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Laboratory studies of the thermal exposure effect on the rock properties at the Lyaelskaya area at the Yaregskoye field

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Лабораторные исследования влияния теплового воздействия на свойства горных пород Лыаельской площади Ярегского месторождения

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Since 2010, the technology of thermogravitational reservoir drainage (TGRD) has been applied at the Lyaelskaya area of the Yaregskoye field. The development efficiency of the area is strongly influenced by the features of its structure, namely: the presence of tectonic faults and a dense network of open and extended fractures, a high degree of reservoir heterogeneity in terms of permeability, which is expressed in the presence of highly permeable formation zones composed of unconsolidated sandstone, as well as unproductive impermeable interlayers, composed of mudstones, siltstones and silty sandstones. The presence of impermeable interlayers in the productive strata reduces the efficiency of the thermogravitational drainage process, since they shield the advancement of the steam chamber and lead to its deformation, which in turn reduces the oil recovery factor, the rate of deposit development, and also contributes to the growth of the steam-oil ratio (SOR) and creates additional uncertainties in forecasting development indicators. However, according to the data of scientific and technical literature, as a result of thermal impact on the reservoir, creation of cracks in the formation is possible, including zones that are composed of unproductive impermeable interlayers. This entails the possibility of developing a steam chamber above the impermeable interlayer, increasing the formation heating zone, thereby improving the development efficiency as a result of thermal treatment.
The results of experimental studies of the temperature influence on the reservoir rocks properties at the Lyaelskaya area of the Yaregskoye field are presented. As studies have shown, thermal impact in the conditions of the Lyaelskaya area has a noticeable effect on the change in the reservoir properties of both low-permeability and high-permeability rock samples, which can affect the efficiency of the process of thermogravitational reservoir drainage under the considered object conditions.

Ключевые слова:
высоковязкая нефть, Лыаельская площадь, тепловые методы, лабораторные исследования, керн, фильтрационные исследования, модель пласта.

На Лыаельской площади Ярегского месторождения с 2010 г. применяется технология термогравитационного дренирования пласта. На эффективность разработки площади сильное влияние оказывают особенности ее строения, а именно: наличие тектонических разломов и плотной сети раскрытых и протяженных трещин, высокая степень неоднородности коллектора по проницаемости, которая выражается в наличии высокопроницаемых зон пласта, сложенных несцементированным песчаником, а также непродуктивных непроницаемых пропластков, сложенных аргиллитами, алевролитами и алевритистыми песчаниками. Присутствие непроницаемых пропластков в продуктивной толще снижает эффективность процесса термогравитационного дренирования, так как они экранируют продвижение паровой камеры и приводят к ее деформации, что, в свою очередь, снижает коэффициент извлечения нефти, темпы разработки залежи, а также способствует росту паронефтяного отношения и создает дополнительные неопределенности при прогнозировании показателей разработки. Однако, согласно данным научно-технической литературы, в результате теплового воздействия на залежь возможно образование трещин в пласте, включая зоны, которые сложены непродуктивными непроницаемыми пропластками. Это влечет за собой возможность развития паровой камеры выше непроницаемого пропластка, увеличивая зону прогрева пласта, тем самым улучшая эффективность разработки в результате термического воздействия.
Приводятся результаты экспериментальных исследований по изучению влияния температуры на фильтрационно-емкостные свойства горных пород Лыаельской площади Ярегского месторождения. Как показали проведенные исследования, термическое воздействие в условиях Лыаельской площади оказывает заметное влияние на изменение фильтрационно-емкостных свойств как низкопроницаемых, так и высокопроницаемых образцов горных пород, что может повлиять на эффективность процесса термогравитационного дренирования пласта в условиях рассматриваемого объекта.

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Introduction

At present, thermal methods of reservoir stimulation are the only alternative for the development of high-viscosity oil and natural bitumen (HVO and NB) fields. One of the most widespread technologies of thermal stimulation is thermogravitational reservoir drainage (TGRD). TGRD has been used since 2010 for the development of the Lyayelskaya area of the Yaregskoye field located in the Komi Republic. The Lyaelskaya area is characterised by the presence of extended impermeable interlayers represented by mudstones, siltstones ans islty sandstones, which complicates the process of its development using TGRD technology (Fig. 1).

Studies to investigate the influence of impermeable interlayers located in the productive strata of reservoirs saturated with HVO and NB on the process of steam chamber development when applying the TGRD technology were first performed by Young and Butler [1]. In this work, the influence of a horizontal impermeable reservoir with an extent equal to that of the model on the temperature distribution under different vapour injection configurations was considered. The authors concluded that when the steam chamber reaches the impermeable formation, its thermpconductive heating takes place, due to which the temperature of the overlying rocks above the impermeable barrier rises. Further studies have shown that the presence of interlayers leads to an increase in the accumulated steam-oil ratio [2], uneven steam chamber spreading [3] and a reduction of TGRD efficiency. Significant TGRD deficiency is observed at a sufficiently large proportion of impermeable interlayers in the volume of the entire reservoir [4]. The efficiency of TGDP also strongly depends on the location of impermeable interlayers relative to well pairs [5, 6]. Extended interlayers increase the risk of vapour breakthrough into production wells and complicate the regulation of steam chamber development [7].

Apparently, the thermal effect on the reservoir can lead to an irreversible change in the reservoir properties (RQ) of rocks, in particular, impermeable rocks. This phenomenon is widely covered in the works of various authors. The mechanism, as well as the nature of changes in the reservoir properties of rocks, can be different with the temperature rise. The results of the studies vary greatly: from no effect of temperature on RQ to a significant change. This can be explained by the fact that the change in the reservoir properties of rocks is largely influenced by the nature of the saturating agent (liquid, gas), as well as the type, composition and physical properties of rocks. If water is used as a saturating liquid, permeability may reduce with the temperature increase [8–11]. In some cases [10], the permeability of rocks can reduce to 65% of the original. The reduction of permeability is primarily associated with the thermal expansion of the mineral skeleton of the rock, which leads to a decrease in the size of the pores and an increase in the tortuosity and roughness of the void space [12]. At sufficiently high temperatures, complete closure of the pores is possible due to the expansion of the rock grains. Reduction of porosity can also occur due to an increase in the compressibility of rocks at heating. In some cases, thermal expansion of rocks contributes to structural failure caused by differences in the coefficients of thermal expansion of rock minerals. Different minerals have not only different thermal expansion coefficients, but for each mineral the thermal expansion coefficient can hold a dictinction in different crystallographic directions. These discrepancies in thermal expansion lead to stress concentrations at grain contact points when the rock is heated, and, as a result, to the possibility of fracture of individual mineral grains and/or rock segregation and increased pore volume [13-22].

There is also a geomechanical factor of changes in the permeability of rocks, including clayey ones, with an increase in temperature [21, 23]. Heating can alter the elastic and strength properties of the rock through thermal expansion, chemical reactions, or the accumulation of thermal stress if the rock is under compression conditions. Since large-scale thermal action leads to the heating of significant volumes of the formation, especially when implementing the SAGD technology, it is possible that due to the thermal expansion of various rocks, there may be a redistribution of stresses in the rocks, which can lead to cracking of the layers due to their deformation caused by uneven thermal expansion of the surrounding rocks [23–46].

Clay minerals, being the part of the rocks of impermeable interlayers, can have a significant effect on the process of injected heat transfer fluid propagation. Clays heating to high temperatures leads to irreversible changes in their physical and chemical nature due to changes in the structure, geological aspect and phase state of clays [14]. Depending on the predominant type of clay mineral included in the rock composition, both rock swelling and shrinkage can be observed when the rock is in contact with the heat transfer medium. Intracrystalline swelling of clay rock is explained by active interaction of the heat transfer medium with interparticle bonds. The swelling pressure of clay rock during wetting can reach 1.0-1.5 MPa. Shrinkage of clay rocks occurs during prolonged drying of the rock, as a result of which the volume of clay decreases by 25–30 %. Such volume reduction dramatically increases the permeability of clay rocks, which may contribute to the efficiency of thermal action. However, this

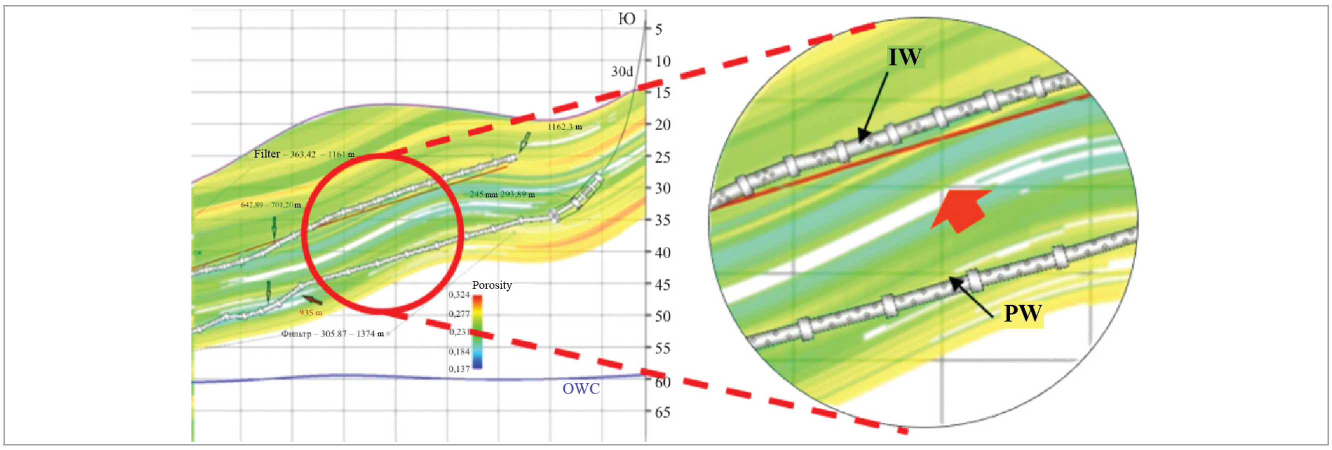

Fig. 1. Profile section of the OPU-5 area along the 30d-30n well line (NS – injection well, DS – production well)

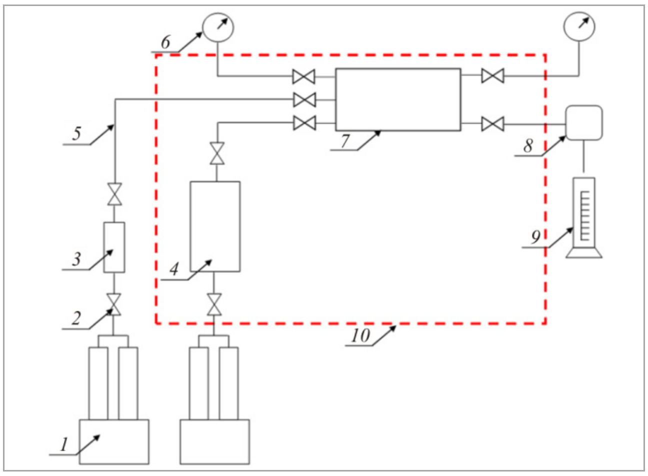

Fig. 2. Diagram of the laboratory unit for studying the effect of temperature on the reservoir properties of highly permeable samples

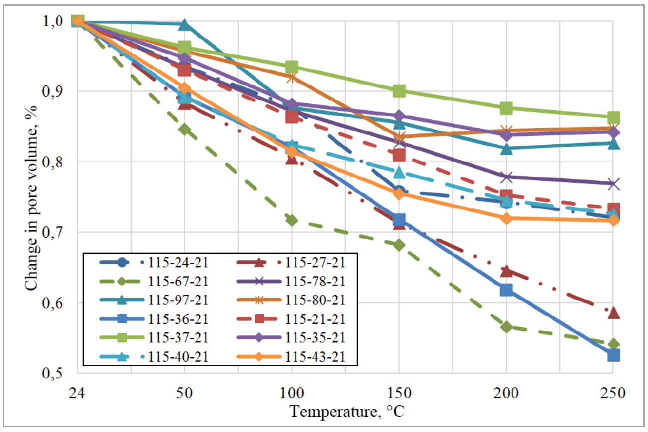

Fig. 3. Relative change in sample pore volume due to thermal expansion of the rock skeleton

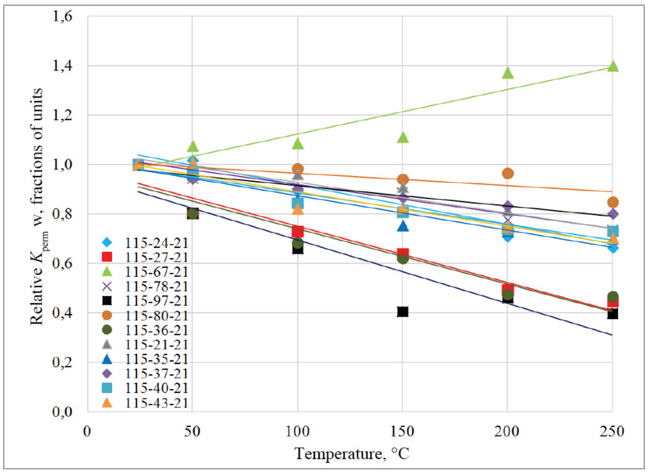

Fig. 4. Relative change in water permeability coefficient of highly permeable core samples

effect was observed in the process of heating clays at atmospheric pressure. It is known that all montmorillonites lose adsorption water in the temperature range of 100-200 °C, causing formation of a "compressed structure" in montmorillonite, and when heated above this temperature, such a change in structure becomes irreversible, which may eventually lead to a significant increase in porosity and permeability of the rock [15].

In this paper we studied the influence of heating temperature on RQ of high-permeable and low-permeable rocks of Lyayelskaya area of the Yaregskoye deposit in the temperature range from 50 to 250 °C without taking into account geomechanical and mineralogical factors.

Description of laboratory unit

The laboratory unit for performing experiments was a core holder *7*, to the input of which high-pressure piston pumps *1* were connected. One pump, connected to the core holder by hydraulic tubes *5* through a tank with a volume of 200 cm^3 *3*, was used to pump water as the temperature increased. A second pump was used to deliver water from a 5000 cm^3 tank *4* to measure water permeability at each temperature stage. A back pressure valve *8* and a measuring cylinder *9* were installed at the outlet end of the core holder. The pressure at the ends of the test sample was measured by pressure gauges *6*. Core holder *7* and spacer container *4* were in thermostatically controlled cabinet *10*. Differential pressure sensors were used to measure differential pressure. Depending on the stage of the experiment, the corresponding blocks of the unit were cut off by valves *2* in order to avoid the effect of the expansion of water and oil in them on the results of the experiments. The diagram of the laboratory installation is shown in Fig. 2

Description of the methodology of the experiments

The effect of thermal influence on the rock of Lyaelskaya area of Yaregskoye deposit was studied by conducting a series of laboratory tests: on high-permeability samples (reservoir) and on low-permeability samples (nonreservoir) at temperatures of 24 °C and from 50° to 250 °C in increments of 50 °C.

Experiments for assessing the change in the reservoir properties of highly permeable samples under thermal exposure were carried out in the following sequence:

a) a rock sample saturated with distilled water was placed in a core holder, after which the effective pressure on the sample and the initial temperature of the experiment were simulated;;

b) the volume of liquid on the pore pressure pump was zeroed. The pore pressure maintenance mode was set on the pump. The core holder with the sample was heated to the next temperature stage;

c) as the temperature stabilized by pore pressure pumps, the volume of water displaced from the sample was recorded;

d) based on the volume of pumped water and the initial volume of pores, the change in the volume of the void space of the reservoir rock was calculated:

$$V_{\text{por after}} = V_{\text{por before}} - V_{\text{pumpout}}, \tag{1}$$

where $V_{\text{por before}}$ – the volume of pores of the model before temperature exposure (at room temperature), cm^3, $V_{\text{por after}}$ – pore volume of the model after heating to a set temperature, cm^3, V_{pumpout} – the volume of the produced water model pumped out by the pump, см^3;

a) water was filtered through the reservoir model at the temperature of the reservoir model until the differential pressure between the ends stabilized and in a volume of at least $3V_{\text{por}}$ in order to measure the permeability coefficient.

б) The reservoir model was heated to the temperature of the next stage, after which the above points were repeated.

For each sample, the volume of displaced water and the water permeability coefficient were measured for each temperature regime.

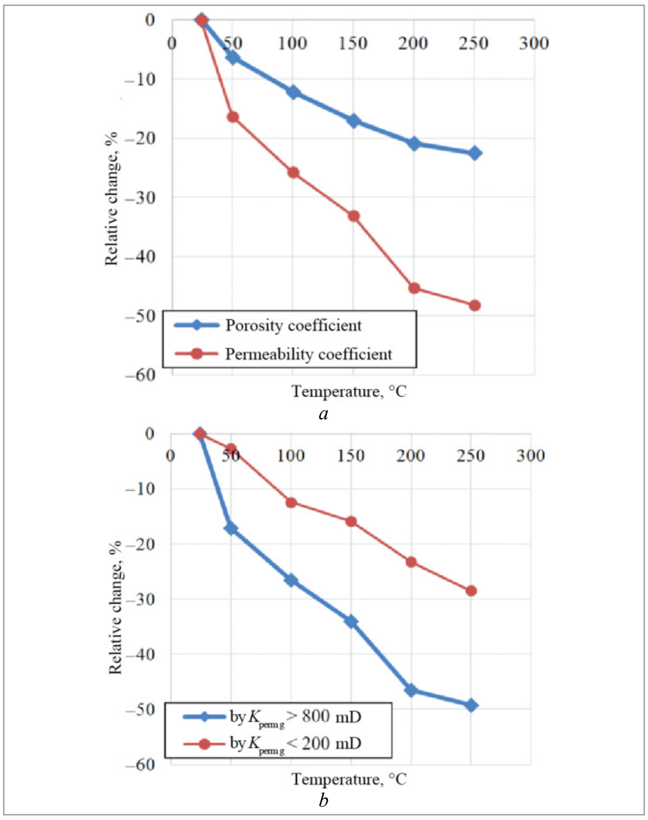

Fig. 5. Relative change with increasing temperature: permeability and porosity of samples (*a*), permeability for samples with different permeability (*b*)

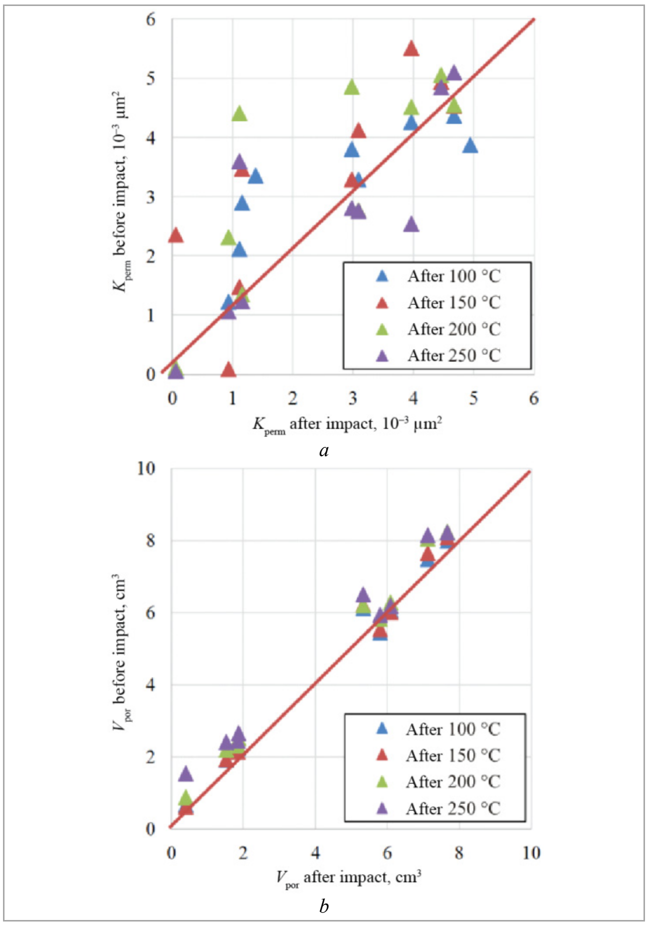

Fig. 6. Results of studying the effect of temperature on RQ of low-permeability samples: *a* – change of permeability coefficient; *b* – change of porosity coefficient

The assessment of the effect of temperature on the reservoir properties of low-permeability samples (non-reservoir rocks) was carried out as follows:

a) dry samples were weighed and saturated with distilled water under vacuum;

b) samples were weighed in order to determine the porosity coefficient by liquid saturation method;

c) the samples saturated with water were placed in a thermo-cabinet heated to a given temperature;

d) the samples were heated to the required temperature step and held for 24 h with constant control of the mass of the samples.

24 h with constant control of the mass of samples;

e) cooling the samples to the initial (room) temperature and measuring the gas permeability of the samples;

f) the above-mentioned operations were repeated for each temperature regime from 50° to 250 °C with a step of 50°.

The results of the research and their discussion

Within the framework of research of temperature influence on reservoir properties of permeable rocks, 12 experiments on stepwise heating of sandstone samples were performed. The results of the experiments are presented in Figs. 3 и 4.

As laboratory studies have shown, with increasing the heating temperature from 24 to 250 °C there is a noticeable decrease in the pore volume of the samples (see Fig. 3) and, accordingly, in the porosity coefficient. The reduction of the pore volume of the samples under thermal influence correlates well with the behaviour of water permeability as the temperature increases. The dependences of the relative change in the water permeability coefficient of the samples with increasing temperature are shown in Fig. 4.

For the majority of samples permeability declines linearly with increasing temperature up to 250 °C. The obtained research results correlate well with earlier studies, where the relative permeability reduction was about 20 % when the temperature was increased up to 100 °C [8]. The permeability reduction in this case can be related to the expansion of the rock skeleton at a fixed effective pressure, increase in tortuosity and roughness of pore channels, as well as the clamping of small pores. The permeability of sample 115-67-21 increased with the rise of the temperature, while the porosity coefficient reduced as it was heated (see Figure 3). This effect may be related to the opening of existing micro- and macrocracks.

For each temperature step the permeability and porosity values were averaged, and the samples were conditionally divided into two groups with permeability more than 0.8 μm^2 and permeability less than 0.2 μm^2. Dependences of relative change of permeability and porosity values of samples are presented in Fig. 5.

As can be seen from Fig. 5, *a*, temperature rise leads to monotonic decrease of porosity and permeability of highly permeable samples. At 250 °C, porosity decreases by 23 %, permeability – by 48 %. It was observed that the decrease in permeability of highly permeable samples is almost twice as strong, compared to samples with lower permeability, at the same increase in temperature (Fig. 5, *b*).

The results of studies of changes in the reservoir properties of low-permeability non-reservoir rocks after exposure to temperatures in the range from 50 to 250 °C are presented in Fig. 6, *a*, values for 24 and 50 °C are not shown as no significant changes were observed.

The red line in Fig. 6 shows the equality of the values of the parameter under consideration before and after the thermal action. Points located above the red line indicate a tendency to increase the corresponding parameter after the thermal impact.

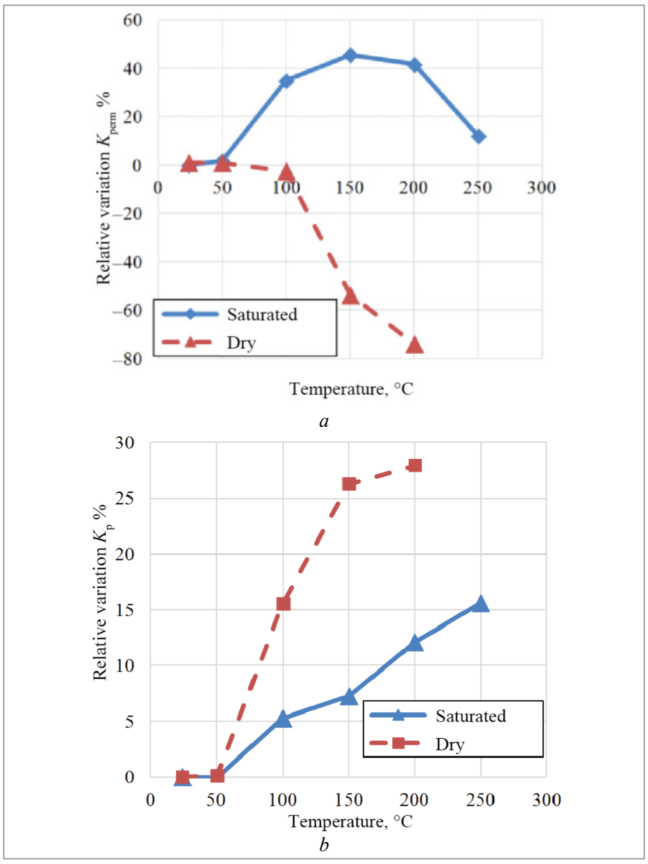

Fig. 7. Variation of average values of permeability coefficients (*a*) and porosity coefficients (*b*) of saturated and dry core samples with the temperature rise

Most values of the permeability coefficient of the samples after their heating to temperatures of 100°, 150° and 200 °C were above the red line, indicating a tendency to increase permeability (see Fig. 6, *a*). Moreover, the relative permeability increase is slightly higher for samples with lower permeability compared to more permeable samples (area on the left). After heat treatment there is also a tendency to increase the volume of void space of samples (see Fig. 6, *b*), and with each new heating step the porosity coefficient of samples irreversibly increases.

Fig. 7 shows the diagram of variations of the average values of permeability coefficient (*a*) and porosity (*b*) of low-permeability samples as a function of heating temperature. Average values were calculated for two groups of samples: a group of samples saturated with water and a group of dry samples.

As can be seen from Fig. 7, *a*, for water-saturated low-permeability samples, with the temperature rise up to 150 °C there is an increase in the permeability coefficient by 45.6 % on average; with the subsequent increase in temperature up to 250 °C there is a decrease in the permeability coefficient to 12 % of the initial value at 24 °C. This effect may be associated with two different mechanisms, manifested in different temperature ranges. Up to 150 °C the increase of permeability can be related to the effect of pore unclining due to thermal expansion of water and increase of stresses inside the pores (the samples were not under all-round compression). At temperatures from 150 to 250 °C the permeability decrease is apparently connected with redistribution of rock particles relative to each other and change of tortuosity of filtration channels. In the case of heated dry samples, a constant permeability decrease of 74 % was observed as the temperature increased up to 200 °C. The permeability decrease can also be caused by the change of the void space structure due to the redistribution of rock particles by changing the tortuosity of filtration channels. In general, the differences in the character of change of permeability coefficient of saturated and dry samples with temperature rise from 24° to 150 °C are connected exactly with the effect of pore unclining at the expense of thermal expansion of water.

From Fig. 7, b, it can be seen that for both saturated and dry samples there is a constant increase in the average porosity coefficient by 15.6 and 28 %, respectively, in the whole range of heating temperature changes. It can be seen that changes in porosity and permeability with increasing temperature in the temperature range from 100-150° to 250°C are multidirectional (permeability of samples decreases – porosity increases), which may indicate that the growth of permeability does not depend directly on the increase in porosity, but rather due to changes in the structure of the void space as a result of thermal expansion of the mineral skeleton of the rock (since the behaviour of dry and saturated samples is similar). Changes in porosity and permeability of saturated samples with increasing temperature in the temperature range from 24 to 150 °C are co-directional, indicating the mechanism of pore unclination due to thermal expansion of water.

Conclusion

The following conclusions can be drawn from the results of the performed studies of samples from the Lyaelskaya area of the Yaregskoye field:

1. For highly permeable reservoir samples at constant effective pressure with increasing temperature there is a decrease in the pore volume of samples on average by 23 % and permeability on average by 48 %, which may be caused by thermal expansion of the rock skeleton. At that, permeability decrease with temperature is more active for samples with higher permeability.

2. Within the framework of studies of nonreservoir rocks, it was found that the increase in temperature from 50° to 150 ° C leads to an increase in permeability of water-saturated samples by an average of 45.6 %. With the temperature rise from 200° to 250 ° C, a decrease in the average permeability incremental growth to 12 % (relative to the initial K_{perm}) is observed, which may be associated with changes in the structure of the void space at he expense of the redistribution of rock particles. The porosity coefficient of saturated samples increases in the whole range of temperature increase by 15.6 %.

3. For dry samples (non reservoir rocks) in the same temperature range, a decrease in the permeability coefficient by 74 % is observed, while the porosity coefficient grows to 28 % on average.

4. Differences in the behaviour of permeability coefficient change of saturated and dry samples (nonreservoir rocks) with temperature rise can be related to the effect of pore unclining due to thermal expansion of water and increase of internal stresses..

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