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Calculation of Oil-saturated Sand Soils' Heat Conductivity

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Nowadays, there are significant heavy high-viscosity oil reserves in the Russian Federation with oil recovery coefficient not higher than 0.25-0.29 even with applying modern and efficient methods of oil fields development. Thermal methods are the most promising out of the existing ways of development, main disadvantage of which is large material costs, leading to the significant rise in the cost of extracted oil. Thus, creating more efficient thermal methods and improving the existing ones, is the task of great importance in oil production.

One of the promising trends in enhancing thermal methods of oil recovery is the development of bottomhole electric steam generators. Compared to the traditional methods of thermal-steam formation treatment, which involve steam injection from surface, well electrothermal devices can reduce energy losses and improve the quality of steam injected into the formation. For successful and efficient organization of oil production and rational development of high-viscosity oil fields using well electrothermal equipment, it is necessary to take into account the pattern of heat propagation, both in the reservoir and in the surrounding space, including the top and bottom. One of the main values characterizing this process is the heat conductivity λ of oil-bearing rocks.

The article describes composition of typical oil-saturated sand soils, presents studies of heat and mass transfer in oil-saturated soils, reveals the effect of various parameters on the heat conductivity of a heterogeneous system, proposes a method for calculating the heat conductivity of oil-bearing soils by sequential reduction of a multicomponent system to a two-component system and proves the validity of the proposed approach by comparing acquired calculated dependencies and experimental data.

Key words: oil-saturated soil; heat methods of oil production; heat conductivity; multiphase system; interpenetrating components

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Introduction. The most priority task in the field of oil production today is the rational development of heavy high-viscosity oils (HVO) deposits. Explored reserves of HVO on our planet reach 700 billion tons, and the main regions by the volume of reserves are the following: Canada ~ 300 billion tons; Venezuela ~ 200 billion tons; USA ~ 25 billion tons; Russian Federation ~ 9 billion tons, more than 50 % of which are in the North-West region of the Russian Federation. In the natural regime of wells exploitation oil recovery usually equals 5-10 %, therefore, in conditions of oil horizons' depletion in oil producing regions, as well as the gradual exhaustion of extensive oil field resources, serious attention in industrialized countries is paid to the development of methods for enhanced oil recovery [1, 2, 5, 7]. To date, non-alternative methods of enhanced oil recovery, recognized by modern experts, are thermal impact on productive HVO reservoirs [2, 3, 6, 11, 19, 24].

In Russia, the thermal methods are mostly used in the production of HVO at Usinskoe (Komi Republic) and Gremikhinskoe (Udmurt Republic) fields, which makes up no more than 3 % of all deposits in the Russian Federation. The limited use of thermal methods is explained by their main drawbacks: high material and capital intensity of heat and power equipment, heat losses in the distribution pipeline system and well, reduced efficiency, determined by burning part of the extracted oil or gas in steam generators, and significant environmental degradation in oil production areas [2, 10, 16].

The development of bottomhole steam generators is by far one of the most promising trends for the development of thermal production methods, which, in contrast to the traditional methods of steam and thermal treatment of formations, do not require steam pumping from the surface. Bottomhole electrothermal devices can reduce energy losses and improve the quality of steam injected into the reservoir [4, 8-10, 17]. For the successful and efficient organization of oil production and the rational development of high-viscosity oil fields using bottomhole electrothermal

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equipment, it is necessary to take into account the nature of the distribution of thermal impact both in the reservoir and in the surrounding area, including the top and bottom of the reservoir, and also have a clear understanding of the formation structure and the thermal and physical properties of the rocks composing them.

Ways to solve the problem. It is known that the oil reservoir rocks are mainly comprised by sandstones with carbonate or clay cement, carbonate rocks and unconventional reservoir rocks, called Bazhenov formation. Therefore, to assess the physical and reservoir properties of oil formation rocks, to generalize existing experimental data and to establish a correlation between different physical properties, it is advisable to consider theoretical research methods.

Physical and reservoir properties of the formation include thermal conductivity λ, dielectric permittivity ε, electrical conductivity σ, gas permeability k, etc., which can be combined with the concept of generalized conductivity Λ, because they are all described by a phenomenological equation of the form:

$$\overline{A} = -\Lambda \nabla B ,$$

connecting the specific flow $\overline{A}$ with the potential gradient ∇B of one kind or another in nonequilibrium thermodynamic systems. For example, the laws of Fourier and Darcy are usually represented as:

$$\overline{q} = -\lambda \nabla T , \ \overline{v} = -\frac{k \nabla P}{\eta},$$

where $\overline{q}$ – specific heat flow; $\overline{v}$ – velocity of a liquid (gas) flowing through a porous material; $\nabla T, \nabla P$ – temperature and pressure gradient; λ, k, η – heat conductivity, permeability and viscosity of the flowing fluid.

Finding a temperature field in an oil-bearing soil, where all the mechanisms of heat transfer operate, is an extremely complex task, and its only correct solution is to compile and solve for each particular case a system of four initial equations: heat transfer by conduction, convection, radiation, and moisture.

Moreover, the creation of an equivalent thermal conductivity model [12, 13, 15, 21] can serve as an effective tool to avoid these difficulties and successfully solve many practical problems. This is an equation describing the process of effective heat conductivity in an inhomogeneous material. In this case, the material is considered as some quasihomogeneous substance, to which the heat conductivity equation is applicable. Due to the processes of radiation, convection and transport of matter in porous media, the heat transfer parameters will be characterized by effective values. Thus, for the analysis and determination of the temperature field in heterogeneous materials, it is possible not to use the system of equations of conductive, radiation, and mass transfer conductivity, but to refer to only one heat conductivity equation with the dependence of the coefficients complicated by all these factors.

It should be also considered that the processes of transfer through the liquid and gas phases are complex and, in addition to convective transfer, include a number of mechanisms, the main of which is heat transfer due to: diffusion vapor transfer, thermal diffusion, thermal sliding, thermosmosis effect, film flow of liquid under the influence of propping pressure. A numerical analysis showed that the contribution of these heat transfer mechanisms to the effective thermal conductivity is 2-3 orders of magnitude smaller than other heat and mass transfer mechanisms and, accordingly, they can be neglected [12, 14, 18, 23].

The objective of this study is to analytically determine the generalized conductivity Λ and, in particular, the effective heat conductivity λ of oil-saturated soil, depending on the minimum and available information about the properties of the formation and its constituent components.

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The methodology for calculating the effective heat conductivity of oil-saturated soils is based on the assumption that it is possible to distinguish a frame of particles in the system and moisture located in the places of particles' contact (in case the liquid wets the grain surface), or air (in the case when the liquid does not wet the grain surface). The remaining part of the pore space, which may be a single-phase or two-phase system, together with the selected frame, can be considered as a structure with interpenetrating components. Thus, the technique is based on the following calculations: first, heat conductivity of the frame is determined; next – heat conductivity of the remaining fraction of the pore space; and finally, it becomes possible to determine the effective heat conductivity of the entire system as a whole.

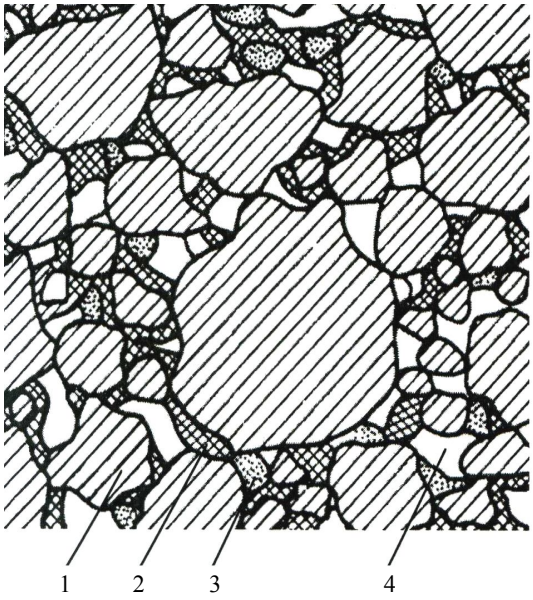


Fig.1. Structure of oil-bearing sandstone
1 – particles of SiO_2, 2 – binding cement, 3 – liquid (water, oil), 4 – vapors of liquid, gas

The most typical oil-bearing soils are sedimentary rocks such as spar, mica, represented in figure 1 by particles 1, cemented mainly by carbonaceous and clay cement 2. Grains, in combination with cement, form a solid skeleton, the pores of which contain liquid 3 (water, oil) and its vapors 4.

At analyzing oil-bearing rock samples, the following parameters and properties are being determined:

1. The total porosity (the ratio of the pores' volume to total volume $m = V_p/V$), and the effective porosity m_{ef} (the ratio of the pores' volume with flowing liquid inside the pores, when they are completely saturated with this liquid, to the total volume) $m = V_{p\,ef}/V$;

2. The granulometric composition – medium sizes of grains d_i and their weight concentrations g_i;

3. The saturation of rocks with liquid (oil, water, gas) $\omega = V_l/V_p$ – the ratio of the volume of liquid to the total volume of pores.

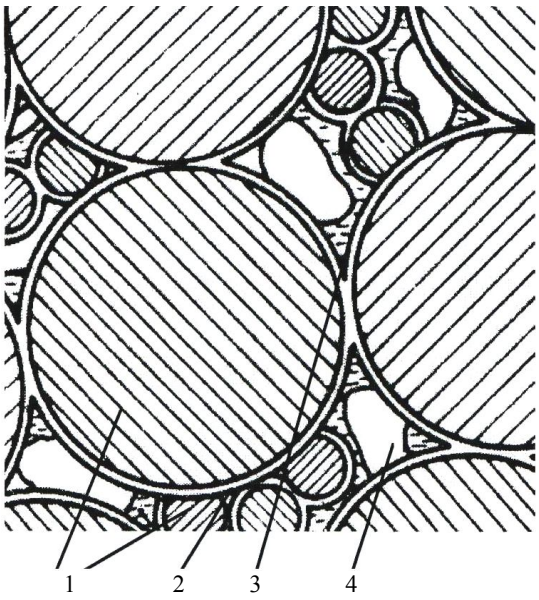


Fig.2. The model of oil-bearing sandstone structure
1 – grains, 2 – porous cement, 3 – liquid, 4 – vapor-gas phase

At creation of sedimentary rock model following assumptions were adopted:

• granulometric composition of the rock, on the basis of data analysis, is limited to grains of two sizes – d_1 and d_2 and corresponding weight concentrations g_1 and g_2;

• cementing binder is not monolithic, but porous, and the volume of pores in the binder – the volume of cracks V_{cr} – is equal to difference in volumes between the volume of all pores, and the volume of pores, taken into account for the effective porosity ($V_{cr} = V_p$-$V_{p\,ef}$);

• porous cementing binder is distributed between grains of large and small diameter proportionally to their specific surface areas;

• liquid in a form of jacket surrounds the contacts of large grains, envelops small grains and fills a part of the cracks in the binder, leaving the remaining cracks dry.

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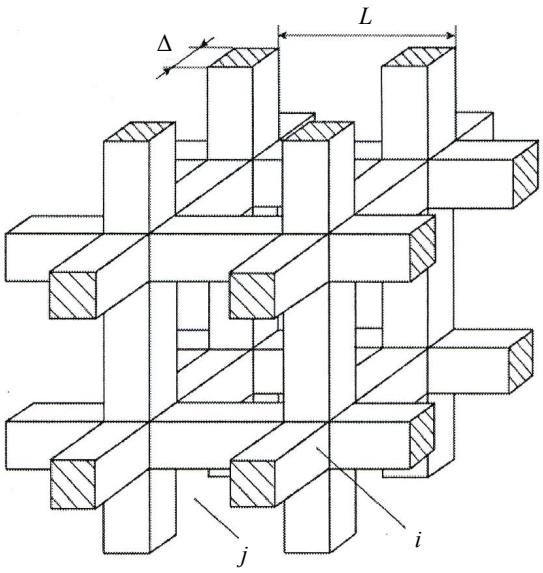


Fig.3. Binary system structure with interpenetrating components *i* and *j*

Based on the mentioned above, sandstone model can be seen as a form of a polydisperse structure, consisting of grains 1 of two diameters, bound together by porous cement 2. The pores, depending on moisture and oil content, contain both liquid 3 and gas 4 (Fig.2). The effective heat conductivity λ_{ef} analysis of this oil-bearing rock model is disclosed in [12], using the averaged element method with conductivity and basic geometric parameters equal to the corresponding parameters of the model.

Studying the influence of various parameters on the heat conductivity of an inhomogeneous system, such as the oil-bearing soil, has shown the possibility of its further simplification. Oil-bearing soil can be viewed as a multicomponent system with the following interpenetrating components: a solid skeleton (volume V_s), formed by grains (1), cemented by the cementing binder (2), and pores filled with liquid V_l and a vapor-gas mixture V_{vg}. Consider heat conductivity λ_{ij} of a two-component system with interpenetrating components *i* and *j*, the heat conductivity is equal to λ_i and λ_j, correspondingly (Fig.3)

At present, the intention to find rather simple analytical expressions for the effective heat conductivity of inhomogeneous media resulted in the occurrence of numerous approximate methods for solving the problem. The Rayleigh cross-section method [12, 17], which turned out to be the most effective, consists of the following: an inhomogeneous system elementary cell, which heat conductivity is equal to the effective heat conductivity of the system as a whole, is divided by auxiliary infinitely thin surfaces, some of which are isopotential surfaces (isotherms), and others are impermeable for streamlines (adiabats). Such a division allows localizing the initial potential field, significantly simplifying the problem solving. It is possible to choose a combination of cell division by two types of planes, wherein the obtained effective heat conductivity will slightly differ from the true one.

As shown in [12], for a combined method of an elementary cell division, heat conductivity of such a binary system can be derived from the formula:

$$\frac{\lambda_{ij}}{\lambda_i} = \frac{C^2 + v_{ij}C(1-C)}{v_{ij}C(1-C)+(1-C+C^2)} + v_{ij}\frac{C(1-C)+v_{ij}(1-C)}{C(1-C)+v_{ij}(1-C+C^{2)}}, \quad (1)$$

where $v_{ij} = \lambda_j/\lambda_i$; $m_i = V_i/(V_i + V_j)$; $m_j = V_j/(V_i + V_j)$; $m_i + m_j = 1$; $C = C(m_j)$.

Parameter $C = \Delta/L$ – relative size of the component «beam» *i* in the elementary cell (Fig.3), is derived from the solution of the cubic equation

$$2C^3 - 3C^2 + 1 = m_j \quad (2)$$

and can be found according to the formula

$$C = 0.5 - \cos\left(\frac{\arccos(2m_j - 1) + \pi}{3}\right). \quad (3)$$

With a high degree of approximation, one can determine heat conductivity of a multicomponent system, by sequential reducing it to a two-component system. It was experimentally proved

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that the heat conductivity of moisture-containing materials depends on the pattern of liquid distribution in the pore space. The wetting contact angle, formed at the boundary of the solid body, liquid, and gas, usually serves as surface wetting characteristic. The heat conductivity of the same material with the same liquid content can differ by several times depending on the pattern of liquid distribution in the material [20, 22]. In the case when a granular, weakly bounded system is considered, and heat conductivity is greatly influenced by the contact thermal resistance between grains, it is feasible, at the first stage, to calculate the solid skeleton heat conductivity, taking into account wetting by liquid and the formation of liquid jackets at the contact points of grains. At the second stage, heat conductivity of the entire moistened granular system is calculated according to formulas (1)-(3), wherein heat conductivity of the vapor-gas mixture $\lambda_j = \lambda_g + \lambda_s$ in the pore space is equal to the sum of the heat conductivity of gas λ_g and the heat conductivity λ_s, caused by diffusive vapor transfer in the pore space under a pressure P and temperature T. The value of λ_s is derived from the formula [12]

$$\lambda_s = \frac{DM}{\mu RT} \cdot \frac{P}{P - P_s} \cdot \frac{dP}{dT} r , \tag{4}$$

where the diffusion resistance coefficient $\mu = D/D_p$ is equal to the ratio between the vapor diffusion coefficients with the molar mass M in air D and in the porous body D_p, R – universal gas constant, P_s – partial vapor pressure at given temperature, and r – heat of vaporization.

To calculate the diffusion resistance coefficient μ in wet porous materials based on a model of a structure with interpenetrating components of a solid frame and pore space with a liquid, the following formula can be recommended, showing good agreement with experimental data for both granular materials and porous systems with interpenetrating components:

$$\mu = 1 + \frac{C}{(1 - C)^2} . \tag{5}$$

Thus, to calculate heat conductivity of oil-bearing soils, the method of sequential reduction of a multicomponent system to a two-component system can be used, namely: at the first stage, the thermal conductivity of the pore space, containing liquid and vapor-gas mixture is derived from formulas (1)-(5); at the second stage, heat conductivity of the entire material, represented by a system with interpenetrating components: frame – pore space, is determined via using the same formulas.

Discussion. Effectiveness of this approach can be explained by the fact that even in view of moisture content low values, by virtue of percolation phenomena in the pore space, the liquid phase can form, due to interflow of separate isolated inclusions, extended clusters and, as a result, a structure with interpenetrating components is being formed. In addition, if the thermal effect distribution at temperatures, close to the vaporization temperature of the liquid phase is considered, it will be the diffusion component λ_s that makes key contribution to the heat conductivity of the pore space and, thereby, the distributional pattern of the liquid phase in the pores is not significant.

In particular, by using the formula (1) and the Odelevski formula for a structure with isolated inclusions

$$\frac{\lambda_{ij}}{\lambda i} = 1 - \frac{m_j}{\frac{1}{1 - v_{ij}} \cdot \frac{1 - m_j}{3}} ,$$

it can be shown that for $\lambda_i >> \lambda_j$ and for $m_j < 0.3$, the divergence in the calculation results does not exceed a few percent.

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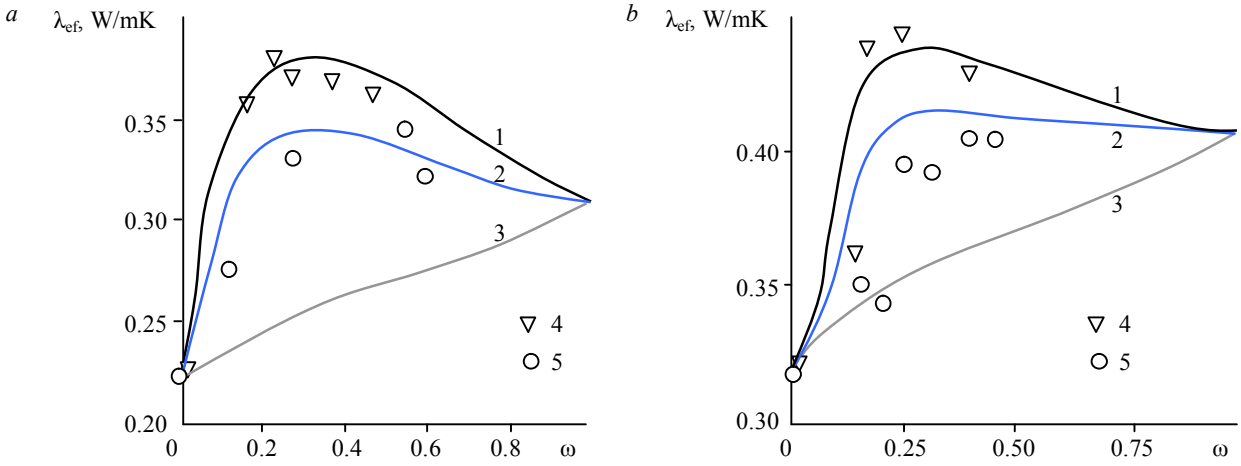


Fig.4. Dependence of the effective heat conductivity of foam concrete for $m = 0.8$ (*a*) and porous glass for $m = 0.4$ (*b*), saturated with kerosene, on moisture content

1-2 – calculation for C_9H_{20} at $T = 120$ and 110 °C; 3 – calculation for $C_{17}H_{36}$; 4,5 – the experimental results at $T = 120$ and 110 °C

To simulate heat and mass transfer in oil-bearing soils, simulation experiments were carried out, using the comparative λ-calorimeter method, on samples of foam concrete and porous glass that were saturated with kerosene. The experimental results for different temperatures are shown in Figure 4.

Due to the complex fractional composition of kerosene, the uncertainty relative to the choice of parameters characterizing the heat transfer via the diffusion of kerosene vapors have arose during performing of calculations. To assess effective heat conductivity «from above» and «from below», the calculations were carried out for the most low-boiling hydrocarbon and hydrocarbon with the highest boiling point of kerosene, whereas boiling point of kerosene is within the range of 150-300 °C. Saturated hydrocarbons (alkanes) form the largest part of the fractional composition of kerosene. For performing calculations, n-nonane C_9H_{20} ($T_{boil} = 150.8$ °C) and n-heptadecane $C_{17}H_{36}$ ($T_{boil} = 302.6$ °C) were chosen. Figure 4 shows calculation dependences for C_9H_{20} at temperatures 120 °C and 110 °C (curves 1, 2). The dependences of effective heat conductivity for $C_{17}H_{36}$, also represented therein, are merged into one curve 3, because the diffusion component value for n-heptadecane at the given temperatures is extremely low.

Each of the curves for C_9H_{20} at the appropriate temperature in combination with the curve 3 for $C_{17}H_{36}$ limits the range of values for the effective heat conductivity of samples, which includes the experimental values. Thus, it can be seen that the experimental results are in good agreement with calculation dependences obtained for the low-boiling component of kerosene C_9H_{20}, since it makes the key contribution to the diffusion component of heat transfer in the pore space.

Conclusion. One of the values characterizing the process of heat effect propagation in oil-saturated formation is effective heat conductivity λ of oil-bearing rocks, which are multicomponent inhomogeneous system. If data about structure, fractional and granulometric composition is available, the method of sequential reduction of a multicomponent system to a two-component system can be quite efficient. At the first stage, efficient heat conductivity of the structure with interpenetrating components of a solid frame and water-oil mixture is defined, at the second stage, heat conductivity of the oil-saturated soil as a whole is calculated considering diffusion component of air-vapor mixture heat conductivity. The validity of proposed methodology is confirmed by comparing the acquired calculation dependencies and experimental data.

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