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ASSESSMENT OF THE EFFECT OF FERROMAGNETIC LIQUIDS ON OIL RECOVERY OF BITUMINOUS SANDS

Ibrahim Habibov
Corresponding author
Doctor of Technical Sciences, Professor*
E-mail: h.ibo@mail.ru

Tarana Yusif Sadigova
Assistant*

Sevinc Malik Abasova
Candidate of Technical Sciences, Associate Professor*

*Department of Industry Machine
Azerbaijan State Oil and Industry University
Azadlig ave., 20, Baku, Azerbaijan, AZ 1010

In Azerbaijan, in addition to natural oil, there are large reserves of it in the form of bituminous rocks. The largest reserves are concentrated in the Balakhani part of the Kirmaki mountain, which are more than 50 million tons.

In order to extract oil from bituminous rocks, various methods are used. Including such methods of extracting oil from bituminous rocks (BR): boiling BR with water without additives and with alkaline type additives; extraction method using various solvents; thermal cracking of BR; flotation method and supercritical fluid extraction. In addition to these, methods of influencing bituminous sands with various physical fields are also used, one of which is the use of ferromagnetic fluids (FMF).

The use of alkali reactive reagent with iron nanoparticles is an improvement of the method for extracting heavy oil components from bituminous rocks and an environmentally friendly innovative technology.

The study of the influence of the magnetic field with tension to 10 A/m on the process of oil extraction from bituminous rocks before and after the use of ferromagnetic fluid showed an increase in oil recovery by 7–8 % and 8–11 %, respectively. Further increase in the external magnetic field strength with the maximum tight bond of the magnetic moment with ferromagnetic particles of nanometer sizes can lead to the appearance of additional tangent stresses caused by the braking of the particle rotation field, the subsequent increase of the effective viscosity of the colloid solution. A numerical method for determining the threshold value of the magnetic field strength has been proposed to analyze this phenomenon, at which the value of the dynamic viscosity of the magnetic fluid is achieved, which is the limit for oil from the field corresponding to the extraction of oil from bituminous rocks

Keywords: bituminous sands, ferromagnetic liquid, dynamic viscosity, nanoparticle, magnetic field strength, oil recovery

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1. Introduction

Natural bitumens, also called tar sands or oil sands, are super-heavy oils, but have even greater density and viscosity and require even deeper processing than conventional oils. Tar sandstone deposits are found all over the world. The largest of these are the Venezuelan heavy oil field, located in the Orinoco oil belt, and the tar sands deposits of the Fort McMurray field in Canada, Northeast Alberta.

In total, about 600 bituminous sand deposits have been discovered in the world [1] and the identification of development technologies is as important as their existence.

The world's largest bituminous sand deposits belong to Canada and Venezuela. Russia is one of the leading countries in terms of bituminous sand and heavy oil reserves, after Canada and Venezuela. The next places are the United States, Saudi Arabia, Republic of Kazakhstan and others.

In Azerbaijan, bituminous sandstone deposits are located mainly in the Balakhani part of Kirmaki, Umbaki, Ziyulpichi, Shubany and other regions. The largest is the Kirmakinsky deposit.

Since access to the bulk of the bitumen reserves in tar sands deposits is very difficult, non-standard solutions are required to turn bitumen into liquid products, since the properties of conventional oil and bitumen differ significantly. To obtain target products from oil-bituminous rock, it is first necessary to extract bitumen from the rock, and only after that it is possible to process them further.

Extraction of oil from tar sands (oil sands) can be carried out by various methods: the use of aqueous solutions, extraction with hydrocarbon solvents, thermal methods, etc. Modern refineries are not focused on the use of these technologies. Therefore, the actual problem is the development of bitumen processing complexes and promising technologies, taking into account their physical and chemical properties.

2. Literature review and problem statement

In [2], experimental studies in laboratory conditions have shown the possibility of recovery of heavy oil based extraction components from bituminous rocks by alkaline reservoir waters. This method has been used by the authors [3] to set up an empirical formula for the dependence of the indicator of sand separation on oil from oil-bitumen rock (OBR), n determined by the ratio of the sand amount before and after separation on the following factors: t – the temperature of the solution, k – the ratio of the amount of rock to be cleaned and the washing liquid, t_{per} – the duration of mixing of the rock contact with the liquid, $t_{sediment}$ – the settling time.

An improvement in the extraction method was obtained in [4], where the authors, using a reagent based on alkaline formation waters containing iron nanoparticles, can significantly increase oil recovery from tar sands. The authors of the study also propose a new method of enhanced oil recovery – displacement from tar sands using physical fields, in particular, an electromagnetic field. The proposed method for extracting oil from bituminous rocks is an environmentally friendly innovative technology.

In the latter period, for the intensification of the volume of oil and bituminous rocks, the methods of exposure to physical fields, as well as ferromagnetic liquids are used.

A ferromagnetic liquid (magnetic liquid, ferrofluid) is a colloidal solution consisting of nanometer-sized ferromagnetic particles suspended in a carrier liquid, which acts as an organic solvent or water. Sufficiently small ferromagnetic particles (particle size about 10 nm) are single-domain, so the magnetic moment of a single colloidal particle turns out to be approximately 105 times greater than the magnetic moment of transition or rare earth metals. The possible value of the Langevin paramagnetic susceptibility of a colloidal solution is greater by the same order [5]. Magnetite particles Fe_3O_4 (ferrites) are commonly used as the magnetic phase in a ferromagnetic liquid. To ensure the stability of such a liquid, ferromagnetic particles bind to a surfactant that forms adsorption layers as a protective shell around the particles and prevents their sticking together due to Van der Waals or magnetic forces. To create an aggregately stable colloidal solution of magnetic fluid (MF), it is important:

1) to produce ferromagnetic particles with a size of at least 0.01 microns;

2) to form an adsorption layer on the surface of the particles, providing wettability – lyophilization of the particles.

The properties of the MF are determined by the set of characteristics of its components (solid phase, carrier liquid and stabilizer) and by their varying it is possible to change the physicochemical parameters of the MF within a fairly wide range, depending on the specific use conditions. The uniqueness of MF is that they combine high fluidity with high magnetization – tens of thousands of times greater than that of conventional liquids. The reason for such a high magnetization is that a huge number of small spherical particles, which are miniature permanent magnets, are embedded in an ordinary liquid. Each microscopic magnet moves chaotically in a liquid medium under the influence of thermal motion [6].

The external magnetic field orients the magnetic moments of the particles, which leads to a change in the magnetic and rheological solution properties. The high sensitivity of the properties of the solution to the external field allows controlling the behavior of magnetic fluids. Each magnetic particle in the MF is covered with a thin layer of a protective shell in the form of surfactants, which prevents coalescence (adhesion) of particles, and thermal motion scatters them throughout the liquid volume. Therefore, the particles in the MF, unlike conventional suspensions, do not settle to the bottom and can maintain their performance characteristics for many years. Nevertheless, the surfactant (SAS) in the liquid has the disintegrating property over time (about a few years) and, eventually, the particles will stick together, separate out from the liquid and stop affecting the reaction of the liquid to the magnetic field. Ferromagnetic liquids also lose their magnetic properties at their Curie temperature, which for them depends on the specific material of ferromagnetic particles, surfactants (SAS) and the carrier fluid [7].

As it is noted in [5], the nonlinear relaxation equation of magnetization obtained earlier in [6], considering the rotational Brownian motion of colloidal particles, gives incorrect results at high hydrodynamic vortex intensities. The linearization of this equation was obtained for the initial section of the colloid flow curve, which in real cases covers the velocity range up to 10^4–10^5 s^1. From the system of equations obtained after such linearization describing the flow of dilute colloids with single-domain spherical particles, it can be seen that the uncollinearity of the vectors of the magnetic moment M and the field strength H resulting from the hydrodynamic disorientation of the dipoles leads to the appearance of additional tangential stresses. These stresses are caused by the deceleration of the particle rotation field, which is the reason for the increase in the effective viscosity of the colloid in the field, the so-called negative magnetically viscous effect.

3. The aim and objectives of the study

The aim of the work is to assess the effect of ferromagnetic liquids on oil recovery of bituminous sands. This is of practical importance for the oil industry.

To achieve this aim, the following objectives are set in the work:

– to investigate the effect of ferromagnetic nanoparticles under the influence of a magnetic field on the process of oil displacement from bituminous sandstone;

– to set the threshold of the magnetic field strength at which the maximum value of the dynamic viscosity for a given deposit of bituminous rock is reached.

4. Materials and methods of research

Studies have been carried out to assess the effect of ferromagnetic nanoparticles under the influence of a magnetic field on the process of oil displacement from bituminous sandstone, as well as to assess the threshold of magnetic field strength at which the maximum value of dynamic viscosity for this deposit is reached for bituminous sands from the field under consideration.

The studies were carried out on a laboratory installation, the schematic diagram of which is shown in Fig. 1.

Extensive research fluids were used in the extraction studies to wash bituminous rocks, and three of them were retained after initial testing:

1) polymer-based composition (PC);

2) reagent containing natrisilicate (NC);

3) ferromagnetic fluid (FMF).

The formulation of the composition is accepted as follows:

1) polymer (CXC carboxymethyl cellulose)-based reagent composition: CXC 1.8–20 %; sulfanol 0.8–1.0 %; alkali 4.5–5.0 %; nanoparticles (Fe) 0.01 %; and the rest is water;

2) natrisilicate-based reagent composition (NC). In the initial version, the composition was supplemented with sodium nitrile salt (chemical formula Na_2SiO_3), rosin, mineral water, and in the second version, metallic nanoparticles (Fe) were added;

3) ferromagnetic fluid (FMF). The composition is a mixture of nano-sized iron particles and organic solvents.

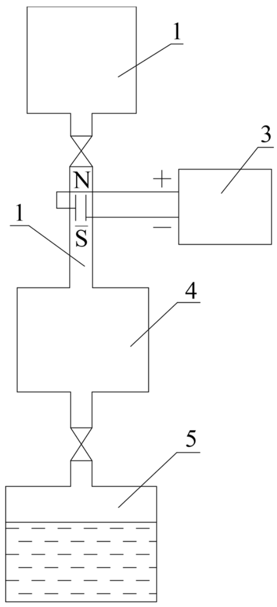

Fig. 1. Schematic diagram of the experimental setup: 1 — reagent tank; 2 — diamagnetic tube; 3 — power supply; 4 — capacity for bituminous sand; 5 — capacity for displaced oil

5. Results of research according to estimates, the effect of the magnetic field on oil displacement

5. 1. The results of theoretical studies on the effect of ferromagnetic nanoparticles under the influence of a magnetic field on the process of oil displacement from bituminous sands

Below are the results of studying the theoretical foundations of the influence of ferromagnetic nanoparticles under the influence of a magnetic field on the process of oil displacement from bituminous sands.

In this regard, when studying the problem of the influence of electric and magnetic fields on the process of extracting oil from bituminous rocks using magnetic fluids, the problem of estimating the limit value (threshold) of the strength H of the external magnetic field arises at which the limit viscosity value of the magnetic fluid (for OBR from the field under consideration) is reached.

The formula for incrementing the effective viscosity of the colloid during flow in a flat capillary in the field H=(Hcos, 0,Hsin$a$), superimposed at an angle α to the hydrodynamic vector has been used to solve this problem:

$$\Delta\eta = \frac{1}{4}\tau_1 M_0 H \sin^2\alpha.$$

Hence it is clear that the increment of the effective viscosity of the colloid is maximal in the field transverse to the hydrodynamic vortex vector and absent in the field directed along it (α=0).

Here, $\tau_1=2\tau_\delta L(\xi)/(\xi-L(\xi)$, $L(\xi)$ is a Langevin function defined by the formula; $L(\xi)=\mathrm{cth}\xi-1/\xi$, $\mathrm{cth}\xi= =(e^{\xi}+e^{-\xi})/(e^{\xi}-e^{-\xi})$; $\tau_\delta=\alpha/2kT$ is the characteristic time of the rotational Brownian motion of ferro-particles, $\alpha=6\vartheta_T\cdot\eta$ is the rotational friction coefficient of spherical particles in dilute colloid viscosity η, moving with the speed ϑ_T at temperature T, k – the Boltzmann's constant; $M_0=nmL(\xi)$ h – magnetization colloid in a thermodynamic equilibrium state, n – a selected axis in the crystal (uniaxial ferromagnet); m – the magnetic moment of the particle. For the case of uniaxial particles, the following relations are valid:

$$\boldsymbol{h}=\boldsymbol{H}/H,\quad \xi=mH/kT,\quad \sigma=KV/2kT, \tag{1}$$

where K and σ are, respectively, the constant and the parameter of the magnetic anisotropy of the particles.

Considering the dependence $M_0=nmL(\xi)$ share effective viscosity, $\Delta\eta=1/4M_0H$ called the rotational viscosity, can be written in the form of the expression:

$$\Delta\eta=\frac{3}{2}c\eta\frac{\xi L^2(\xi)}{\xi-L(\xi)}. \tag{2}$$

Describing the saturation nature of the magnetically viscous effect in a dilute colloid with an increase in field strength in the approximation of a rigid magnetic moment [8]. The rotational viscosity in the limit $\xi\to\infty$ equals ⅔ $c\eta$, c is the effective hydrodynamic fraction of colloidal particles in a magnetic fluid.

Let's note that all the conclusions obtained within the framework of the rigid dipole approximation regarding the dependence of the magnetically viscous effect on the mutual orientation of the field and the hydrodynamic vortex remain unchanged with a slight difference in the particle shape from the spherical one.

For the increment of the effective viscosity of the colloid during the flow in a flat capillary, the ratio is as follows:

$$\Delta\eta=\frac{3}{2}c\eta\cdot\Delta\eta, \tag{3}$$

where

$$\Delta\eta=\frac{a^2(\xi)}{2b(\xi)+a(\xi)-4\big(a_1(\xi)+b_1(\xi)\big)}, \tag{4}$$

with the functions, $a(\xi)$, $b(\xi)$, $a_1(\xi)$, $b_1(\xi)$ defined for a fixed parameter of magnetic anisotropy σ in the form:

$$a(\xi)=A(\sigma)L_2(\xi),$$

$$b(\xi)=B(\sigma)+\frac{A(\sigma)L_1(\xi)}{\xi},$$

$$a_1(\xi)=A_1(\sigma)+\frac{C_1(\sigma)L_2(\xi)}{\xi^2}+\frac{2B_1(\sigma)L_1(\xi)}{\xi},$$

$$b_1(\xi)=B_1(\sigma)L_2(\xi)+\frac{C_1(\sigma)L_3(\xi)}{\xi},$$

$$A(\sigma)=\frac{3}{2}\left(F'(\sigma)/F(\sigma)-\frac{1}{3}\right),$$

$$A_1(\sigma)=\frac{1}{8}\big(1-F'(\sigma)/F(\sigma)+F''(\sigma)/F(\sigma)\big),$$

$$B_1(\sigma)=\frac{1}{8}\big(6F'(\sigma)/F(\sigma)-5F''(\sigma)/F(\sigma)-1\big),$$

$$C_1(\sigma)=\frac{1}{8}\big(3-30F'(\sigma)+35F''(\sigma)/F(\sigma)\big),$$

$$L_0(\xi)=1,\quad L_1(\xi)=\mathrm{cth}\xi-1/\xi,$$

$$L_{n+1}(\xi)=L_{n-1}(\xi)-(2n+1)L_n(\xi),(n\geq 1). \qquad (5)$$

Dependence of the anisotropy factor $A(\sigma)$ ($A(\sigma)=a(\sqrt{\sigma})$ is represented graphically as a function $a(\sqrt{\sigma})$. By the known values σ and $A(\sigma)$ from expression (5) for $A(\sigma)$, we find

$$F'(\sigma)/F(\sigma)=\frac{2}{3}A(\sigma)+\frac{1}{3}. \qquad (6)$$

Discrediting parameter σ with a sufficiently small step $\Delta\sigma$, the values of $A(\sigma_i)$, σ_i from the graph for the function $a=a(\sqrt{\sigma})A(\sigma_i)=a\sqrt{\sigma_i}$, i=1, ..., n with 2-D program for the function $y=A(x)$, $x=\sigma$ approximation will be obtained (curve 2 in Fig. 2)

$$y=0.2372\ln x-0.0346,$$

with, R^2=0.8448, better matching on the interval [0, 100] with the graph of the function $a=a\sqrt{\sigma}$, the comparison having the approximation $y=-0.001x^2+0.0192x+0.3197$ with R^2=0.8425 (curve 2 in Fig. 1). A graph of the function $a\sqrt{\sigma}=A(\sigma)/\sigma=\left(\sqrt{\sigma}\right)^2$ is presented in Fig. 1.

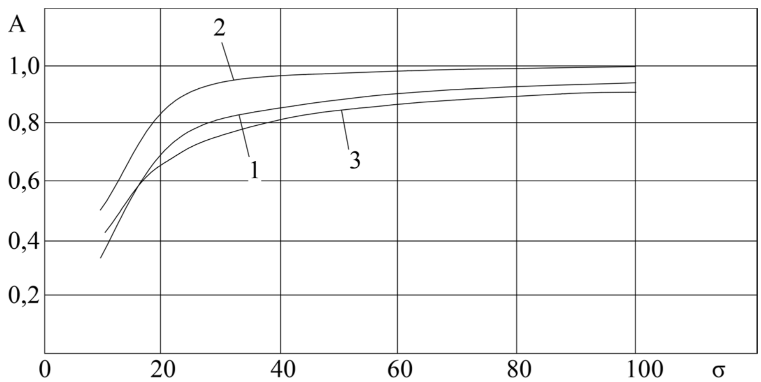

Fig. 2. Approximation of the function $A(\sigma)$ by analytical dependencies y=0.2372ln(x)–0.0346 (curve 1), y=–0.0001x^2+0.0192x+0.3197 (curve 2) and the graph of the function A(σ) [6]

The function $F(\sigma)$ is defined by the integral $F(\sigma)=\int_0^1 e^{\sigma^2}\mathrm{d}x$, $(\sigma>0)$, for which, after substitutions $\sigma=\hat{\sigma}^2$, $\hat{\sigma}x={}^0y$ the following is:

$$F(\sigma)\Big|_{\sigma=\hat{\sigma}^2}=\frac{1}{\hat{\sigma}}e^{\hat{\sigma}^2}W(\hat{\sigma})=\frac{1}{\sqrt{\sigma}}e^{\sigma}W\left(\sqrt{\sigma}\right). \qquad (7)$$

The tables of the function $W(z)=e^{-z^2}\int_0^z e^{x^2}\mathrm{d}x$ for any complex z are given in [10].

Calculating the derivatives with respect to σ of the first and second orders by the direct differentiated integral F(σ) with respect to the parameter σ, we will obtain

$$F'(\sigma)=-\frac{1}{2\sigma\sqrt{\sigma}}e^{\sigma}W\left(\sqrt{\sigma}\right)+\frac{e}{2\sigma}W(1), \qquad (8)$$

$$F''(\sigma)=\frac{1}{2\sigma\sqrt{\sigma}}\left(\frac{3}{2\sigma}-1\right)e^{\sigma}W\left(\sqrt{\sigma}\right)+\frac{2e}{2\sigma}\left(1-\frac{1}{2\sigma}\right)W(1). \qquad (9)$$

Substituting (7)–(9) in (5), we find a fixed value of σ depending on the coefficients ξ $a(\xi)$, $b(\xi)$, $a_1(\xi)$, $b_1(\xi)$ included in (4). Taking into account the dependence of ξ on H defined by (1), with known values of m and T (in the thermodynamic temperature scale measured in Kelvin (K)), expression (4) can be regarded as a function of H. Using this function, the smallest (threshold) value H^* of the magnetic field strength H is found at which the increment of viscosity $\Delta\eta$ leads to the limiting viscosity $\eta_1=\eta_0+\Delta\eta$ for the OBR for the field under consideration.

In the case of inaccessibility of tables [9] used to calculate the integral $F(\sigma)=\int_0^1 e^{\sigma x^2}\mathrm{d}x$, it is proposed to use the fol lowing method for determining the threshold of tension H^*.

The ratio (3) in the limit at $\xi\to\infty$ gives [10]

$$\Delta\eta=\frac{9}{2}\frac{\left(\frac{F'}{F}-\frac{1}{3}\right)^2}{\left(1-\frac{3F'}{F}+4\frac{F''}{F}\right)}. \qquad (10)$$

The ratio F'/F is directly found from the formula (6), where σ is defined by (1).

The theoretical dependence of the increment of magnetic viscosity $\Delta\eta$ on σ in the approximation of local equilibrium condition (2) for large ξ yields:

$$\Delta\eta=\Delta\eta_{\infty}\left(1-\frac{D(\sigma)}{\xi}\right), \qquad (11)$$

where

$$D(\sigma)=6+\frac{33F'/F-40F''/F-3}{1-3F'/F+4F''/F}. \qquad (12)$$

In the case of large ξ, the formula (10) is used for $\Delta\eta$. Then from (10)–(12), we get

$$\Delta\eta= =\tfrac{3}{4}c\eta\sigma\left[1-\tfrac{1}{\xi}\left(6+\frac{33F'/F-40F''/F-3}{1-3F'/F+4F''/F}\right)\right]. \qquad (13)$$

Equating the right sides of equations (2), (13), we will obtain the equation, solving it relatively to F''/F, the following will be obtained:

$$\frac{F''}{F}=\frac{2}{L_1^2\left[10\cdot\frac{L_1}{\xi}+5L_2\left(1-\frac{7}{\xi^2}\right)-\frac{35L_3}{\xi}-1\right]}\times$$
$$\times A^2L_2^2(\xi-L_1)-\xi L_1^2x,$$

$$x\left\{\begin{array}{l}\frac{1}{2}-\frac{L_1(1+2A)}{\xi}+\\ +L_2\left[\frac{\left(\frac{7}{2}+10A\right)}{\xi^2}-\left(2A+\frac{1}{2}\right)\right]+L_3\left(\frac{7}{2}+10A\right)/\xi\end{array}\right\}. \qquad (14)$$

$$L_i=L_i(\xi),\ \ i=1,2,3;\ \ A=A(\sigma).$$

By substituting the expression F''/F from (14) and $F^\wedge/F$ in (5) for the coefficients included in (4), we obtain the dependence of $\Delta\eta$ on $\xi=mH/kT$ from (4). This dependence for known σ, m, T is a complex function $\delta\xi(\xi(H))$ of H, on the basis of which the threshold value H^* of the value H is determined.

5. 2. The results of the study of the effect on the process of oil displacement from bituminous sands

Let's consider a magnetic liquid obtained by precipitation of fine magnetite from a solution of Fe(II), Fe(III) salts, including washing the precipitate with distilled water, nonpolar solvent and peptization of the precipitate in a nonpolar solvent with the addition of oleic acid at a temperature of 90–110 °C. Such a process, based on the use of surfactants and a nonpolar liquid as a carrier, makes it possible to obtain a stable colloidal solution of high concentration magnetite. The magnetic liquid obtained as a result of this cooking process, containing 5 % ferroparticles, had a viscosity of $\eta=2.64\cdot10^{-3}$ Pa·s at a magnetic field voltage H=10 kGs. The anisotropy of the distribution of the axes of single-domain ferromagnetic particles, fixed during the curing of the sample in a magnetic field, can be investigated by a magnetic anisometer. In this way in [11] for the constant K of the magnetic anisotropy of colloidal magnetite particles, the value of $K=4.6\cdot10^5$ erg/cm^3 has been obtained.

Below are the results of studies to assess the dependence of the viscosity of the magnetic fluid n on the strength of the external magnetic field H.

In Fig. 3, the solid line corresponds to the EXCEL dependence image built on the observed values (η_i, H_i), i=1, ..., n, while the dotted line above the regression model was obtained by the method of trend construction according to the experimental data.

Regression model $y=0.0051x^2-0.2248x+5.1588$, with R=0.955, approximating the dependence of $\eta(N)$ on the interval [20, 35] has been constructed for the observed dependency of dynamic viscosity η of the magnetic fluid on tension N, the external magnetic field in the notation $y=\eta$, $x=H$.

To calculate the threshold value N^* of the magnetic field strength at which the viscosity of the magnetic fluid with initial condition $\eta_0=2.64\ 10^{-3}$ Pa·s reaches the limit value $\eta_1=3.88\cdot10^{-3}$ Pa·s viscosity oil deposits of oil sands from which oil-bitumen rock under consideration has been taken, the following initial data have been used:

R=14 nm, $m=5.8\cdot10^{-15}$ Gf·cm^3,

$K=4.6\cdot10^5$ erg/cm^3.

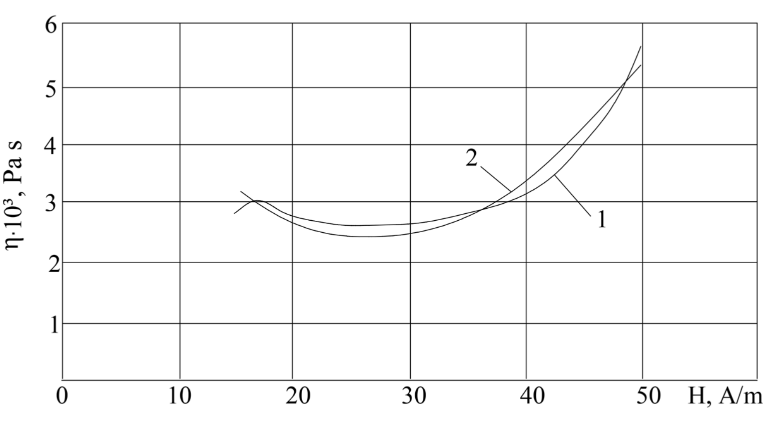

Fig. 3. Dependence of the viscosity of the magnetic fluid n on the strength of the external magnetic field H: Excel image η (H), constructed from experimental observations (curve 1) and the dependence η (H) calculated from the regression model (curve 2)

Under the condition $\Delta y=y(x+\Delta x)-y(x)>0$ and $\Delta y<\eta n$ where $\Delta\eta$ is the increment caused by the magnetically viscous effect, the value $<\Delta\eta$ has been calculated using formulas (3)–(5) and (14). As a result of the proposed approach, the value H^*=16 A/m has been obtained.

The results of laboratory studies on the use of magnetic fluid for the extraction of oil from bituminous rocks carried out on a specially designed experimental installation are shown in Table 1.

Table 1

Influence of the method on the oil output amount

Temperature, °C	Oil yield, %		
	Degree of the output		
	K-1, with the use of reagent	K-2, with the use of magnetic treatment	K-3, with the use of FML
20	24.2	91.8	92.5
25	84.4	92.2	94.2
30	84.6	92.8	95.8

From the analysis of the data given in Table 1, it can be seen that the volume of oil extraction from bituminous rocks under the magnetic influence increases oil recovery by 7–8 %, and the use of FMF gives an additional increase of 1–3 %. It was also found that the change in the temperature of the reagents (20, 25 and 30 °C) slightly affects the process of oil displacement from bituminous sands.

6. Discussion of the results of the study of the effect of the magnetic field on the process of oil displacement from bituminous sand

The results of the study of the process of oil displacement from bituminous sand by extraction using a reagent based on alkaline reservoir waters containing iron nanoparticles during magnetic treatment and additional use of ferromagnetic liquid showed (Table 1) that the magnetic effect increases oil recovery by 7–8 % and gives an additional increase of 1–3 % when using FMF.

To determine the range of changes in the dynamic viscosity of the magnetic fluid from the voltage H of the external field for the field under study, an approximation of the function $\eta(H)$ was constructed on the basis of experimental data in the form of a polynomial regression model (curve 2, Fig. 3), which is in good agreement with experimental observations (curve 1, Fig. 3).

Based on the obtained analytical dependencies $A(\sigma)$ and η(H), formulas (3)–(5), (14), a computer calculation of the increment of $\Delta\eta$ depending on σ and H was carried out and a threshold value N^* of the value H for the studied deposit was obtained.

The proposed method has limitations and a number of advantages. The limitation includes the fact that for each deposit it is necessary to determine the degree of influence of the magnetic field and the threshold of its value.

The advantages are the uniqueness of the method, the simplicity of its implementation.

The feature of the proposed method, compared with existing ones [2, 4], is the use of a reagent with iron nanoparticles and a surfactant that forms adsorption layers in the form of a protective shell around ferromagnetic particles (iron and ferromagnetic liquid), preventing their adhesion. The uniqueness of the use of FMF consists in the combination of the properties of high fluidity and high magnetization in these particles forming an internal magnetic field due to the introduction of small spherical magnets into the liquid. The external magnetic field orients the magnetic moments of the particles, changing the magnetic and rheological properties of the solution.

The main results of the work are solving the problem of studying the magnet-viscous effect within the framework of the rigid dipole approximation and the dependence of this effect on the mutual orientation of the field and the hydrodynamic vortex. The limit value (threshold) of the external magnetic field strength, at which the limit value of the viscosity of the magnetic fluid is reached, is estimated.

The obtained threshold estimate is set depending on the range of oil viscosity inherent in each field in the bituminous sand used.

The proposed method for estimating such a threshold is semi-empirical in nature and is associated with small perturbations of computational costs. Its main advantage is that it does not require the use of hard-to-access tables for calculating the integral representing the functions $F(\sigma)$ and the derivatives of this integral included in the formula for the dependence of the viscosity increment due to the magnetically viscous effect.

Of interest is the development of the threshold of the limit value of the magnetic strength depending on the parameters characterizing the rheological properties of the bituminous deposit from which oil is extracted and the rheology of magnetic colloids in the field. In this case, we will have to consider a nonlinear relaxation equation that takes into account the rotational motion of colloidal particles. And to solve a rather difficult problem of its linearization.

7. Conclusions

1. The results of the research have shown that with an extremely rigid connection between the magnetic moment and the particle, an increase in the viscosity of the medium can occur (the so-called magnetoviscous effect). Two methods are proposed for estimating the intensity threshold of an external magnetic field used for processing a colloidal solution with tar sand. The first of them requires the use of hard-to-reach tables for calculating the integral for the function $F(\sigma)$ and the subsequent application of numerical algorithms for its first two derivatives. The second semi-empirical method is associated with low computational costs and is based on the use of approximations for the functions $A(\sigma)$ and $\eta(H)$ and the use of formulas (3)–(5) and (14).

2. It has been found that after magnetic treatment, the viscosity of the solution decreases due to the destruction (reduction of the radius) of aggregates containing ferromagnetic particles in their composition. The tests carried out showed that without the use of auxiliary reagents (in the form of iron salts), the electromagnetic effect gives a lower result than when using a magnetic fluid, which is a conductive nanostructured medium in a magnetic field. The use of ferrofluid increases the yield of oil from bituminous rock by 1÷3 % compared to magnetic treatment without FMF.

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