INNOVATIVE DEVELOPMENT METHODS OF KEROGEN-BEARING RESERVOIRS THAT PROMOTE OIL GENERATING POTENTIAL

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Abstract. In recent years, a very close attention is paid to the problem of search for development methods of Bazhenov Formation. For this purpose, there are at least three reasons. The first deals with the exhaustion of light oil. The second is due to a quantum leap in the knowledge of the geological and physical properties of reservoirs with reserves difficult to recover. Thirdly, the development of innovative technologies made it possible to develop deposits of unconventional hydrocarbons, which include heavy oil, oil of shale fields with low permeability.

Layers of the Bazhenov Formation are characterized by low porosity and permeability, heterogeneity of structure and composition, the presence of kerogen inclusions, high degree of anisotropy and low percentage of recoverable reserves. All this makes these layers to be the objects of study in the search for new technologies, which should take into account the need to change the structure of the reservoir, including its reservoir properties, to be carried out within the pressure and temperature corresponding to the zone of maximum generation. Experimental study of the kerogen properties, as the main source of additional generation of mobile hydrocarbons, allows not only to close the mathematical model, but also to numerically predict the choice of the most optimal methods of development based on the experience of the combination of the wave, thermal and chemical methods for the development of conventional fields.

The authors conducted an analysis of the current state of research of low-permeability reservoirs, and laboratory experiments on the decomposition of kerogen, generation of mobile hydrocarbon phase. A mathematical model was built based on physical and chemical processes occurring under the influence of heat waves and high pressure waves generated in the reservoir when using thermochemical methods.

Keywords: unconventional hydrocarbons, kerogen, thermochemical methods, decomposition kinetics, mathematical modeling

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Introduction

To date, the search for new effective methods of development of hydrocarbon deposits difficult to recover is as relevant as ever. From the set of proposed technological solutions, part of them essentially repeats the approaches to the development of conventional reservoirs with slight modifications in the sequence of operations. Part is in the testing stage, is used for certain types of resources, such as heavy oils; there is not enough sampling on the stimulation results for reservoirs of another type, for example, with low permeability and kerogen inclusions.

Mostly multiple fracturing techniques, methods of in-situ combustion and integrated EOR combining thermal and thermochemical methods are being tested for the development of low-permeability reservoirs. The ‘modern innovations’ suggested for hydrocarbons difficult to recover are not intended to search for fundamentally new methods of influence on layers, but basically use the special properties and qualities of the rock and saturating fluids, including those that take into account the generation of additional hydrocarbons in reservoirs, originally having a small the volume of mobile oil.

Another kind of hard-to-recover material is no exception to this trend, to which this paper is devoted, and which comprises a huge amount of the world’s hydrocarbon reserves and potential reserves of Russia, namely, the reserves concentrated in kerogen-bearing reservoirs. This group includes the deposits of the Bazhenov and other oil and gas source formations.

Feature of considered deposits is that kerogen contained in the composition of their formation (in solid phase) has a oil and gas generating potential, through which it is able, under certain conditions, to be converted to certain mobile hydrocarbons. In nature, this process occurs spontaneously in the scale of geological time (millions of years) due to a gradual increase in pressure and temperature during sedimentation and is accompanied by a variety of slow-phase transitions and chemical reactions, to the course of which the mineral component of the formation, bacteria and other elements of the environment affect.

However, obtaining an additional inflow from kerogen is possible in a shorter time under artificial external influence (Karpov et al, 1998; Volkov et al, 2016). Therefore, the obvious conclusion is that the main task in the development of discussed class of fields is production of their potential reserves hidden in the kerogen and not counted in the calculation of reserves.

Theoretical bases and experimental studies of decomposition of solid hydrocarbons

For the preparation of hydrocarbons from the organic matter of kerogen in real time, an additional external influence is required on kerogen-bearing rocks, which, according to the researchers (Nesterov et al., (No.11) 1993; Bazhenova et al., 1993), is to ensure conditions of elevated temperature in the formation in the range 300-520 °C, and the presence of fractures in pore space, resulting in migration pathways for kerogen degradation products (Nesterov et al., (No.11, No. 12) 1993; Korovina et al., 2013). Otherwise, generation of liquid hydrocarbons from kerogen is inhibited regardless of the temperature (Korovina et al., 2013) and pressure level (Nesterov et al., (No.12) 1993).

At the same time a number of papers (Korovin et al., 2013; Kayukova et al., 2013; Volf, Petrov, 2006) notes the formation or increase in size and number of migratory channels and pores as a result of thermal effects on kerogen-bearing rocks.

Summarizing the results of studies in this field, it is necessary to point out that the process of conversion of kerogen organic matter is definitely connected with thermodynamic conditions (temperature, heating speed, size of kerogen formations, the presence of oxygen in the composition of kerogen-bearing rocks, etc.), and depending on them it can proceed differently.

In the world practice nowadays mainly thermal methods are implemented, combined with hydraulic fracturing and horizontal drilling. The main objective of these techniques is heating up rocks and increase their capacity. In Russia, thermo-gas method is considered as the most promising, used today in deposits of the Bazhenov Formation. Method is comparable to the in-situ combustion, however, instead of combustion, it includes low- temperature oxidation reaction.

All the technologies to a greater or lesser extent can be accompanied by the processes of generating hydrocarbons from kerogen.

However, often, the authors in describing the nature of the technology, designate production of immobile hydrocarbons, which are concentrated in low-permeability rock matrix as the main task, instead of generating processes. This situation stems from the problem of hydrodynamic description of filtration in conditions of kerogen-bearing reservoirs.

The mathematical description of multiphase filtration in kerogen-bearing reservoirs, arranged during the development with the use of any method, is complicated by the need to consider the features of rocks and the processes occurring in them, such as influx of mobile phase, increase in pore volume, change in reservoir properties and thermodynamic state of the system as a whole due to the absorption and release of energy during physical-chemical reactions of kerogen transition into hydrocarbons and others.

The aim of this study was to create a mathematical model of multiphase filtration in complex anisotropic formation that takes into account the presence of physical-chemical reactions and an additional influx of hydrocarbons due to their generation from kerogen.

Generating capability of heavy hydrocarbons can be assessed from the point of view of the thermodynamic potential as a metastability measure of heavy hydrocarbons. The possibility of decomposition of heavy hydrocarbons is characterized by a phase diagram P-T. Construction of the phase diagram and its analysis for kerogen will provide an opportunity to evaluate the best options for exposure, if the conditions of the process implemented will meet the metastable zone of solid (kerogen) phase.

According to the diagram of kerogen decomposition (Tissot, Velde, 1981), at depths below 1000 meters (with a pressure of about 107 Pa) kerogen at thermal exposure decomposes to liquid hydrocarbons, and at pressure of 108 Pa only gas is generated from solid hydrocarbons.

The paper (Karpov et al., 1998) studied the question of heavy hydrocarbons decomposition into methane and solid carbon at high pressure and temperature zone. The authors noted that in the layers in the temperature range from 170 to 230 °C the half-life of heavy hydrocarbons is the magnitude of geological time. This corresponds to the accumulation depth of geologically generated oil and solid carbon (up to 7 km), and carbon in a pair with a hydrocarbon gas (up to 10 km), which is consistent with the diagram B. Tissot and D. Velde on the occurrence and composition of the reservoir fluid.

However, it is noted that in the temperature range 300-700 °C, conditions of solid hydrocarbons decomposition may be realized in the deeper layers of rocks closer to the mantle, and the decomposition time can be reduced by thousands of years to few days. Temperatures in the hydrocarbon formations to depths of up to 7 km do not exceed 250 °C (Kontorovich, 1972). Since the rate of phase decomposition increases dramatically with increasing temperature, it means that at a depth of more than 7 km metastable hydrocarbons can exist – they decompose to a mixture of hydrocarbon gas and carbon solid.

Figure 1, P-T diagram of carbon shows the above results (Karpov et al., 1998) in the high pressure (about 10^8 Pa) and temperature range (about 1000 °C): shaded area corresponds to the boundary zone of solid hydrocarbons metastability. In the same paper it is noted that the HC equilibrium zone correlates with the equilibrium line of diamond-graphite (line 1).

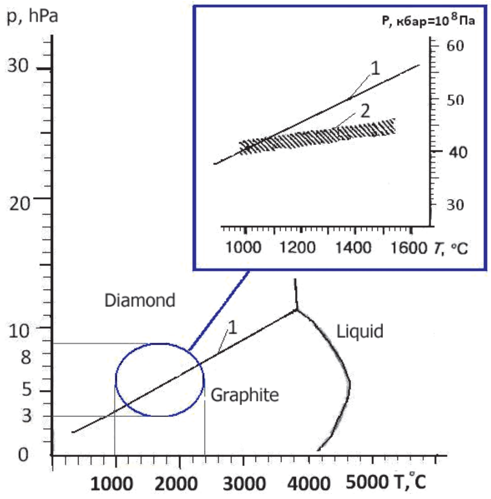


Figure 1. Phase diagram of the graphite-diamond (line 1) and the equilibrium zone for HC (line 2).

Figure 2 shows the line of phase equilibrium for HC (Karpov et al., 1998), which compared with the equilibrium line of diamond-graphite (according to the correlation (Kravchenko, Nigmatulin, 1986), constructed from experimental data (Bundy, 1963)) and the reservoir conditions of kerogen existence for deposits in the Bazhenov Formation (Tarasova et al., 2012).

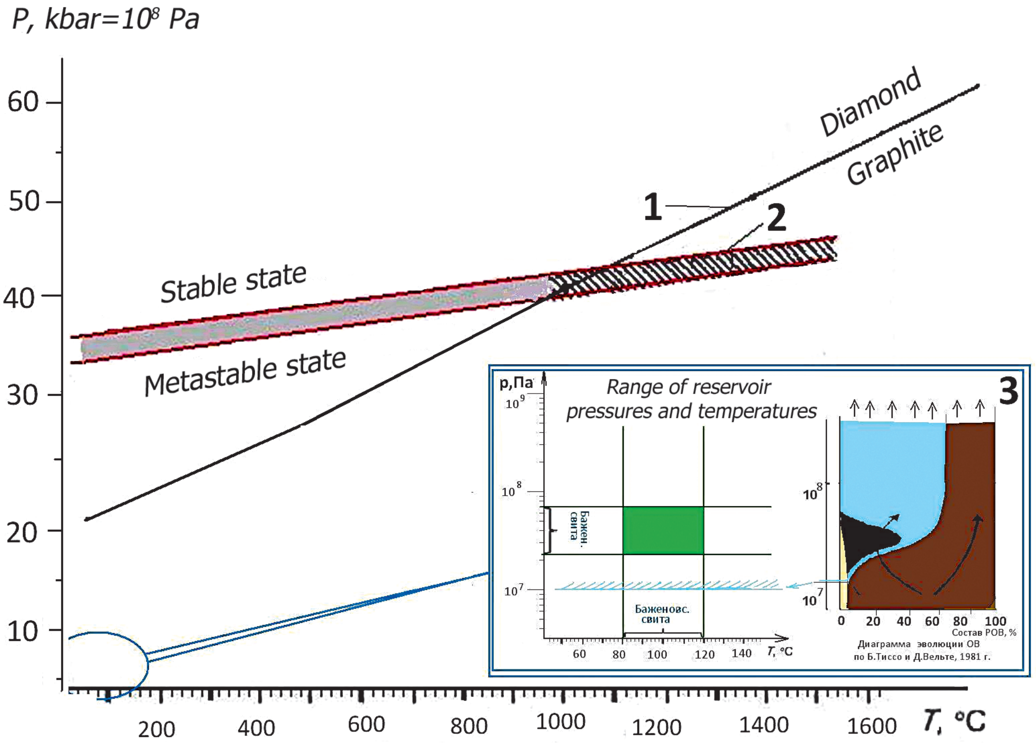


Figure 2. P-T diagram of solid hydrocarbons decomposition and analysis of kerogen in rocks of the Bazhenov Formation. 1 – line of the graphite-diamond equilibrium state. 2 – boundary of phase equilibrium for methane – heavy hydrocarbons. On the tab black color shows area of liquid oil formation, blue color – generation of the gas phase, brown – the presence of kerogen in the formation, green color indicates reservoir pressures and temperatures corresponding to the Bazhenov Formation.

Thus, non-conventional metastable non-flowing hydrocarbons above the equilibrium zone can be stimulated to decompose, only significantly increasing the temperature, stimulating the transition of kerogen in the metastable state. At the same time the energy transition barrier can be calculated from the difference between the internal energy of solid and decomposed hydrocarbon.

Mathematical model and calculation results

The proposed general mathematical model is based on the postulates of mechanics of interpenetrating multiphase continua, and analyzing the results of theoretical and experimental studies of different authors on the behavior of kerogen at different temperature and pressure conditions:

$$\frac{\partial}{\partial t}\left(m c \rho_{в} s_{в}\right)+div\left(c\rho_{в} w_{в}\right)=-J_1-J_3,$$

$$\frac{\partial}{\partial t}\left(m\rho_{в}(1-c)s_{в}\right)+div\left((1-c)\rho_{в} w_{в}\right)=J_1+J_2,$$

$$\frac{\partial}{\partial t}\left(m \rho_{н} s_{н}\right)+div\left(\rho_{н} w_{н}\right)=b_{к} J_1,$$

$$\frac{\partial}{\partial t}\left[(1-m)\rho_k\right]=-J_2-b_{к}J_1+J_3,$$

$$\vec{w}_{в}=-\frac{k_0 k_{в}}{\mu_{в}}\, grad\, p_{в};\ \ \vec{w}_{н}=-\frac{k_0 k_{н}}{\mu_{н}}\, grad\, p_{н},$$

$$\frac{\partial}{\partial t}\left[\sum_i \alpha_i\rho_i c_{vi}T\right]+div\left[\sum_i w_i\rho_i c_{vi}T\right]=\sum_i div(\lambda_i gradT)+JW_{к}$$

$$b_{к}=b_{к}(T,p,c,E_a),\ \ k_i=k_i(m).$$

where m – porosity; c – concentration of the chemical reagent in aqueous solution; S_w and S_o – water and oil saturation; Ww, Wo – filtration rate of water and oil phases, respectively; J_1 – the rate of mass change of the chemical reagent, spent on rock dissolution reaction per time unit; J_2 – the inflow rate of aqueous phase in the kerogen decomposition and rock dissolution per time unit; J_3 – the inflow rate of coke mass at the decomposition of kerogen, per time unit; v_k – function that relates the amount of spent chemical reagent with the amount of hydrocarbons formed from kerogen; k_0 – absolute permeability; k_i ($i = w, o$) – the relative permeabilities of water and oil, respectively); μw, μ_o – viscosity of water and oil, respectively; α_i – volume concentration of phases for $i = w, o, k$, which corresponds to water, oil and solid portions of the formation; ρ_i – actual density of phases for $i = w$, o, k (water, oil and solid portions of the formation); c_{vi} – the specific heat of phases for $i = w, o, k$ (water, oil and solid portions of the formation); λ_i – the thermal conductivity of phases for $i = w, o, k$ (water, oil and solid portions of the formation); J – intensity of kerogen decomposition; W_k – energy released by the decomposition of kerogen per mass decomposition unit.

Analysis of the available at the moment commercial and experimental studies of kerogen and data used in numerical simulations, has shown the absence of a single view of the kinetics of oil generating reactions.

Based on the analysis of kerogen phase diagram, the authors have set the phase transition kinetics of solid hydrocarbons decomposition on the same principle as the kinetics of the phase transition from graphite to diamond (Kravchenko, 1990).

At the first stage the simple isothermal multiphase filtration model was built with the kinetics of chemical reaction that only qualitatively defines transition of kerogen into liquid hydrocarbons by taking into account in the model of reactive agent, which provides start-up of kerogen decomposition reaction (Volpin et al., 2010). This model has allowed to analyze the filtering features in terms of increasing the porosity, and creation

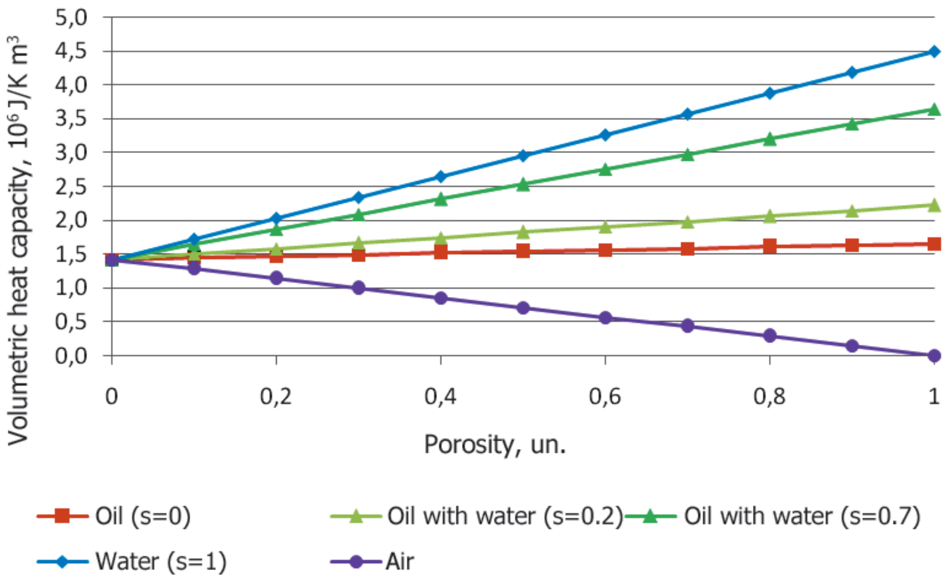
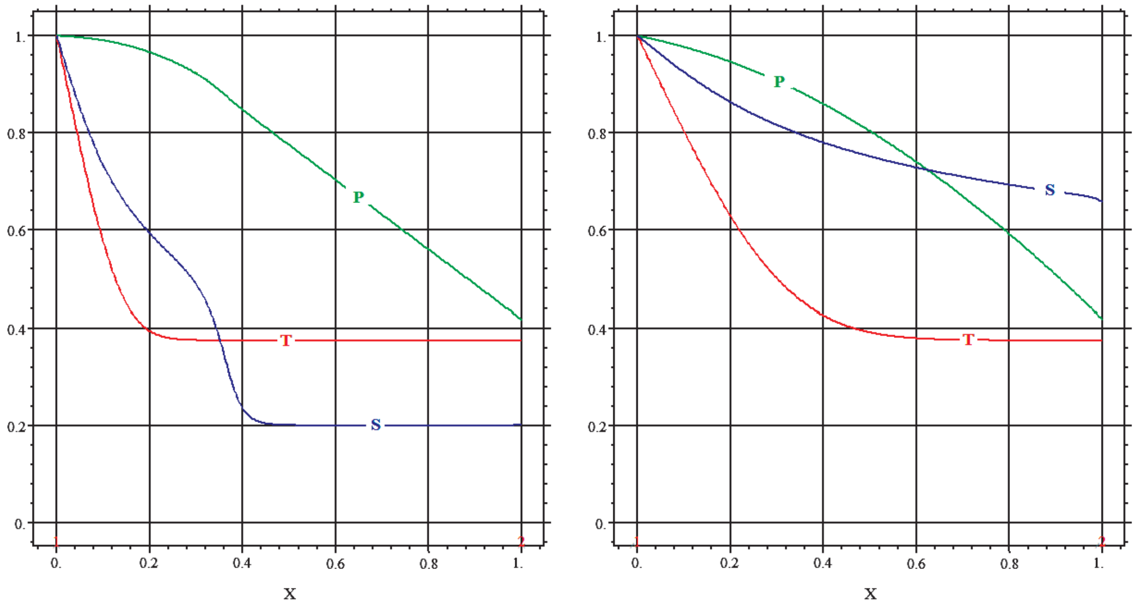


Figure 3. The volumetric heat capacity of sandstone saturated with different phases, depending on the porosity.



t=0.2

t=1

Figure 4. Comparison of pressure (green line), saturation (blue) and heat (red) wave propagation rates in a saturated reservoir (dimensionless time).

of additional inflow of liquid oil generated from solid kerogen matrix.

Sufficiently broad array of input parameters of the model revealed the relationships of field output data (the total amount of additional inflow, time of its achievement) obtained as a result of exposure (development method) with parameters reflecting the formation properties (e.g., oil generating potential of kerogen), and the process of fluid displacement (e.g., the rate of phase front propagation).

In particular, dependences of decomposition time of all kerogen mass were defined, which corresponds to implementation of the full potential of kerogen, depending on the rate of decomposition and injection rate of active agent into the formation. Also, the dynamics of the pore space changes, which affects the change in conductivity was found.

The next step in the simulation was a series of calculations (mathematical experiments), the purpose of which was to monitor the distribution dynamics of the reservoir pressure and temperature waves stimulated by a wave thermal gas-chemical exposure (Volpin et al., 2014) using binary mixtures (based on nitrate ammonium). The model allowed us to estimate ranges of the process parameters (pressure, volume of injected reactive and buffer liquids, the remoteness of reaction zone, etc.) with different arrangement of exposure, knowledge of which is necessary to ensure the safe operations.

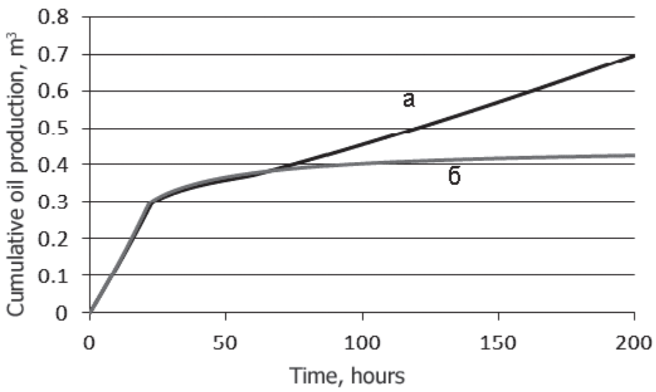


Figure 5. Dynamics of cumulative oil production at displacing it with an aqueous solution of chemically active substance: a) in the layer containing kerogen; b) in the formation and excluding kerogen decomposition.

By means of the model we can ‘observe’ the emergence in space of formed filtration field areas, taking into account the anisotropy of the reservoir properties distribution, and changes in porosity and absolute permeability in the reaction converting the kerogen into liquid hydrocarbons.

Separately, an analysis was performed of changes in thermal parameters of rocks at its saturation by different fluids, the results of which are taken into account in the model (Figure 3). Figure 4 shows the results of comparing the pressure, saturation heat waves propagation rates. As you can see, the pressure is set much faster in the formation than the two other fronts. Therefore, we can consider the wave and the heat task subsequently.

The comparison is carried out of filtration results in an inert formation and kerogen-bearing formation, taking into account the decomposition of kerogen to form mobile hydrocarbons (Figure 5).

The calculations are made that simulate actual commercial experiments to stimulate oil inflow by thermochemical effects on the some oil fields. The simulation results showed qualitative agreement with the results of actual field experiments; stepwise approach is justified to the analysis of the simulated technological process. On the basis of generalization of theoretical, experimental and field research in the wave, thermal and explosive effects on kerogen, the possibility is justified for effective application of thermo-gas-chemical exposure methods on kerogen-bearing formations such as the Bazhenov formation (Dieva et al., 2015).

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