Processing of high-viscosity oils by complex electromagnetic treatment

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Abstract: At present, a promising method for improving the rheological properties of high-viscosity oils is their electromagnetic treatment. This is confirmed by a number of scientific and theoretical works of modern researchers. The positive effect of the impact is due to the presence of dispersion areas in the electromagnetic fields of certain frequencies. In order to improve the energy efficiency of the preparation of high-viscosity oils and develop an innovative installation, studies were carried out. A complex treatment process was used: a high-frequency electromagnetic field; microwave electromagnetic field; a static magnetic field, and then the change in the rheological characteristics of the oil was recorded.

1. Introduction
The high-viscosity oil of the Russian Federation (more than 30 mPa-s) is concentrated in the West Siberian (54%), Volga-Ural (26%) and Timano-Pechora (17%) oil and gas provinces, its geological reserves are estimated at 7.2-11.0 billion tons. [1]. High-viscosity, ultra-high viscosity (200-10,000) [mPa·s] oil and solid bitumen are characterized by a high content of arenes, resinous-asphaltene substances, high concentration of metals and sulfur compounds, high density, cocking behavior, which leads to high production costs, oil-trunk pipeline and low-profit oil refining. In 2014, the Russian Federation produced about 5.4 million tons of oil from deposits containing ultra-high viscosity oil and solid bitumen, which accounts for 18% of the total production of hard-to-recover hydrocarbons in Russia. But measures of state support and economic stimulation of involvement in the development of hard-to-recover hydrocarbon reserves are predictably leading to an increase in oil production from hard-to-recover reserves in Russia from the current 30 million tons per year to 80 million tons per year in 2035, which is about 16% of the total oil production in the country.

For example, when calculating the extraction tax rate for ultra-high viscosity oil, a special coefficient is provided, resulting in a rate of about 35% of the standard, for deposits of solid bitumen (with a viscosity of more than 10,000 [mPa·s]), the extraction tax rate is zero [2]. It is also indicative that the duty in the Russian Federation for the export of high-viscosity oil in 2016 is indicative: in January to $ 8.7 from $ 10.9 per ton in December 2015, in February to $ 5.9.

These trends will undoubtedly affect the transportation volumes of hard-to-recover reserves, including high-viscosity and ultra-high-viscosity oils. Predominantly in the territory of the Russian Federation, transportation of high-viscosity oil is carried out by pipelines. On the basis of the analysis it was found out that today the most common technologies for transportation of high-viscosity oils are: pumping in mixture with a low-viscosity diluent, heat treatment and addition of depressors. The main objective of each method is to create favorable conditions for transporting oil through the pipeline, among which the main one is to reduce the dynamic viscosity. Each of the described methods has
significant drawbacks: high energy costs; use of the transported product as fuel; corrosion of pipes; high operating costs; The absence of universal additives and the need for their development for a particular oil product [3, 4].

2. Formulation of the problem
To date, a number of developments are being explored in large oil and gas companies and scientific and technical communities to identify the effectiveness of electromagnetic treatment methods to improve the rheological characteristics of high-viscosity oils. Special attention is paid to the following methods of treatment:

- static magnetic field;
- high-frequency electromagnetic field;
- microwave electromagnetic;
- magnetic vibration activation.

Each of these methods has its advantages in processing high-viscosity oils before conventional methods. However, the method is not always economically feasible for operation in industrial conditions because of the insufficiently developed scientific and practical basis for research in this area.

The research is aimed at solving the problem of reducing the viscosity of oils. A characteristic feature of this type of oil is the high content of resins, paraffins and asphaltenes, which are in need of creating special conditions. It is necessary to heat oil to a certain temperature during preparation.

The object of the study is high-viscosity oil under the influence of complex processing by a high-frequency magnetic field with a frequency of oscillations of 140 MHz, a microwave electromagnetic field with a frequency of oscillations of 2.4 GHz, and the action of a static magnetic field based on neodymium magnets with an intensity of 8 A/m. Characteristics of the component composition of high-viscosity oil are presented in Table 1.

Table 1. Characteristics of the component composition of high-viscosity oil

| No. | Dipole molecule | Percentage in total volume, % |
|-----|----------------|-------------------------------|
| 1   | Water          | 0.5 - 1                       |
| 2   | Asphaltenes    | 3.2                           |
| 3   | Paraffins      | 15.6                          |
| 4   | Resins         | 23                            |

The main tasks of the scientific research:

- to substantiate the choice of the optimum frequency of high-frequency electromagnetic radiation and microwave electromagnetic radiation;
- to experimentally investigate changes in the dynamic viscosity of oil during treatment by each selected method of electromagnetic treatment separately and in complex;

3. Results and discussion
There are many works related to the study of the effect on the high-viscosity oil of the electromagnetic field. A method for treating high-viscosity oil by a magnetic inductor is widely used, which results in a decrease in asphaltene deposits and corrosive activity in wells and pipelines. Also, a positive effect was achieved using the method of oil product separation and melting of rod wax in wells and pipelines based on microwave radiation [5, 6].

Analyzing the trends in the development of pipeline transport of high-viscosity oils, taking into account the basic requirements for high-viscosity oil preparation systems for transportation via the main pipeline, the main features of its component composition were identified, a solution based on the combined effect of electromagnetic fields and a static magnetic field was formulated. The method consists in a high-frequency action of an electromagnetic field of 140 MHz frequency, microwave interference with a frequency of 2.4 GHz, and exposure to a static magnetic field produced by
neodymium magnets. The frequency spectrum was chosen on the basis of the positive experience of work of this direction of other researchers and preliminary estimation. A complex solution allows each component to locally affect a certain component of a high viscosity oil product [7].

Experiments were carried out in the laboratory on the basis of the Industrial University of Tyumen. Five identical samples of high-viscosity oil with a component composition: 23.5% paraffins, 3.64% resins, 1.4% asphaltenes, 1% water, at an initial oil temperature of 25 °C, were individually exposed to each of the above fields and sequentially complexed (a constant magnetic field (MF), a high-frequency electromagnetic field (HFMF) and a microwave electromagnetic field (MEF)). The graphs (Figures 1, 2, 3, 4) show the results of the action, which reflect the decrease in the dynamic viscosity of the oil.

![Graph](image1.png)

**Figure 1.** Dependence of the change in dynamic viscosity on the effect of a static magnetic field, initial oil temperature 25 °C.

![Graph](image2.png)

**Figure 2.** Dependence of the change in the dynamic viscosity of oil on the effect of microwave radiation, the initial oil temperature of 25 °C.
Figure 3. Dependence of the change in the dynamic viscosity of oil on the influence of high-frequency radiation, the initial oil temperature of 25 °C.

Figure 4. The dependence of the change in the dynamic viscosity of oil on the complex effect, the initial oil temperature of 25 °C.

The positive effect of treatment is due to the presence of dispersion areas in the electromagnetic fields of certain frequencies. In order to increase the efficiency of transportation of highly viscous oils and to develop a unit for transporting high-viscosity oils along the main oil pipeline, studies were conducted on the effect of the complex treatment type on the change in rheological characteristics.

The degree of influence of the electromagnetic field depends on the frequency of the field and the dielectric properties of the components of high-viscosity oil, such as the relative permittivity $\varepsilon'$ and the tangent of the dielectric loss angle $\tan\delta$.

The water molecules that are present in the transported oil product in small quantities have resonant peaks $\tan\delta$ at a frequency of 2.4 GHz, when the prototype oil images are affected by an electromagnetic field of the appropriate frequency, the energy of the microwave waves is absorbed by the water molecules and converted into energy of thermal motion, which is transferred to all components of the oil product.
To assess the influence of the microwave electromagnetic field on high-viscosity oil, the problem of determining the degree of field influence on an emulsion drop was considered. This approach is relevant for the concentration of water molecules in oil not more than 1%, provided that the droplets do not behave like dipoles. Under these conditions, it is necessary to consider the process of thermal conductivity through a system of equations in oil and water in a spherical coordinate system \((r, \theta, \phi)\), where \(\phi\) and \(\theta\) are the azimuth and zenith angles, respectively.

Since the thickness of the armor shell is \(\Delta \ll r_0\) (\(r_0\) is the radius of the drop), the polarization in it can be neglected. A drop of water is placed in an external uniform microwave field. The center of the drop is the center of the coordinate system. The axis of rotation of the drop passes parallel to the field, so there is no dependence with the coordinate \(\phi\). There is also symmetry with respect to the angles \(\theta = 0\) and \(\pi/2\), the drop consists of 4 equal quadrants. So, solving the problem, it is necessary to investigate the 1-st quadrant in the region from \(\theta = 0\) to \(\pi/2\). Taking into account the above-mentioned conditions, the problem is formulated by the following system of heat equation:

\[
\frac{\partial T_i}{\partial t} = \frac{1}{r^2 c_i \rho_i} \frac{\partial}{\partial r} \left( \lambda_i r^2 \frac{\partial T_i}{\partial r} \right) + \frac{1}{r^2 \sin \theta c_i \rho_i} \frac{\partial}{\partial \theta} \left( \lambda_i \sin \theta \frac{\partial T_i}{\partial \theta} \right) - \frac{U_r}{r} \frac{\partial T_i}{\partial r} - \frac{U_\theta}{\rho_i} \frac{\partial T_i}{\partial \theta} + q_i \tag{1}
\]

where \(i = 1, 2\) indices related to water and oil, respectively;

\(T\) – area temperature, \(^0\text{C}\);

\(\lambda\) – thermal conductivity, \(\text{W/(m} \cdot \text{K)}\);

\(c\) – specific heat, \(\text{J/(kg} \cdot \text{K)}\);

\(\rho\) – density of medium; \(\text{kg/m}^3\);

\(U_r\) and \(U_\theta\) – components of the velocity vector of motion both inside and outside the drop (oil, water), initiated by the electric stress tensor,

\(q\) – thermal sources, \(\text{J}\).

Calculation of distribution of thermal sources is made solutions of an electrodynamic task

\[
q_i^e = \frac{\omega \varepsilon_0 \varepsilon_i \delta_i^{(j_i)}}{2} E_i^2 \tag{2}
\]

where \(E\) – electric field strength, \(\text{V/m}\)

\(\omega\) – rate of phase change, \(\text{Hz}\)

\(\varepsilon_0\) – electric constant

The boundary and initial conditions are based on the conductor heat transfer of the environment and the drop:

\[
T_1(r, \theta, 0) = T_2(r, \theta, 0) = T_0 = \text{const}, \tag{3}
\]

\[
\lambda_1 \frac{\partial T_1(r_0, \theta, t)}{\partial r} = \lambda_2 \frac{\partial T_2(r_0, \theta, t)}{\partial r}, \tag{4}
\]

\[
T_1(r_0, \theta, t) = T_2(r_0, \theta, t), \tag{5}
\]

\[
\frac{\partial T_1(l, \theta, t)}{\partial r} = 0, \quad T_2(l, \theta, t) = T_0, \tag{6}
\]

\[
\frac{\partial T_1(l, \theta, t)}{\partial \theta} = 0, \quad \frac{\partial T_2(l, \theta, t)}{\partial \theta} \tag{7}
\]

where \(l\) – boundary of the region of thermal action.
The system of equations (1) with conditions (2) - (6) is solved by a finite-difference method according to the implicit scheme. At the end of the calculations, the temperature fields were determined both outside the drop and inside it.

If we talk about the degree of influence of a high-frequency electromagnetic field on high-viscosity oil, it should be taken into account that the resonant peaks of $\tan\delta$ paraffins and resins, which are present in significant amounts in the component composition of oil, appear at a frequency of 140 MHz. Therefore, when the experimental field of oil is exposed to an electromagnetic field of 140 MHz frequency, intensive absorption of energy by molecules of paraffins and resins takes place, which leads to a rapid decrease in the viscosity of the oil product. In this case, the formula for sources of heat release is preserved analogous to the process of action of the microwave field:

$$q_i^e = \frac{\omega\varepsilon_0\varepsilon_i\tan\delta_i}{2} E_i^2$$  \hspace{1cm} (8)

The process of absorption of energy of the RF field is described by the equation of heat conduction for given external heat sources:

$$\rho c_T \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda r \frac{\partial T}{\partial r} \right) + \frac{1}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + Q(r, z, t)$$  \hspace{1cm} (9)

where $T$ – ambient temperature, °C
$\lambda$ – thermal conductivity, W/(m·K)
$c_T$ – specific heat, J/(kg·K)
$\rho$ – density of medium, kg/m³
$Q$ – power density, W/m³.

Decrease in viscosity of high-viscosity oil in the treatment of high-frequency and microwave fields is caused by the absorption of energy fields according to the process described above and is accompanied by an increase in the temperature of the oil product. The process description is reduced to the following equation:

$$\mu = \mu \exp(-\gamma (T - T_0))$$  \hspace{1cm} (10)

It should also be taken into account that, in contrast to the thermal methods of impact on oil environments, electromagnetic fields, in addition to the thermal effect, also exhibit "nonthermal" fractures, manifested at the nano- and micro-levels.

The effect of a constant magnetic field on the decrease in the viscosity of oil is due to a significant increase in the number of paraffin crystallization centers, and is accompanied by the transformation of a coarsely dispersed suspension of paraffin crystals into a finely dispersed volumetric stable suspension. These processes help reduce the viscosity of oil.

It should be noted that during the simultaneous processing by a constant magnetic field, high-frequency and microwave fields in the course of experiments, a synergetic effect is observed and a decrease in the dynamic viscosity of the oil product occurs at a high rate. The process is determined by the combination of all the above-mentioned phenomena of individual influences, which contribute to the intensification of the absorption of field energy by oil.

4. Conclusion
The results of the study can be used in the development of a design relating to devices for preparation for transportation of high viscosity paraffins and tar oils, the design can be used in the oil industry for field and main preparation for transportation of high viscosity oil by reducing its viscosity and increasing the relaxation time of its rheological properties.

The work performed in the future is aimed at solving the task of reducing energy costs in preparation for transportation of high-viscous oils along main pipelines in severe natural and climatic
conditions under negative temperature conditions. In particular, the results of the work can be used on sections of the pipeline similar to the area “Zapolyar’ye – Purpe”.

An important factor for the development of the work is compliance with both the policy of import substitution policy of the Russian Federation and the program of innovative development of PJSC "Transneft" for the period until 2020.

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