размеров частиц дисперсной фазы (агрегатов или одиночных частиц неагрегированной сажи) и молекул масла, а также структурности сажи, характеризуемой стандартным показателем — адсорбцией дибутилфталата.

Ключевые слова

математическая модель, динамическая вязкость, моторное масло, сажа, структура агрегатов, реологические свойства

Поступила: 20.08.2024
Доработана: 16.09.2024
Принята в печать: 21.10.2024

Для цитирования

Лесин А.В., Исаев А.В., Тонконогов Б.П., Дунаев С.В., Куликов А.Б. Математическая модель зависимости динамической вязкости моторных масел от температуры, концентрации сажи и ее морфологии. *Тонкие химические технологии*. 2024;19(6):485–496. https://doi.org/10.32362/2410-6593-2024-19-5-462-478

INTRODUCTION

Among the numerous attributes of motor oil (MO), its viscosity-temperature characteristic (VTC) is of particular significance. The viscosity of the oil is a critical factor in determining the operational characteristics of diesel engines, including the starting properties, time to reach full load acceptance, operational fuel consumption, and energy costs associated with driving its units. The viscosity of the oil affects these characteristics by influencing the friction operation of the engine and the energy required to drive its units. The viscosity of the oil also exerts an influence on the total emissions of toxic substances with exhaust gases, given that the mass of emissions is proportional to fuel consumption, which increases in proportion to the viscosity of the oil, provided that the external load remains constant.

The VTC of MO provides a comprehensive characterization of the rheological properties in question. The VTC of MO is primarily determined by the nature of the base oil. Viscosity-enhancing additives are frequently employed to augment viscosity and viscosity index. The utilization of these compounds facilitates the attainment of oils with a mild VTC. The combination of thickening additives with additives which enhance lubricating properties enables the production of energy-efficient oils [1].

The analysis demonstrates that the viscosity of MO is not a constant during operation and varies in accordance with the accumulation of various contaminants within it. The introduction of engine fuel into the oil results in a reduction in viscosity, while the flash point in the open crucible is also diminished. This is a useful diagnostic parameter for identifying engine malfunctions which may lead to oil liquefaction by engine fuel.

It is typical for a small quantity of wear products to be present in the operational MO. This is due to the formation and removal of such products from the friction zones by the MO. Additionally, the effective removal of these products from the oil stream by cleaning filters, as well as the settling of heavy particles of wear products in the crankcase contribute to the overall reduction in their concentration.

The greatest number of contaminants present within the operational MO, which are perpetually present within the circulating stream, are minute soot particles not retained by the filters. These particles often contain adsorbed products of degradation and chemical transformation of oil components during operation.

The bulletin[1] indicates that the presence of soot in the oil is not problematic until the active components of the additives reach a point of diminishing effectiveness. The accumulation of soot in the crankcase over time leads to the removal of additive components from the surface of the soot. This in turn results in the accelerated wear of the rubbing parts, namely the cylinder piston group and the valve mechanism.

As the concentration of soot in MO increases, its viscosity also increases. This gradual increase reaches a point at which the operation of the diesel engine becomes impossible. At this point, the oil is replaced with fresh oil. Concurrently, augmentation in the viscosity of the oil due to accumulation of soot may be obscured by a reduction in viscosity resulting from the introduction of fuel into the oil.

Given the labor-intensive and economically unprofitable nature of constant monitoring of the condition of the working oil, there is a clear interest in developing a mathematical model for changing the dynamic viscosity of MO in accordance with the increasing concentration of soot during engine operation.

MATERIALS AND METHODS

Materials

To study the rheological properties of suspensions, M-14D_2SE and M-5z/D_2SE oils, routinely used in medium-speed diesel engines (*Shahumyan Production Plant*, Russia), were selected.

The trademarks of carbon black N110, N220, N220p (dusty, selected from the bag filter of the installation before granulation), and N330 of production by *Nizhnekamsktehuglerod* (Russia) were used as the dispersed phase in the research.

In the interests of reducing the volume of the article, the results of experiments for MO of M-14D_2SE and N220p grades, as a dispersed phase, will be further considered.

The approximation for the dependence of pure oil is given by the following equation:

$$\mu(T) = \exp\left(\exp\left(a \cdot T^{-4} + b \cdot T^{-2} + c\right)\right) - 1. \tag{1}$$

The values of the coefficients in Eq. (1) are: $a = -1.29 \cdot 10^{10}$; $b = 1.03 \cdot 10^{6}$; $c = -1.13$.

Methods

The rheological properties of the model samples were investigated utilizing a rotational rheometer (DHR-2, *TA Instruments*, USA) with a cone-plane measuring unit

---

[1] Cummins service Bulletin 4960819-07. 2002. 15 p.

(plane diameter 40 mm, cone angle 2°). The temperature dependencies of viscosity were obtained at a constant shear rate of 100 c^{-1} and a temperature change rate of 2°C/min with an increase in temperature from 20 to 120°C and with a decrease in temperature from room temperature to −60°C.

Analysis of analytical approaches to the description of VTC soot-oil suspensions

The majority of the dependencies proposed in scientific and technical literature with regard to the dynamic viscosity of dispersed systems can be reduced to the following form:

$$\mu(T,\varphi)=\mu_0(T)\cdot F(\varphi), \tag{2}$$

wherein $\mu_0(T)$ is the dynamic viscosity of the dispersion medium as a function of absolute temperature; $F(\varphi)$ is a function of the volume concentration of the dispersed phase.

One of the first known formulas for calculating the viscosity of suspensions was proposed by A. Einstein [2]:

$$\mu(\varphi)=\mu_0\cdot F(\varphi)=\mu_0\cdot(1+\varepsilon\cdot\varphi), \tag{3}$$

wherein ε is the coefficient for particles of the dispersed phase of an ellipsoid shape (in particular, for spherical particles in the formula theoretically derived by Einstein, with the assumptions he made when calculating energy dissipation when a viscous liquid flows around a solitary sphere, the value ε is 2.5, and the experimentally obtained value ε for spherical particles is 2.9); μ_0 is viscosity at a fixed temperature.

It can be observed that Eq. (3) represents a special case of Eq. (2). Consequently, the viscosity of the suspension is dependent on temperature solely in relation to the viscosity of the dispersion medium. It should be noted that the dependence of the form (3) produces correct results only at $\varphi < 0.04$, when the hydrodynamic interaction between the particles of the dispersed phase can be neglected.

At elevated concentrations of dispersed phase particles in suspensions, the interaction of the flow fields of the dispersion medium around neighboring particles becomes discernible. The viscosity exhibits a nonlinear increase as the concentration of the dispersed phase rises. In this instance, a more comprehensive equation is more appropriate [2]:

$$\mu(\varphi)=\mu_0\cdot\left(1+\varepsilon_1\cdot\varphi+\varepsilon_2\cdot\varphi^2+\varepsilon_3\cdot\varphi^3\right), \tag{4}$$

wherein the values of the coefficients ε_1, ε_2, ε_3 are different for different authors. In [3], numerous variants of the values of these coefficients for different ranges of values are given, while in almost all literary sources $\varepsilon_1 = 2.5$, and the remaining coefficients may differ significantly. For example, in [4] the Wand formula with the coefficients $\varepsilon_1 = 2.5$, $\varepsilon_2 = 6.25$, $\varepsilon_3 = 15.6$ is given. They allow a sufficiently high accuracy of calculation of viscosity of suspensions to be obtained with a low content of dispersed phase ($\varphi < 0.3$), when collisions of particles and overlapping of solvate layers formed by a part of the dispersion medium are so rare that their influence on the flow of suspensions is very insignificant.

Formulas are proposed for calculating the viscosity of suspensions in which the volume concentration function of the dispersed phase $F(\varphi)$ has a different form. Thus, in the fundamental monograph by S. Bretschneider [3], the Kunitz formula is given:

$$\mu(\varphi)=\mu_0\cdot(1+0.5\cdot\varphi)\cdot(1-\varphi)^4, \tag{5}$$

However, calculations based on these formulas produce absolutely incorrect and contradictory results to experimental data. This is obviously due to an error in the "–" sign in the second bracket. It is regrettable that this error has been identified in numerous other reviews and reference publications.

Upon replacing the "–" sign with "+", the outcomes of the calculations conducted in accordance with Eq. (5) are observed to be relatively proximate to those derived from other validated approximations.

Kurgaev's formula is also given in [3], which, according to the author [3], gives the best agreement with the results of experimental determination of the dynamic viscosity of suspensions in the range of values $\varphi < 0.25$:

$$\mu(\varphi)=\mu_0\cdot\left(1+\frac{2\cdot\varphi}{\left(1-1.2\cdot\varphi^{\frac{2}{3}}\right)^2}\right). \tag{6}$$

The formula for concentrated suspensions exhibiting non-Newtonian properties, as proposed by Barney and Mirzakhi, is presented in reference [4].

$$\mu(\varphi)=\mu_0\cdot\exp\left(\frac{k_1\cdot\varphi}{1-k_2\cdot\varphi}\right), \tag{7}$$

wherein $k_1 = 2.5$; $k_2 = 0.75 \ldots 1.5$ for different authors.

The approximations (3)–(7) discussed above do not take into account the size and shape of the particles, despite the necessity of such considerations for certain ratios of concentration and particle sizes of the dispersed phase. In this regard, the following approximation is proposed in reference to suspensions comprising spherical particles, as documented in [4].

$$\mu(\varphi)=\mu_0\cdot\left(1+2.5\cdot\varphi+\frac{3}{4}\cdot\varphi\cdot\exp\left(\frac{m\cdot\varphi}{\left(\varphi-\varphi_{\max}\right)^2}\right)\right), \quad (8)$$

wherein $m = 2.2 + 0.033a$; a is the particle size in microns; $\varphi_{\max} = 0.74$ is the concentration of particles with the densest packaging.

G.I. Kelbaliev [4] notes that the results of calculating the viscosity of suspensions by Eq. (8) agree well with the experimental data. However, like the authors of several other works (e.g., M.A. Morozova[2] and P.I. Pilov [5]), he makes an erroneous conclusion that viscosity also increases with increasing particle size of the dispersed phase.

In the work of P.I. Pilov [5], a theoretically justified formula was proposed for calculating the dynamic viscosity coefficient of suspensions. His formula takes into account not only the volume concentration of the dispersed phase φ and the radius of its particles r, but also the properties of their surface by introducing into the formula the thickness of the boundary layer of the dispersion medium on the surface of the particles of the dispersed phase λ:

$$\mu(\varphi,r,\lambda)=\mu_0\cdot\frac{1}{1-\left(1+\frac{\lambda}{r}\right)\cdot\sqrt[3]{\frac{\varphi}{k_v}}}, \quad (9)$$

wherein k_v is the packing coefficient of particles of the dispersed phase, equal to $\pi/6$ for cubic packaging and 0.625 for arbitrary packaging.

As illustrated by Eq. (9), a reduction in the particle size of the dispersed phase is associated with an increase in suspension viscosity. It should be noted that the work [5] is primarily concerned with the gravitational separation of minerals, and therefore pertains mainly to coarse-dispersed suspensions. Therefore, the adequacy of this formula in relation to soot suspensions in MO requires verification.

The work of V.Ya. Rudyak [6], devoted to the study of the viscosity of nanofluids (that is to say, dispersed systems consisting of liquid and nanoparticles, which include non-aggregated carbon black in MO), demonstrated that the dependence of the viscosity of the suspension on the concentration of nanoparticles, regardless of the particle material, can be described by the formula:

$$\mu(\varphi)=\mu_0\cdot\left(1+\varepsilon_1\cdot\varphi+\varepsilon_2\cdot\varphi^2\right), \quad (10)$$

in which the coefficients ε_1 and ε_2 significantly exceed in magnitude the similar coefficients in Eq. (4).

Thus, in the dependencies for suspensions with TiO_2 nanoparticles, they are 5.45 and 108.2, respectively, in contrast to 2.5 and 6.25 in Wand's formula [4]. For suspensions of aluminum oxide(III) particles, ε_1 and ε_2 are equal to 7.3 and 123, and for copper particles, they are 3.645 and 468.72, respectively. From this, the author [6] concludes that the viscosity coefficient of nanofluids increases significantly faster with increasing particle concentration than the viscosity coefficient of a conventional dispersed liquid. The values of the coefficients ε_1 and ε_2 may depend on the size of the nanoparticles and their material.

As a result of molecular dynamic modeling [6], a dependence was obtained:

$$\mu(\varphi)=\mu_0\cdot\left[\mu_{r\mathrm{B}}+\left(5.25\cdot\varphi+40.94\cdot\varphi^2\right)\times\right.$$
$$\left.\times\exp\left(-0.208\cdot\frac{D}{d}\right)\right], \quad (11)$$

wherein $\mu_{r\mathrm{B}} = 1 + 2.5\cdot\varphi + 6.2\cdot\varphi^2$ is the relative viscosity of the suspension in the Batchelor's formula [7], D is the effective diameter of the nanoparticles, d is the effective diameter of the molecules of the dispersion medium. Additionally, as demonstrated in reference [6], the rheological characteristics of non-Newtonian nanofluids can be effectively represented by a model of the following form:

$$\mu(\varphi)=K\cdot\gamma^{n-1}, \quad (12)$$

wherein γ is the shear rate; $n = 1 - 36.3\cdot\varphi + 5\cdot\varphi^2$; $K = 0.001 + \varphi - 230\cdot\varphi^2 + 3700\cdot\varphi^3$.

The author [6] proposes that the Newtonian behavior of nanofluids can be discussed only when the base liquid is Newtonian and the concentration of nanoparticles is not particularly high. The volume concentrations of nanoparticles in this instance does not appear to exceed 10–15%. The coefficient of dynamic viscosity at such concentrations can be represented by the Eq. (10). Nevertheless, the coefficients in this ratio must be functions of the size of the nanoparticles.

$$\mu(\varphi)=\mu_0\cdot\left(1+\varepsilon_1(D)\cdot\varphi+\varepsilon_2(D)\cdot\varphi^2\right). \quad (13)$$

In order to evaluate the suitability of the aforementioned approximations, calculations were conducted to determine the kinematic viscosity of M-14D_2SE oil and soot suspensions based on this oil and carbon black grade N220 (dusty) within a temperature range of 250 to 350 K. The resulting data is presented

---

[2] Morozova M.A. *Thermal conductivity and viscosity of nanofluids*. Diss. Cand. Sci. (Phys.-Math.). Novosibirsk: Institute of Thermophysics SB RAS; 2019. 103 p. (in Russ.).

in Fig. 1. The N220 brand was chosen since, of the available carbon black trademarks, it is morphologically closest to the soot samples described in publications on the problems of soot formation in diesels [8–14].

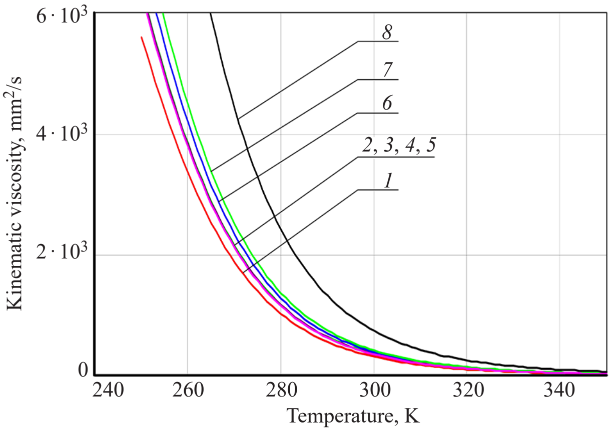

Fig. 1. Approximations for the VTCs of M-14D$_2$SE oil (*1*) and its suspensions with soot (5 vol %) according to the Eqs.: curve (*2*) — Eq. (3); (*3*) — (6); (*4*) — (4); (*5*) — (7); (*6*) — (5); (*7*) — (11); (*8*) — (9)

As can be seen from Fig. 1, all the methods considered for calculating VTCs give a similar nature of dependencies. The majority of formulas which solely consider the volume concentration of the dispersed phase yield highly comparable results for viscosity calculations. Concurrently, the Einstein formula yielded slightly lower viscosity values than the formulas of Kurgaev, Wand, Barney, and Mirzakhi (the latter three yielded almost indistinguishable results).

The VTCs of soot-oil suspensions are also adequately described using the Kunitz model, although it does not account for the particle sizes of the dispersed phase (curve *6* in Fig. 1).

In the context of this study, the model (11) described in the work of V.Ya. Rudyak [6] is the most appropriate when calculating the viscosity of suspensions. This is due to its suitability for a wide range of volume concentrations of the dispersed phase and its consideration of the ratio of particle sizes and molecules of the dispersion medium.

RESULTS AND DISCUSSION

In order to confirm the applicability of the model (11), selected following an analysis of the models available in the scientific and technical literature and a discussion of the same in the previous section, a series of experiments was conducted with the preparation of model mixtures of MO of M-14D$_2$SE grade with different soot contents (N220p dusty, nongranular), followed by the determination of dynamic viscosity. In order to prepare the model samples, soot mass concentrations of 1, 2, 3, 4, 5, and 7 wt % were selected. The 1% step was selected in order to facilitate the observation of the change in viscosity which occurs with an increase in soot concentration. A contamination level of 5 wt % in used oil is typically deemed inadequate, necessitating the replacement of the oil in accordance with the specifications provided by the manufacturers of the associated equipment. The 7 wt % soot content was selected to substantiate the hypothesis that an excess of soot content above the established norm (5 wt %) has a deleterious effect on the rheological characteristics of the oil.

Based on experimental data, approximate dependencies of change of dynamic viscosity of M-14D$_2$SE oil with N220 dusty soot at concentrations of 1, 2, 3, 4, 5, and 7 wt % at absolute temperature were obtained, graphs of which are presented in Fig. 2. The analytical form of the approximating dependencies and the values of the coefficients a, b, and c are presented in Table 1 for reference.

A common feature of the VTCs of M-14D$_2$SE oil samples with soot is the expected steady trend towards an increasingly noticeable shift in viscosity-temperature curves upward relative to the VTC of pure oil as the concentration of soot increases. The highest values of dynamic viscosity can be observed in oil samples with the highest soot content, which in our case corresponds to a concentration of 7 wt %.

Dependence (11) is a suitable method for calculating the dynamic viscosity of suspensions across a wide range of volume concentrations of the dispersed phase and temperatures. In addition to these parameters, it allows for the consideration of only the ratio of the sizes of soot particles and molecules of the dispersion medium (oil). Nevertheless, the outcomes of the calculations indicate that these parameters are inadequate for accurately predicting the VTCs of the oil flow contaminated with soot (Fig. 3).

It is evident that the Eq. (11) does not account for two key factors: firstly, the presence of soot in oil is predominantly in the form of primary aggregates, formed in the gas phase and subsequently captured by oil; and secondly, soot aggregates contain absorbed oil. Given these considerations, the viscosity of soot suspensions in MO must be calculated with a focus on particles of a sufficiently large size, corresponding to the dimensions of soot aggregates. Furthermore, when determining the volume concentration of the dispersed phase, it is essential to take into account the proportion of the dispersion medium which becomes part of the dispersed phase, comparable in volume to the volume of soot.

The average value of the effective particle diameter of the model carbon black (nongranulated carbon black of the N220 brand), designated N220p, considered in this study, is 32 nm, and their primary aggregates are 103 nm [15].

Table 1. Parameters of approximating dependencies of the dynamic viscosity of M-14D$_2$SE oil and suspensions based on it

Product	Dependence coefficients $\mu(T)=\exp\left(\exp\left(a\cdot T^{-4}+b\cdot T^{-2}+c\right)\right)-1$			Correlation coefficient $\mathrm{corr}\left(\left(T^{-4}+T^{-2}\right),\ln\ln\left(\mu+1\right)\right)$
	a	*b*	*c*	
M-14D$_2$SE	$-7.31\cdot10^9$	$8.60\cdot10^5$	−9.84	0.999
M-14D$_2$SE + 1 wt % N220p	$-3.98\cdot10^9$	$7.38\cdot10^5$	−8.75	0.999
M-14D$_2$SE + 2 wt % N220p	$-3.62\cdot10^8$	$6.08\cdot10^5$	−7.62	0.999
M-14D$_2$SE + 3 wt % N220p	$2.01\cdot10^9$	$5.26\cdot10^5$	−6.91	0.999
M-14D$_2$SE + 4 wt % N220p	$5.93\cdot10^9$	$3.71\cdot10^5$	−5.49	0.999
M-14D$_2$SE + 5 wt % N220p	$9.57\cdot10^9$	$2.10\cdot10^5$	−3.92	0.998
M-14D^{2}SE + 7 wt % N220p	$-7.31\cdot10^9$	$8.60\cdot10^5$	−9.84	0.999

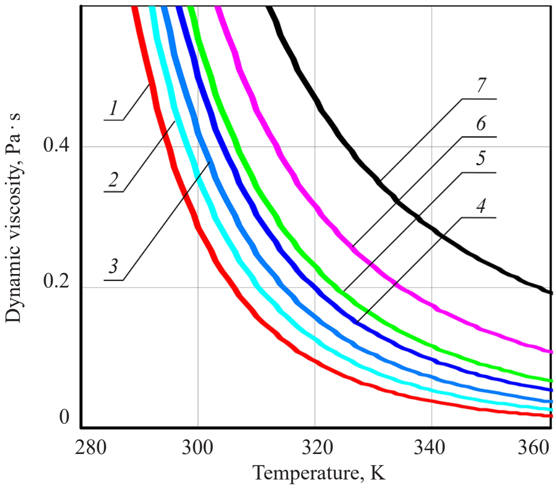

Fig. 2. Approximating dependencies of the dynamic viscosity of M-14D$_2$SE (*1*) oil on temperature at different concentrations of N220 dusty soot:
(*2*) M-14D$_2$SE oil + 1% soot; (*3*) M-14D$_2$SE oil + 2% soot; (*4*) M-14D$_2$SE oil + 3% soot; (*5*) M-14D$_2$SE oil + 4% soot; (*6*) M-14D$_2$SE oil + 5% soot; (*7*) M-14D$_2$SE oil + 7% soot

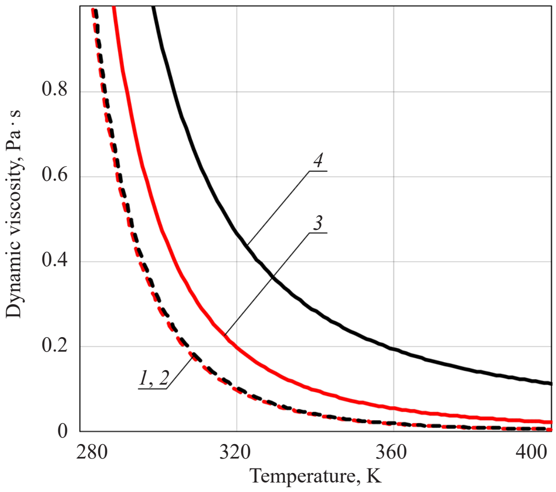

Fig. 3. Results of calculating the dynamic viscosity of 3- and 7-percent suspensions of N220p soot in M-14D$_2$SE engine oil according to Eq. (11) in comparison with the approximation of experimental data:
(*1*) calculation results using Eq. (11) with 3% soot;
(*2*) calculation results using Eq. (11) with 7% soot;
(*3*) M-14D$_2$SE oil + 3% soot; (*4*) M-14D$_2$SE oil + 7% soot

In the absence of consideration of oil absorption by soot aggregates, the dynamic viscosity of soot suspensions in oil, as derived from Eq. (11), exhibits the following dependence:

$$\mu_{s9}\left(g,T\right)=\mu_0\left(T\right)\left\{\left[1+2.5f_{\mathrm{ns}}c_{\mathrm{DP}}\left(g,T\right)+\right.\right.$$
$$\left.+\,6.2f_{\mathrm{ns}}^2c_{\mathrm{DP}}\left(g,T\right)^2\right]+\left[5.25f_{\mathrm{ns}}^2c_{\mathrm{DP}}\left(g,T\right)^2+\right.\qquad(14)$$
$$\left.\left.+\,40.94f_{\mathrm{ns}}^4c_{\mathrm{DP}}\left(g,T\right)^4\right]\exp\left(-0.208\frac{D}{d}\right)\right\},$$

wherein *g* is the mass concentration of soot in the suspension in fractions of one; *T* is the absolute temperature, K; $\mu_0(T)$ is the dynamic viscosity of pure oil, Pa · c (general view of the dependence $\mu(T)$ and the values of the coefficients *a*, *b*, *c* are shown in Figs. 1 and 2 and in Table 1, respectively); f_{ns} is the coefficient of non-sphericity of primary aggregates of soot particles, taking into account the ratio of the large and small axes of the space area occupied by the average aggregate; *D* is the average value of the effective diameter of the aggregates, nm (for N220p soot according to data [15, 16, [3]] D = 103 nm); d is the characteristic value the linear size of the molecules of the dispersion medium (DM), assumed to be 1.5 nm; $c_{\mathrm{DP}}(g,T)$ is the volume concentration of soot in the suspension, calculated by the formula:

$$c_{\mathrm{DP}}(g,T)=\frac{g\cdot\rho_{\mathrm{DM}}(T)}{g\cdot\rho_{\mathrm{DM}}(T)+(1-g)\rho_{\mathrm{DP}}},\qquad(15)$$

wherein ρ_{DP} is the density of the dispersed phase material (soot), assumed to be equal to 1850 kg/m^3; $\rho_{\mathrm{DM}}(T)$ is the dependence of the density of the DM on temperature:

$$\rho_{\mathrm{DM}}(T)=1019-0.661\cdot T.\qquad(16)$$

The calculations, performed according to Eq. (14) and presented in Fig. 4, show an unsatisfactory agreement of their results with experimental data obtained using a rotational viscometer.

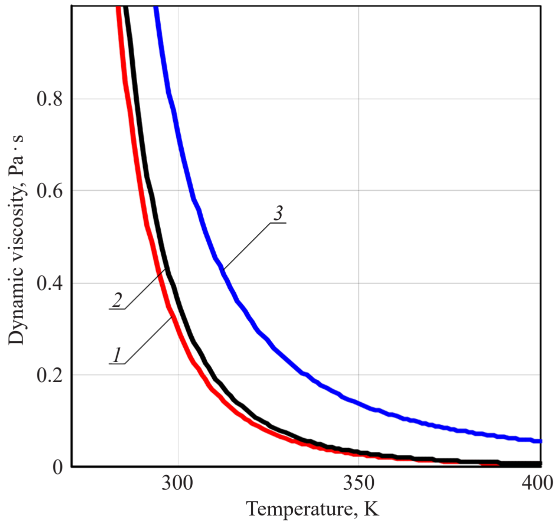

Fig. 4. Results of the calculation of the dynamic viscosity of a 5-percent suspension of N220p soot in M-14D$_2$SE engine oil according to Eq. (14) in comparison with the approximation of experimental data:
(*1*) M-14D$_2$SE oil;
(*2*) calculated value according to Eq. (14);
(*3*) M-14D$_2$SE oil + 5% soot

One of the reasons for this result, clearly, is that Eq. (14) does not take into account the structure of soot, usually characterized by such an indicator as the absorption of dibutyl phthalate k_{DBP}, cm^3/100 g of soot. The value of this indicator is approximately equivalent to the volume of oil absorbed by the primary soot aggregates and subsequently removed from the dispersion medium. This results in an increase in the volume concentration of the dispersed phase in the suspension, with a higher k_{DBP} value leading to a greater degree of separation.

In this case, the volume concentration of the dispersed phase is equal to

$$c_{\mathrm{DP}}(g,T,K_{\mathrm{DBP}})=\frac{g\cdot\left[1+\rho_{\mathrm{DP}}K_{\mathrm{DBP}}\right]\rho_{\mathrm{DM}}(T)}{g\cdot\rho_{\mathrm{DM}}(T)+(1-g)\cdot\rho_{\mathrm{DP}}},\qquad(17)$$

wherin $K_{\mathrm{DBP}} = k_{\mathrm{DBP}}\cdot 10^{-5}$, m^3/kg.

Taking into account (17), Eq. (14) takes on a different form:

$$\begin{aligned}\mu_{s10}(g,T,K_{\mathrm{DBP}})&=\mu_0(T)\times\\ &\times\Big\{\Big[1+2.5f_{\mathrm{ns}}c_{\mathrm{DP}}(g,T,K_{\mathrm{DBP}})+\\ &+6.2f_{\mathrm{ns}}^2c_{\mathrm{DP}}(g,T,K_{\mathrm{DBP}})^2\Big]+\\ &+\Big[5.25f_{\mathrm{ns}}^2c_{\mathrm{DP}}(g,T,K_{\mathrm{DBP}})^2+\\ &+40.94f_{\mathrm{ns}}^4c_{\mathrm{DP}}(g,T,K_{\mathrm{DBP}})^4\Big]\exp\left(-0.208\frac{D}{d}\right)\Big\}.\end{aligned}\qquad(18)$$

It should be noted that with a mass concentration of soot in a suspension g = 0.05, the volume concentration calculated by Eq. (15) at a temperature of 293 K is 0.023, and according to Eq. (17) in the case of M-14D$_2$SE oil (K_{DBP} = 115 cm^3/100 g) it is 0.072, which causes the larger, than according to Eq. (14), proximity of the obtained viscosity values to those measured experimentally (Fig. 5).

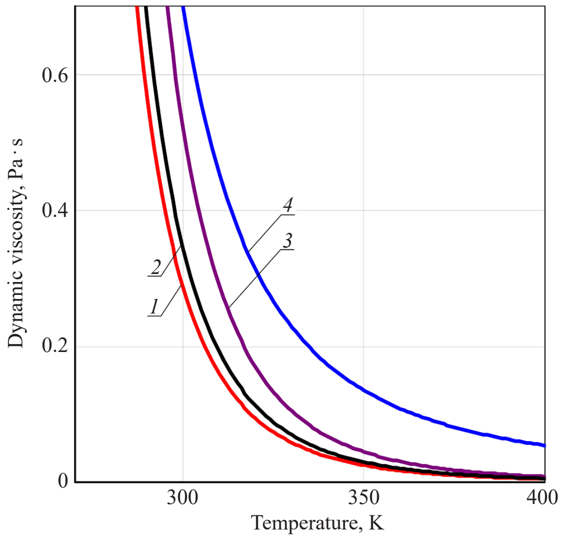

Fig. 5. Results of calculating the dynamic viscosity of a 5-percent suspension of N220p soot in M-14D$_2$SE engine oil according to Eqs. (14) and (18) in comparison with the approximation of experimental data:
(*1*) M-14D$_2$SE oil;
(*2*) calculated value according to Eq. (14);
(*3*) calculated value according to Eq. (18);
(*4*) M-14D$_2$SE oil + 5% soot

---

[3] Razdiakonova G.I. *Dispersed carbon.* An educational electronic publication of local distribution. Omsk: OmSTU, 2013. 231 p.

Nevertheless, the calculated values of the dynamic viscosity of the oil obtained by Eq. (18) remain significantly disparate from the experimental data. Similar discrepancies were observed for other values of the mass concentration of soot in the suspension, ranging from 0.01 to 0.07.

In light of the aforementioned considerations, an effort was made to incorporate the impact of the shape of primary soot aggregates on the viscosity of suspensions. In the case of N220p, the electron microscopy data presented in [15, 17] indicate that the shape deviates significantly from a spheroidal or ellipsoidal form, exhibiting a branched structure with an average number of soot particles in aggregates equal to 33.

Given that the primary aggregates of N220p soot in size can be classified as Brownian particles, which, due to their branched shape, exhibit a higher resistance to shear motion of the dispersion medium than spherical particles, Eq. (18) was transformed by introducing an additional complex parameter $K(T)$ into it.

$$K\left(T, K_{\mathrm{DBP}}\right)=\left(\frac{K_{\mathrm{DBP}}}{30}\right)\cdot\left(\frac{T}{T_{\mathrm{cr}}}\right)^{0.6}\times \times\left\{\exp\left[-\left(\frac{273}{T}\right)^{3}\right]\right\}^{0.8}, \tag{19}$$

where T_{cr} is the pour point of the oil (for M-14D$_2$SE, $T_{\mathrm{cr}} = 261$ K).

In this instance, the formula for calculating the dynamic viscosity is given by the following expression:

$$\begin{aligned}\mu_{s11}\left(g, T, K_{\mathrm{DBP}}\right)=\mu_0(T)\times\\ \times\left\{\left[\left(K\left(T, K_{\mathrm{DBP}}\right)\right)^2\cdot\left(c_{\mathrm{DP}}\left(g, T, K_{\mathrm{DBP}}\right)\right)^{0.3}+\right.\right.\\ 2.5 f_{\mathrm{ns}} c_{\mathrm{DP}}\left(g, T, K_{\mathrm{DBP}}\right)+\\ \left.+6.2 f_{\mathrm{ns}}^2 c_{\mathrm{DP}}\left(g, T, K_{\mathrm{DBP}}\right)^2\right]+\\ +\left[5.25 f_{\mathrm{ns}}^2 c_{\mathrm{DP}}\left(g, T, K_{\mathrm{DBP}}\right)^2+\right.\\ \left.\left.+40.94 f_{\mathrm{ns}}^4 c_{\mathrm{DP}}\left(g, T, K_{\mathrm{DBP}}\right)^4\right]\exp\left(-0.208\frac{D}{d}\right)\right\}.\end{aligned} \tag{20}$$

The results of the calculation of the dynamic viscosity of oils in accordance with Eq. (20) are shown in Fig. 6.

The relative position of the VTCs of soot suspensions obtained by calculation according to Eq. (20) and the approximate dependencies obtained as a result of processing the experimental data by regression analysis methods indicate a sufficiently high reliability of predicting the viscosity of oils contaminated with soot using Eq. (20).

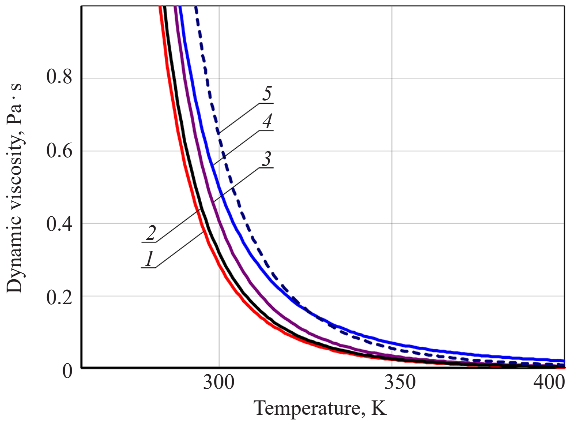

Fig. 6. Results of calculating the dynamic viscosity of a 5-percent suspension of N220p soot in M-14D$_2$SE engine oil according to Eqs. (14), (18), and (20) in comparison with the approximation of experimental data:
(*1*) M-14D$_2$SE oil;
(*2*) calculated value according to Eq. (14);
(*3*) calculated value according to Eq. (18);
(*4*) M-14D$_2$SE oil + 5% soot;
(*5*) calculated value according to Eq. (20)

CONCLUSIONS

The results obtained indicate that, in order to adequately describe the VTCs of MOs containing soot, the characteristics of the structure of the primary aggregates of soot particles need to be taken into account. The developed mathematical model of VTCs of oils in the form of dependence of their dynamic viscosity on temperature, soot mass concentration, density of particles material, degree of aggregates non-sphericity, ratio of particle sizes of dispersed phase (aggregates or single particles of non-aggregated soot) and oil molecules, as well as soot structure characterized by adsorption of dibutyl phthalate, allows the VTCs of oils contaminated with soot formed in the course of diesel operation to be sufficiently reliably predicted.

Authors' contributions

A.V. Lesin—planning and conducting experimental studies, processing test results, preparing the data obtained for publication.

A.V. Isaev—setting objectives, planning the experimental studies, theoretical studies of dispersed phase characteristics effect on the viscosity of suspensions, preparing the data obtained for publication.

B.P. Tonkonogov—setting objectives, processing the data obtained, preparing of the data obtained for publication.

S.V. Dunaev—setting objectives, planning the experimental studies, processing the data obtained, preparing the data obtained for publication.

A.B. Kulikov—setting objectives, planning the experimental studies, processing the data obtained, preparing the data obtained for publication.

The authors declare no conflicts of interest.

REFERENCES

1. Anisimov I.G., *et al. Topliva, smazochnye materialy, tekhnicheskie zhidkosti. Assortiment i primenenie* (*Fuels, Lubricants, Technical Fluids. Assortment and Application*). Shkolnikov V.M. (Ed.). Moscow: Tekhinform; 1999. 596 p. (in Russ.). ISBN 5-89551-006-X
2. Matveenko V.N., Kirsanov E.A. The viscosity and structure of dispersed systems. *Moscow Univ. Chem. Bull*. 2011;66(4): 199–228. https://doi.org/10.3103/S0027131411040079

   [Original Russian Text: Matveenko V.N., Kirsanov E.A. The viscosity and structure of dispersed systems. *Vestnik Moskovskogo Universiteta. Khimiya*. 2011;52(4):243–246 (in Russ.).]
3. Bretshnaider S. *Svoistva gazov i zhidkostei. Inzhenernye metody rascheta* (*Properties of Gases and Liquids. Engineering Calculation Methods*). Transl. from Polish. Moscow, Leningrad: Khimiya; 1966. 535 p. (in Russ.).

   [Bretsznajder S. *Wlasności Gazów i Cieczy*. Warszawa: Wydawnictwa Naukowo-Techniczne; 1962. 739 p.]
4. Kelbaliev G.I., Rasulov R.S., Tagiev D.B. *Mekhanika i reologiya neftyanykh dispersnykh system* (*Mechanics and Rheology of Petroleum Dispersed Systems*). Moscow: Maska; 2017. 462 p. (in Russ.).
5. Pilov P.I. *Gravitatsionnaya separatsiya poleznykh iskopaemykh* (*Gravity Separation of Minerals*). Dnepropetrovsk; 2003. 123 p. (in Russ.).
6. Rudyak V.Ya. Morden status of researches on nanofluids viscosity. *Vestnik Novosibirskogo gosudarstvennogo universiteta. Seriya: Fizika = Vestnik NSU. Series: Physics*. 2015;10(1):5–22 (in Russ.).
7. Batchelor G.K. Brownian diffusion of particles with hydrodynamic interaction. *J. Fluid Mechanics.* 1976;74(1): 1–29. https://doi.org/10.1017/S0022112076001663
8. Shkolnikov E.I., Grigorenko A.V., Lipatova I.A., Kumar V., Vlaskin M.S. Methane Impurity Effect in the Acetylene Decomposition on Size and Morphology of the Appearing Soot Particles. *Vestnik MGTU im. N.E. Baumana. Ser. Estestvennye nauki = Herald of the Bauman Moscow State Technical University. Series Natural Sciences*. 2023;2(107): 110–125 (in Russ.). http://doi.org/10.18698/1812-3368-2023-2-110-125
9. Likhanov V.A., Lopatin O.P., Kozlov A.N. Modeling soot formation in cylinder of diesel engine. *Nauchno-tekhnicheskie vedomosti SPbPU. Estestvennye i inzhenernye nauki = St. Petersburg Polytechnic University Journal of Engineering Science and Technology*. 2019;25(1):47–59 (in Russ.). https://doi.org/10.18721/JEST.25105
10. Naumenko O.F., Yur G.S., Results of a numerical study of the process of blowing suspended particles of diesel soot in a disturbed gas environment. *Polzunovskiy Vestnik.* 2006;4: 128–130 (in Russ.).
11. Rudnev B.I., Povalikhina O.V. Optical Parameters of Soot Particles and Parameters of Radiative Heat Exchange in Diesel Engine Combustion Chamber. *Vestnik TOGU = Bulletin of PNU*. 2014;2(33):133–140 (in Russ.).
12. Rudnev B.I., Povalikhina O.V. Diesel soot of nanostructure particles. *Nauchnye trudy Dal'rybvtuza = Scientific Journal of DALRYBVTUZ*. 2015;36:86–92 (in Russ.).
13. Shurupov S.V. Regularities of formation of dispersed carbon during isothermal pyrolysis of hydrocarbon raw materials. *Gazokhimiya.* 2009;9:64–72 (in Russ.).
14. Yurlov A.S. Physical properties, composition and structure of soot particles formed in the diesel engine cylinder. *Vestnik Vyatskogo GATU = Bulletin of Vyatka State Agrarian University*. 2023;4(18):253–261 (in Russ.).

СПИСОК ЛИТЕРАТУРЫ

1. Анисимов И.Г. и др. *Топлива, смазочные материалы, технические жидкости. Ассортимент и применение*: справочник; под ред. В.М. Школьникова. М.: Издательский центр «Техинформ»; 1999. 596 с. ISBN 5-89551-006-X
2. Матвеенко В.Н., Кирсанов Е.А. Вязкость и структура дисперсных систем. *Вестник Московского университета. Сер. 2. Химия.* 2011;52(4):243–276.
3. Бретшнайдер С. *Свойства газов и жидкостей. Инженерные методы расчета*: пер. с польск. М., Л.: Химия; 1966. 535 с.
4. Келбалиев Г.И., Расулов Р.С., Тагиев Д.Б. *Механика и реология нефтяных дисперсных систем*. М.: Маска; 2017. 462 с.
5. Пилов П.И. *Гравитационная сепарация полезных ископаемых*. Днепропетровск: Национальный горный университет; 2003. 123 с.
6. Рудяк В.Я. Современное состояние исследований вязкости наножидкостей. *Вестник Новосибирского государственного университета. Серия: Физика*. 2015;10(1):5–22.
7. Batchelor G.K. Brownian diffusion of particles with hydrodynamic interaction. *J. Fluid Mechanics.* 1976;74(1): 1–29. https://doi.org/10.1017/S0022112076001663
8. Школьников Е.И., Григоренко А.В., Липатова И.А., Кумар В., Власкин М.С. Влияние примеси метана при разложении ацетилена на размер и морфологию частиц образующейся сажи. *Вестник МГТУ им. Н.Э. Баумана. Сер. Естественные науки.* 2023;2(107):110–125. https://doi.org/10.18698/1812-3368-2023-2-110-125
9. Лиханов В.А., Лопатин О.П., Козлов А.Н. Моделирование сажеобразования в цилиндре дизеля. *Научно-технические ведомости СПбПУ. Естественные и инженерные науки*. 2019;25(1):47–59. https://doi.org/10.18721/JEST.25105
10. Науменко О.Ф., Юр Г.С. Результаты численного исследования процесса обдува взвешенных частиц дизельной сажи возмущенной газовой средой. *Ползуновский вестник*. 2006;4:128–130.
11. Руднев Б.И., Повалихина О.В. Оптические параметры частиц сажи и характеристики радиационного теплообмена в камере сгорания дизеля. *Вестник Тихоокеанского государственного университета* (*Вестник ТОГУ*). 2014;2(33):133–140.
12. Руднев Б.И., Повалихина О.В. Наноструктуры частиц дизельной сажи. *Научные труды Дальрыбвтуза*. 2015;36: 86–92.
13. Шурупов С.В. Закономерности образования дисперсного углерода при изотермическом пиролизе углеводородного сырья. *Газохимия*. 2009;9:64–72.
14. Юрлов А.С. Физические свойства, состав и структура частиц сажи, образующихся в цилиндре дизельного двигателя. *Вестник Вятского ГАТУ*. 2023;4(18):253–261.
15. Гюльмисарян Т.Г., Капустин В.М., Левенберг И.П. *Технический углерод: морфология, свойства, производство*. М.: Изд-во «Каучук и резина»; 2017. 586 с.
16. Раздьяконова Г.И., Лихолобов В.А., Кохановская О.А. *Технологии модификации технического углерода*: монография. Омск: Изд-во ОмГТУ; 2017. 160 с. ISBN 978-5-8149-2437-7
17. Стебелева О.П., Кашкина Л.В., Вшивкова О.А. Структура и морфология сажевых частиц, образующихся при испарении водных суспензий. *Российские нанотехнологии*. 2022;17(4):465–471. https://doi.org/10.56304/S1992722322040252

15. Gyulmisaryan T.G., Kapustin V.M., Levenberg I.P. *Tekhnicheskii uglerod: morfologiya, svoistva, proizvodstvo* (*Carbon Black: Morphology, Properties, Production*). Moscow: Kauchuk i rezina; 2017. 586 p. (in Russ.).
16. Razdiakonova G.I., Likholobov V.A., Kohanovskaya O.A. *Tekhnologii modifikatsii tekhnicheskogo ugleroda* (*Carbon Black Modification Technologies*): monograph. Omsk: OmSTU; 2017. 160 p. (in Russ.). ISBN 978-5-8149-2437-7
17. Stebeleva O.P., Kashkina L.V., Vshivkova O.A. Structure and morphology of carbon-black particles formed during the evaporation of aqueous suspensions. *Nanotechnol. Russia*. 2022;17(4):489–494. https://doi.org/10.1134/s2635167622040255
[Original Russian Text: Stebeleva O.P., Kashkina L.V., Vshivkova O.A. Structure and morphology of carbon-black particles formed during the evaporation of aqueous suspensions. *Rossiiskie nanotekhnologii*. 2022;17(4):465–471 (in Russ.). https://doi.org/10.56304/S1992722322040252]

About the authors

Anatoly V. Lesin, Researcher, A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences (TIPS RAS) (29, Leninskii pr., Moscow, 119991, Russia). E-mail: lesinav@ips.ac.ru. RSCI SPIN-code 7729-5478, https://orcid.org/0000-0002-1686-8125

Alexander V. Isaev, Dr. Sci. (Eng.), Leading Researcher, A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences (TIPS RAS) (29, Leninskii pr., Moscow, 119991, Russia). E-mail: a_isaev@ips.ac.ru. RSCI SPIN-code 7271-4416, https://orcid.org/0009-0004-7139-7524

Boris P. Tonkonogov, Dr. Sci. (Chem.)**,** Professor, Head of the Department of Chemistry and Technology of Lubricants and Chemmotology, Gubkin University (65/1, Leninskii pr., Moscow, 119991, Russia). E-mail: bpt734@gmail.com. Scopus Author ID 6506284001, ResearcherID B-7698-2018, https://orcid.org/0000-0003-1141-0120

Sergey V. Dunaev, Cand. Sci. (Mil.), Leading Researcher, A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences (TIPS RAS) (29, Leninskii pr., Moscow, 119991, Russia). E-mail: dunaevsv@ips.ac.ru. RSCI SPIN-code 1969-5765, https://orcid.org/0000-0001-6939-8713

Albert B. Kulikov, Cand. Sci. (Chem.), Deputy Director, A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences (TIPS RAS) (29, Leninskii pr., Moscow, 119991, Russia). E-mail: akulikov@ips.ac.ru. Scopus Author ID 7103153889, ResearcherID A-8738-2014, RSCI SPIN-code 3258-4823, https://orcid.org/0000-0003-1756-282X

Об авторах

Лесин Анатолий Викторович, научный сотрудник, ФГБУН Ордена Трудового Красного Знамени Институт нефтехимического синтеза им. А.В. Топчиева, Российская академия наук (ИНХС РАН) (119991, Россия, Москва, Ленинский пр., д. 29). E-mail: lesinav@ips.ac.ru. SPIN-код РИНЦ 7729-5478, https://orcid.org/0000-0002-1686-8125

Исаев Александр Васильевич, д.т.н., ведущий научный сотрудник, ФГБУН Ордена Трудового Красного Знамени Институт нефтехимического синтеза им. А.В. Топчиева, Российская академия наук (ИНХС РАН) (119991, Россия, Москва, Ленинский пр., д. 29). E-mail: a_isaev@ips.ac.ru. SPIN-код РИНЦ 7271-4416, https://orcid.org/0009-0004-7139-7524

Тонконогов Борис Петрович, д.х.н., профессор, заведующий кафедрой химии и технологии смазочных материалов и химмотологии, ФГАОУ ВО «Российский государственный университет нефти и газа (национальный исследовательский университет) им. И.М. Губкина» (119991, Россия, Москва, Ленинский пр., д. 65, корп. 1). E-mail: bpt734@gmail.com. Scopus Author ID 6506284001, ResearcherID B-7698-2018, https://orcid.org/0000-0003-1141-0120

Дунаев Сергей Васильевич, к.воен.н., ведущий научный сотрудник, ФГБУН Ордена Трудового Красного Знамени Институт нефтехимического синтеза им. А.В. Топчиева, Российская академия наук (ИНХС РАН) (119991, Россия, Москва, Ленинский пр., д. 29). E-mail: dunaevsv@ips.ac.ru. SPIN-код РИНЦ 1969-5765, https://orcid.org/0000-0001-6939-8713

Куликов Альберт Борисович, к.х.н., заместитель директора, ФГБУН Ордена Трудового Красного Знамени Институт нефтехимического синтеза им. А.В. Топчиева, Российская академия наук (ИНХС РАН) (119991, Россия, Москва, Ленинский пр., д. 29). E-mail: akulikov@ips.ac.ru. Scopus Author ID 7103153889, ResearcherID A-8738-2014, SPIN-код РИНЦ 3258-4823, https://orcid.org/0000-0003-1756-282X

Translated from Russian into English by N. Isaeva
Edited for English language and spelling by Dr. David Mossop