Analytical filtration model for nonlinear viscoplastic oil in the theory of oil production stimulation and heating of oil reservoir in a dual-well system

Vladimir Ivanovich Astafev, Sergey Igorevich Gubanov¹, Valeria Alexandrovna Olkhovskaya, Anastasia Mikhailovna Sylantyeva and Alexey Mikhailovich Zinovyev

Oil and Gas Development and Operation Department, Samara State Technical University, 443100 Samara, Russia

¹Gubanov0393@gmail.com

Abstract. Production of high-viscosity oil and design of field development systems for such oil is one of the most promising directions in the development of world oil industry. The ability of high-viscosity oil to show in filtration process properties typical for non-Newtonian systems is proven by experimental studies. Nonlinear relationship between the pressure gradient and the rate of oil flow is due to interaction of high-molecular substances, in particular, asphaltenes and tars that form a plastic structure in it. The authors of this article have used the analytical model of stationary influx of nonlinear viscoplastic oil to the well bottom in order to provide rationale for the intensifying impact on a reservoir. They also have analyzed the method of periodic heating of productive reservoir by means of dual-wells. The high-temperature source is placed at the bottom of the vertical well, very close to the reservoir; at the same time the side well, located outside the zone of expected rock damage, is used for production. Suggested method of systemic treatment of reservoirs with dual wells can be useful for small fields of high-viscosity oil. The effect is based on the opportunity to control the structural and mechanical properties of high-viscosity oil and to increase depletion of reserves.

1. Introduction

Global development prospects of world fuel and energy complex are closely connected today with production of high-viscosity oil. Unconventional approach shall be applied while making design and technological decisions on regulating the development of high-viscosity oil fields. In most cases it is impossible to produce oil without using thermal treatment and increasing drawdown pressure due to the fact that viscosity significantly influences the rate of hydrocarbons filtration. Use of thermal treatment is subject to productive reservoir depth, structure and spatial profiling of mine workings. At the oilfields where the production is carried out by means of vertical wells, the following methods are widely used: thermal steam reservoir treatment, hot water drive, cyclic steaming of well bottom zones, combined treatment technologies: impulse dosing thermal treatment, thermal cycling treatment and their modifications. For this purpose ground-based heat producing installations requiring high capital expenditures and maintenance costs are used. Moreover, fuel combustion processes needed to produce steam are accompanied by the emission of pollutants into the atmosphere.
2. Theoretical background
To model the stress–deformation behavior of viscoplastic materials, different constitutive equations have been proposed. The complete descriptions of such models are available in many books [1-7] and review papers [8-10]. Rheological studies established deviation from Newton’s law of viscous friction, namely the violation of the linear relationship between the shear stress $\tau$ and the shear strain rate $\gamma$, as a particular case—the existence of the critical shear stress (yield stress) $\tau_0$. Such effects accompany the flow of viscoplastic fluid, prone to formation of internal solid-like structure which begins to break down when the stress increases. The most popular equations that have been used to describe oils with yield stress $\tau_0$ are the Bingham, Casson and Herschel–Bulkley models [11-13], i.e.

$$\tau = \tau_0 + \mu \cdot \gamma, |\gamma| \geq \tau_0 \quad \text{Bingham},$$

$$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\mu \cdot \gamma}, |\gamma| \geq \tau_0 \quad \text{Casson},$$

$$\tau = \tau_0 + K \cdot \gamma^n, |\gamma| \geq \tau_0 \quad \text{Herschel-Bulkley},$$

where $\mu$ is dynamic viscosity; $n$ is the exponent that characterizes the measure of deviation of the fluid behavior from Newton’s law; $K$ is consistency index, determined experimentally.

Oil as viscoplastic fluid is characterized by rheological parameters: yield stress $\tau_0$ and dynamic viscosity $\mu$ (or nonlinearity parameters $n$ and $K$). If the shear stress $\tau$ is less than the yield stress $\tau_0$, the flow is absent, i.e. the shear strain rate $\gamma = 0$.

At zero yield stress $\tau_0$, Eq. (1.3) is transformed into Ostwald–de Waele relation

$$\tau = K \cdot \gamma^n,$$

which is considered adequate for pseudo-plastic ($n<1$) or dilatant ($n>1$) types of flow.

In many cases, the relation of rheological parameters becomes more complicated, which gives reason to believe: the fluidity of viscoplastic media is the variable characteristic of the substance, as it depends on its strain rate [14, 4].

The authors [15] found experimentally and justified theoretically the fact that under non-linear viscoplastic oil possess, there are two critical shear stresses: the stress $\tau_r$, corresponding to the beginning of the destruction of the inner oil structure and the stress $\tau_m$, corresponding to its complete destruction. In this case, the oil flow is considered within a continuum (the volume of a capillary or a pore), and the restructuring processes taking place where the oil contacts with the wall of the channel, leading to the formation of marginal layers are ignored.

Instrumental studies of phase transitions in the reservoir fluids [16, 17] have proved the existence of hierarchical levels of structural organization. Nano- and microstructures of different scale, present in the oil disperse systems, are able to interact with each other and realign under the influence of external factors. Successive states are characterized by different granularity, whereupon the oil should be considered as a dynamic system with complex rheological behavior. The basic particles that control the process of structure formation in the oil are asphaltenes, resins and paraffin. Graphic constructions characterizing the most common types of stationary rheological fluid flow are shown in figure 1.

The diversity of permolecular structure types causes non-linear deviations in the behavior of oil disperse systems not only from Newton’s law, but also from Darcy’s law. As shown by the flow experiments [4, 15], in a porous medium at the pressure above the saturation pressure of the oil with gas and in the absence of an aqueous phase within a certain range of pressure gradients and rates of flow, the relation between these parameters for the structured oil becomes non-linear. The fact is noteworthy because the linearity of Darcy’s law is an approximation implemented in the vast majority of hydrodynamic simulators.
Figure 1. Fluids flow curves: 1 – Newtonian; 2 – dilatant; 3 – pseudoplastic; 4 – linear viscoplastic; 5 – nonlinear viscoplastic

The rate of oil flow cannot obey linear Darcy’s law in case of a certain combination of thermobaric factors. The degree of non-Newtonian properties manifestation of nonlinear viscoplastic oil depends on the permeability of the reservoir, the relation and component composition of the hydrocarbon phase—the presence of paraffin, asphaltenes, resins, nitrogen, methane and ethane.

In the popular model of ‘‘black oil’’, the reservoir hydrocarbon system is regarded as a pseudo-binary mixture. The block of initial data on the properties of the oil component at the input to the model includes dependences on the PVT parameters [18]. Such representation is not enough for high-viscosity oil with proved non-Newtonian properties, because in a real porous medium at the same pressure, structure-forming oil components can interact in very different ways, which is reflected in the distribution of seepage flow.

3. Geological conditions and laboratory experiment

Over the past decades a number of oilfields have been developed and brought into production in Volga-Ural oil producing region; many of them are represented by the oil deposits with high (over 30 mPas∙s) viscosity. Some of oilfields can be placed in a separate group – those that are located in a conjunction zone of southeast and east sides of Melekess depression, Sokskaya saddle and South-Tatar arch.

Reserves of the southeast side of Melekess depression (within the Samara region) are located in carbonate upper devonian-tournaisian and terrigenic visean oil and gas plays. Oil of productive reservoirs is heavy, sulfurous; its viscosity grows from low stratigraphic screened accumulations to upper. There is a typical weighting up of oil up the section; content of tars, asphaltenes, paraffines and such elements as nickel and vanadium also grows. Thus, the oil of test reservoir B₂ of Strelkovskoe oilfield is of high viscosity, contains a large amount of structuring components – asphaltenes, tars, paraffines (between 3,68 and 11,51%, between 9 and 13% and between 4,17 and 7,4% respectively).

Accumulations at the territory under review had been forming approximately at the same time under the influence of similar geological processes, which is, most probably, the reason of comparability of rocks collecting properties and oil parameters. According to a number of Russian scientists, oil accumulations in coal deposits had been forming during the last stages of Hercinyan cycle of tectogenesis, but Melekess depression itself acquired modern shapes during the final stages of Alpine phase of tectogenesis. Fluxes of thermal energy and migration of thermal waters in the bodies...
of sedimentary rocks should have boosted the oxidation of hydrocarbons and redistribution of some microelements in accumulations. It is interesting to note that the most viscous oils (above 400 mPa·s) are limited to Bashkirian deposits, for which depositional break is typical.

It is logical to assume that with the opulent similarity of filtration-volumetric parameters, lithofacies characteristic of reservoir rocks and reservoir fluids parameters, non-Newtonian properties of high-viscosity oil found by special examinations will show themselves almost similarly. It can be proposed as a premise that for accumulations similar to those that are located within the territory of Melekest depression, the influence of these properties on the process of development will also be identical. Consequently, the unified analytical model can be used to describe non-Newtonian flow of oil and typical effects; there is a possibility to add the initial data box according to the principle of analogy, which simplifies the procedure of modeling significantly.

3.1. Analytical and experimental evaluation of structural and mechanical properties of oil from reservoir B2 of Sterlkovskoe oilfield

In the process of hydrodynamic modeling it is possible to use both data of filtration experiment and generalized mathematical relations linking boundary pressure gradients with shear stresses and reservoir permeability. Correlations enabling to evaluate the value of critical dynamic shear stress (CDSS) on the basis of mass content of asphaltenes and tars in oil, nitrogen, methane, ethane in accompanying gas with allowance for the temperature of reservoir have been proposed for carbonic oils of Tatarstan oilfields by the group of experts led by V.V. Devlikamov and presented in academic paper [15]. By a number of criteria these oils can be considered as analogues of oil from terrigenic reservoir B2 of Sterlkovskoe oilfield, which is located within the territory of the Samara region [19].

Estimated value of critical dynamic shear stress of waterless degassed oil from reservoir B2 amounted to 0,0170 Pa, taking into the account quantity and content of oil-dissolved gas - 0,0655 Pa. Results of rheological parameters calculation for reservoir B2 for the range of temperatures between 28 °C and100 °C are given in table 1 and in figure 2.

| Parameter | 28    | 40    | 45    | 60    | 70    | 80    | 90    | 100   |
|-----------|-------|-------|-------|-------|-------|-------|-------|-------|
| CDSS of oil at reservoir temperature, Pa | 0,0594 | 0,0439 | 0,0399 | 0,0319 | 0,0285 | 0,0259 | 0,0239 | 0,0223 |
| Dynamic shear pressure gradient of waterless oil $H$ (DSPG), MPa/m | 0,004 | 0,003 | 0,0026 | 0,0021 | 0,0019 | 0,0017 | 0,0016 | 0,0015 |
| Pressure gradient of critical structure destruction $H_m$, MPa/m | 0,006 | 0,0046 | 0,0042 | 0,0035 | 0,0032 | 0,003 | 0,0028 | 0,0026 |
| Critical pressure gradient of paraffin-base oil $H_{cr}$, MPa/m | 0,0075 | 0,0057 | 0,0051 | 0,0042 | 0,0038 | 0,0035 | 0,0032 | 0,003 |
Experimental tests on the influence of temperature on macrorheological parameter - dynamic viscosity of oil samples – have been carried out with due regard to geological and physical characteristic of reservoir B2 of Strelkovskoe oilfield. Measurements were carried out using laboratory equipment Modular Compact Rheometer MCR52 (Anton Paar GmbH, Austria) in a “plate-plate” PP50 measuring cell at the shear rate 40 s⁻¹. The first group of tests has been carried out in 3 stages – firstly, heating in the range of temperatures from 28 °C to 75 °C, then cooling till 9 °C and then again heating till 28 °C. The second group of test has also been carried out in 3 stages - firstly, heating in the range of temperatures from 28 °C to 80 °C, then cooling till 28 °C and then again heating till 80 °C.

Figure 3 shows a thermograph of viscosity that is used for validation of dual-wells flow rates and the modes of reservoir heating. According to the form of thermographs [20] typical for oilfields with high-viscosity oil, the ratio of maximum and minimum viscosity (μ₀ and μₘ) was taken in calculations as 8.

4. **Technology basics of periodic heating of a reservoir in a dual-well**
Technology of reservoir drilling by means of a dual-well includes periodic heating of reservoir with high-temperature source located in close proximity to targeted object. It is proposed [21-22] to develop oilfields of high-viscosity oil by using vertical wells with drilling an additional side well;
moreover, both vertical and side wells strike the same oil-filled reservoir. Bottom of a vertical hole intended for production can be equipped, in case of necessity, with a sand filter. Small-size downhole pumping equipment is lowered to the well, with, for example, placing the pump in a side hole. The possible option of equipment arrangement is shown in figure 4.

High-temperature heating source, container with hydro-oxidative or combustible oxidizing compound along with packer and anchor device are delivered to the bottom of a vertical hole on logging cable or on tubing. In some popular technologies using downhole pressure accumulators [23] the reservoir in well bottom zone is exposed to thermal and chemical treatment during the combustion of priming charges and also to mechanical impact as a result of formation of big amount of propellant gases. In the interval isolated by a packer, the pressure grows significantly and a chemical agent heated by combustion-product gases comes to a reservoir in a single gas-liquid flow via perforated vertical hole. After thermal treatment the heating stops, the pump is activated and the process of oil uptake from the side well starts. Duration of a cycle varies according to production rate decline, then the uptake of oil stops and the cycle of reservoir heating starts again without taking the equipment off the well. Then the well operation continues again in the mode of oil uptake.

![Figure 4](image)

**Figure 4.** Dual-well system: submersible AC electric motor; telemetric system; downhole pressure accumulator; TBG - tubing

This method has the following advantages:

1. There are no limitations related to the growth of reservoir’s temperature and to modifications going on into it. While using propellant charge, for example, its mass may be increased (optimized) in order to reach the necessary temperature at a specified distance from the vertical hole of the well. If a high-temperature solid-fuelled source is located at the bottom of vertical hole and the uptake of oil is carried out through the additional side hole located out of the zone of expected rock damage caused by its mechanical destruction or by carbonization of heavy oil components, it is possible to avoid partial or complete blocking of heated formation fluid flow and to increase the efficiency of treatment.

2. Flexibility of performing thermobaroc hemical treatment is achieved by means of reducing the number of RIH/POOH operations, interchangeability of energy carriers, periodicity in reservoir heating.

3. Mechanical devices intended for removal of reaction products from the reservoir by drawdown or implosion treatment are not necessary for the inclusion in a complex of equipment, and it is not necessary to consider chemical treating of a well bottom zone as an integral part of technological process.
The main performance indicators within the optimum temperature range are the oil production intensification and the increase of the level of reservoirs recovery. In order to achieve the effect, producing side hole shall be located within the heating radius.

4.1. Calculations of reservoir heating depth and provision of rationale for vertical deviation of side hole

Calculation of parameters of thermobaric treatment (without taking into account chemical reactions) has been carried out on the basis of terrigenic reservoir $B_2$ of Strelkovskoe oilfield. Reservoir depth is 1422 m; deposit – blanket-like; average net oil pay – 11.7 m; porosity factor – 0.27; oil saturation – 0.83; permeability – 0.526 D; initial temperature – 28 °C; initial pressure – 15.4 MPa. According to design data, oil viscosity under reservoir conditions is equal to 595 mPa·s; density – 944 kg/m$^3$.

One of the vertical wells has been considered as a candidate well for performing peridodic heating of the reservoir after drilling the second hole. For calculating the heating depth the authors used the following: a) Le Verrier method, enabling to determine the coordinate of thermal front while injecting the heat transfer agent; b) equation of shock-wave speed represented as a pressure and oil density function [21]. Seeing that the heating is carried out by combustion-product gases, in calculating by Le Verrier method [24] equivalent parameter 4,889 m$^3$/s, was used instead of fluid heat transfer injecting rate; the value of this parameter was determined out of estimated speed of shock-wave 762 m/s, which is created by pressure pulse in thermobaric treatment technology. Filtration area (sum of perforations areas with density of perforation 40 holes/m) has also been used in calculations, and reservoir porosity has been taken into account. Estimated maximum radius of heating was about 24 m. Further, while performing hydrodynamical calculations, the distance from heating source to the bottom-hole of side hole – the point of oil uptake – was taken as approximately the same. Considering that there is a possibility to adjust the value and the time of heating (for example, by changing the mass of solid fuel or linear burning rate) the targeted temperature at the point of oil uptake varied between 40 and 80 °C. Analysis of field data of applying acoustic pressure generator PGDA-M according to technology of intense gadsdynamic impact on reservoir has shown that aggregate temperature gradient in bottom-hole zone of reservoir before and at the time of impact was 17 °C.

It should be noted that with the aim to provide rationale for the heating method, the authors used one of the possible mathematical models – analytical one-dimensional model in radial proximity, which ignores the thermal losses to the top and the bottom of the reservoir [24]. The heating radius equal to 24 m and the levels of temperature obtained on the basis of this model shall be considered as “optimistic”. In shallower depth and lower level of heating, the efficiency of this method may be increased by moving the side hole of producing well closer to the main heating.

4.2. Provision of rationale for the increase of well flow rate

Paired values “rate-drawdown” have been calculated to evaluate the influence of temperature on the production indexes, and indicator diagrams have been constructed according to the conditions corresponding to the ones of production wells of tested object. The influence of temperature on viscosity and rheological characteristic of reservoir oil have been considered while performing calculations. Filtration model included such parameters as boundary pressure gradients and critical dynamic shear stress of oil, evaluation of which, as it shown above, have been conducted with due consideration of temperature changes.

Determination of paired values “rate-drawdown” have been carried out with the use of two equations: 1) the equation of oil influx to the well according to Darcy’s law; 2) the equation of stationary influx of nonlinear viscoplastic oil to the well, proposed by Devlikamov-Habibullin-Kabirov [15]:
\[
Q = \frac{2\pi \cdot k \cdot h \cdot (P_e - P_c)}{\mu_m \cdot \ln \frac{r_m}{R_c} + \mu_0 \cdot \ln \frac{r_d}{R_d} + \frac{\Delta H \cdot \mu_0 + \Delta \mu \cdot H}{\Delta H} \cdot \ln \frac{\Delta \mu}{\Delta H + \frac{\mu_m}{H_m}},
\]

where \(\Delta H = H_m - H\); \(\Delta \mu = \mu_0 - \mu_m\).

While performing calculations, it was taken that radii \(r_m\) and \(r_d\) depend on reservoir flow rate \(Q\) (\(\text{m}^3/\text{s}\)) and are determined by the following formula

\[
r_m = \frac{Q \cdot \mu_m}{2\pi \cdot k \cdot h \cdot H_m},
\]

\[
r_d = \frac{Q \cdot \mu_0}{2\pi \cdot k \cdot h \cdot H_m},
\]

where \(k\) – reservoir permeability, \(\text{m}^2\); \(h\) – thickness of reservoir, \(\text{m}\); \(H\) and \(H_m\) – boundary pressure gradients, \(\text{Pa/m}\); \(\mu_m\) and \(\mu_0\) – respectively, minimum and maximum oil viscosity, \(\text{Pa} \cdot \text{s}\). Other used parameters: \(R_c\) – well radius, \(\text{m}\); \(R_e\) – range of well operation, \(\text{m}\); \(P_c\) – bottom-hole pressure, \(\text{Pa}\); \(P_e\) – reservoir pressure (pressure at the external boarder of filtration area), \(\text{Pa}\).

In contrast to filtration of Newtonian oil, area of reservoir within the radius of well operation according to equation (3.1) is the combination of three subareas: near - with the radius \(r_m\), where oil flows with the minimum viscosity \(\mu_m\) and maximally destroyes the structure; circular - with internal radius \(r_m\) and external radius \(r_d\), where the viscosity of oil is variable (its values grow with increasing distance from the well and reducing pressure gradients); remote - where oil flows with maximum viscosity \(\mu_0\) and most stable structure formed by heavy components.

Results of calculating reservoir flow rates and drawdowns for different temperature conditions, including initial, are given in table 2 and on figure 5.

Calculations of a well stream according to Darcy’s law within the range of drawdowns at which the structural and mechanical properties of oil are revealed show that the values of rates are overestimated comparing to nonlinear flow equation. The same rates at the same drawdowns can be reached at different temperatures. Thus, drawdown 1,5 MPa corresponds to the rate 15 m\(^3\)/24 hrs according to linear filtration model at the initial reservoir temperature 28 \(^\circ\)C. According to nonlinear filtration model, it is necessary to heat the reservoir up to 45 \(^\circ\)C to achieve the same rate at the same drawdown.

| Temperature, \(^\circ\)C | Drawdown, MPa |
|------------------------|--------------|
|                        | 1  | 2   | 3   | 4   | 5   | 6   |
| 28                     | 4  | 8,2 | 16  | 28,4| 52  | 62  |
| 45                     | 9  | 27  | 59,7| 99  | 126 | 144 |
Figure 5. Indicator diagram at drawdown up to 6 MPa (points at lines mean boundary modes allowing for the display of viscoplastic properties of oil, dashed lines – relation between the rate and pressure differences according to Darcy’s law)

5. Conclusions
In reservoirs similar to reservoir B2 of Strelkovskoe oilfield, with permeability less than 1 micron$^3$, it is expected to have strong influence of viscoplastic properties of oil on filtration. At initial temperature equal to 28 $^\circ$C nonlinear viscoplastic flow of oil is detected at high drawdowns (up to 4.6 MPa). With the increase of temperature to 45 $^\circ$C structural and mechanical properties of oil become partially weaker and stop influencing filtration at drawdown equal to 3.2 MPa.

Heating of reservoir enables to weaken structural and mechanical properties of oil. Uptake of oil in dual-well is carried out outside the zone of expected rock damage through the side hole located at some distance from the high-temperature source. It is possible to optimize the level of heating by varying the mass of fuel elements, linear burning rate and burning time. Since there might be significant thermal losses to the top or the bottom of a reservoir, it is necessary to consider at the designing stage the options with smaller distance between bottoms of vertical and side holes.

Reduction of drawdown along with the maintenance of oil production is especially important for incompetent rock reservoirs and those ruining under the growth of pressure gradients. Sloughing of sand makes the equipment operation more difficult and adds to the number of repairs. By limiting drawdowns it will be possible to decrease sloughing of sand; however, at higher temperature there will still be possibility to operate the reservoir with quite high rates. By including sand filter to the composition of dual-well structure it will be possible to decrease the influence of mechanical impurities on the equipment operation.

Acknowledgment
Research was carried out on the Grant of the Russian Science Foundation (Project No. 15-17-00019)

References
[1] Wilkinson W L 1960 Non-Newtonian fluids: fluid mechanics, mixing and heat transfer. *Pergamon Press* (London)
[2] Bird R B, Armstrong R C and Hassager O 1987 *Dynamic of polymeric liquids. fluid mechanics.* vol 1, 2nd edn. (Wiley, New York)
[3] Carreau P J, De Kee D C R and Chhabra R P 1997 Rheology of polymeric systems: principles and applications. *Hanser/Gardner Publications* (Cincinnati, OH)
[4] Khasanov M M and Bulgakova G T 2003 Nonlinear and nonequilibrium effects in rheologically
complex media. *Institute of Computer Science* (Moscow-Izhevsk) (in Russian)

[5] Mirzazdhanzade A Kh, Khasanov M M and Bakhtizin R N 2005 Modelling of oil and gas production processes. *Non-linearity, nonequilibrium, uncertainty*. (Moscow-Izhevsk: Institute of Computer Science) (in Russian)

[6] Chhabra R P and Richardson J F 2008 *Non-Newtonian flow and applied rheology*. engineering applications, 2nd edn (Butterworth-Heinemann, Oxford)

[7] Basniev K S, Dmitriev N M and Chilingar G V 2012 Filtration of nonNewtonian liquid. *In Mechanics of fluid flow* (Wiley, New York) chap. 25 pp 489-512.

[8] Bird R B, Dai G C and Yarussio B J 1983 The rheology and flow of viscoplastic materials. *Rev Chem Eng*. 1 pp 1–70

[9] Chhabra R P, Comiti J and Machac I 2001 Flow of non-Newtonian fluids in fixed and fluidized bed. *Chem Eng Sci*. 56 pp 1–27

[10] Mitsoulis E 2007 Flow of viscoplastic materials: models and computations. *Rheol Rev*. pp 135–178

[11] Bingham E C 1922 Fluidity and plasticity. *McGraw-Hill* (New York)

[12] Casson N 1959 A flow equation for pigment-oil suspensions of the printing ink type. *In: Mill CC (ed) Rheology of dispersive systems*. Pergamon Press. (New York) pp 84-104.

[13] Herschel W H and Bulkley R 1926 Konsistenzmessungen von Gummi-Benzollosungen. *Kolloid Zeitschrift*. 39 pp 291–300

[14] Bermadiner M G and Entov V M 1975 Hydrodynamic theory of anomalous fluid flow through porous media. *Nauka* (Moscow) (in Russian)

[15] Devlikamov V V, Habibullin Z A and Kabirov M M 1975 Abnormal oil. *Nedra Publishers* (Moscow) (in Russian)

[16] Revizskiy Yu V and Dyblenko V P 2002 Research and justification of the mechanism of oil reservoir recovery using physical methods. *Nedra Publishers* (Moscow) (in Russian)

[17] Syunyaev Z I, Safiyea R Z and Syunyaev R Z 1990 Oil dispersion systems. *Khimiya* (Moscow) (in Russian)

[18] Astafev V I, Markelova A M, Olkhovskaya V A and Zinoviev A M 2017 Modelling of non-linear viscoplastic oil flow to a well and development system selection. *J Petrol Explor Prod Technol.* 7 pp 521-529

[19] Zinoviev A M, Olkhovskaya V A and Il’in I V 2017 Experimental study of rheologically-complex oil of the fields in the Samara region (Russia). *Oilfield engineering*. 2 pp 31–38 (in Russian)

[20] Simkin E M 2011 Fundamentals of rock thermodynamics. *Institute of Computer Science* (Moscow-Izhevsk) (in Russian)

[21] Olkhovskaya V A, Zinoviev A M and Gubanov S I 2014 Method of high-viscosity oil field development with periodic lay heating. *Vestnik of Samara state technical university*. Technical sciences series 43 pp 163-173 (in Russian)

[22] Astafev V I, Olkhovskaya V A and Gubanov S I 2016 Warm-up of layer in well with dual-well system and intensification of high-viscosity oil production. *Oil Ind.* 2 pp 66-69

[23] Agiiullin M M, Abdullin V M, Abdullin M M and Kurmaev S A 2004 Development and introduction of thermobarochemical method increasing productivity of oil and gas wells. *Electronic scientific journal “Oil and Gas business”* (in Russian)

[24] Zheltov Yu P 1998 Oilfield development. *Nedra Publishers* (Moscow) (in Russian)