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HEAT AND MASS TRANSPORT IN PETROLEUM-BEARING EARTHS

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A model for the structure of oil-bearing earth is offered together with a method for calculating its thermal conductivity with consideration of diffusion transport. Calculation resutls are presented as is an experimental determination of effective thermal conductivity of model materials and specimens of oil-bearing earths.

A major factor in increasing petroleum output is played by increasing the extractable fraction of geological reserves in oil fields. At the present time extraction methods involving thermal action on the oil stratum are being developed and put into use: heating of crack zones adjoining drillings by vapor, electrical heaters, and chemical reaction heat; forcing heating agents into the stratum — hot water, water vapor, hot gases; and creation of a moving combustion hearth within the stratum.

Study of the nonsteady-state temperature field permits determination of the size of the heated zone and the thermal utilization coefficient — the ratio of the heat accumulated in the stratum to that introduced into the stratum — and selection of a heat agent flow rate to produce desired heating conditions.

To calculate temperature fields within the plate, a knowledge of the thermophysical characteristics of oil-bearing soils is necessary. In the majority of cases measurements have been performed for concrete drillholes and locations, which allows use of such data under other conditions only with serious reservations. Oil-bearing earths are within the class of capillary porous bodies, the pores of which may contain liquid. Heat transport through moist bodies is normally accompanied by molecular transport of vapor and liquid, produced by the temperature gradient. Therefore, the majority of studies have used not true, but effective thermophysical properties, in particular, an effective thermal conductivity. The latter depends on many parameters, including the temperature gradient, pressure, relative direction of the gravitational force and thermal flux vectors, so that it is not as much a physical characteristic of the soil as a regime parameter.

Approximately 85% of oil-bearing locations contain petroleum in sedimentary deposits in the form of sands and sandstones, which consist of grains of quartz, feldspar, and mica, bound together primarily by a carbonate and clay cement. Figure 1 shows a schematic diagram of an oil-bearing soil. The grains and cement form a solid skeleton in the pores of which liquid and vapor are located. Depending on the volume of liquid within the material, the liquid either completely fills the pores (A), or a portion of the pores, spreading over the internal surface of the pore in the general case (B), while a portion of the pores remain dry (C). If we denote the total pore volume within the material by V_p, the dry pore volume by V_d, the liquid volume by V_l, and the gas volume in the pores the walls of which are wet by liquid by V_m (volume of moist pores), then

$$V_p = V_d + V_\ell + V_m. \tag{1}$$

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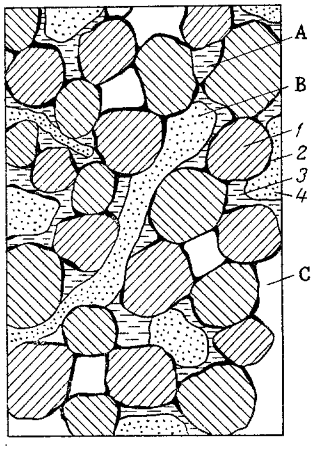

Fig. 1

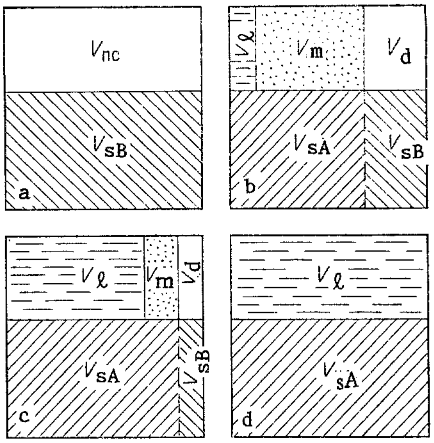

Fig. 2

Fig. 1. Schematic diagram of oil-bearing soil: 1) grain; 2) binding cement; 3) liquid; 4) liquid vapor; A) pore completely filled by liquid; B) pore filled by liquid and vapor; C) dry pore.

Fig. 2. Fractions of pore volume filled by liquid (V_l), liquid vapor (moist pores) (V_m), dry gas (V_d); volumes V_{sA}, V_{sB} occupied by components A and B of skeleton: a) $\omega = 0$, $V_m = 0$, $V_d = 1$; b) $\omega = 0.1$, $V_l = 0.1$, $V_m = 0.6$, $V_d = 0.3$; c) $\omega = 0.8$, $V_l = 0.8$, $V_m = 0.19$, $V_d = 0.01$; d) $\omega = 1.0$, $V_l = 1.0$, $V_d = V_m = 0$.

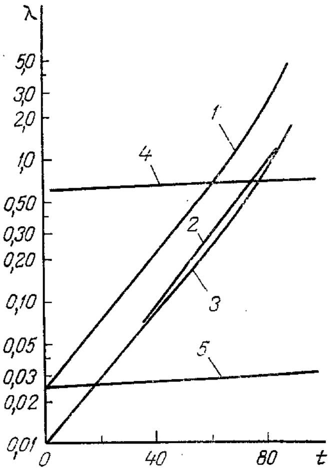

Fig. 3

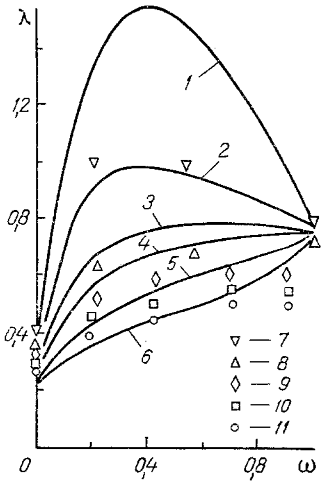

Fig. 4

Fig. 3. Diffusion component of thermal conductivity λ_d vs temperature t at normal pressure: 1) calculation with Eq. (7); 2) experimental curve found by comparing calculated and experimental thermal conductivity values; 3) calculation with Eq. (8) for $\mu = 2.8$; 4) thermal conductivity of water vs temperature; 5) thermal conductivity of air vs temperature at normal pressure; λ, W/(m•K); t, °C.

Fig. 4. Thermal conductivity of glass filters vs moisture content ω at various temperatures: 1, 2, 7) t = 94°C; 3, 8) 83; 4, 9) 67; 5, 10) 50; 6, 11) t = 26°C; 1) calculated, diffusion component λ_d defined by Eq. (7); 2-6) calculated, $\lambda_d = f(t)$ values defined by experimental dependence (curve 2, Fig. 3); 7-11) experimental curves.

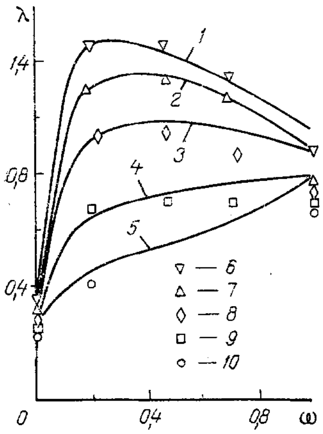

Fig. 5. Effective thermal conductivity of quartz spheres vs moisture content ω at various temperatures: 1, 6) t = 94°C; 2, 7) 83; 3, 8) 67; 4, 9) 50; 5, 10) t = 26°C; 1-5) calculated values; 6-10) experimental data.

TABLE 1. Thermal Conductivity of Oil-Bearing Materials

Specimen	Moisture content ω	Porosity Π	Thermal conductivity, W/(m·K)	
			expt., λ_{ex}	calc. λ
Sandstone	0,0	0,17	1,45	1,47
	0,5		2,10	2,16
Sandstone with clay inclusions	0,5	0,33	0,75	0,74
Oil sand	0,5	0,39	0,66	0,67

Below we will utilize the concepts of porosity Π, moisture content ω, and the parameter b, equal to the ratio of the volume V_m of moist pores to the volume $(V_p - V_l)$ of pores not occupied by liquid:

$$\Pi = V_p/V,\quad \omega = V_\ell/V_p,\quad b = V_m/(V_p - V_\ell). \tag{2}$$

Transforming from Eqs. (1), (2) we obtain volume concentrations

$$V_\ell/V = \omega\Pi,\quad V_m/V = \Pi(1-\omega)b,\quad V_d/V = \Pi(1-\omega)(1-b), \tag{3}$$

and Eq. (1) takes on the form

$$\Pi = \omega\Pi + \Pi(1-\omega)b + \Pi(1-\omega)(1-b). \tag{4}$$

Krisher [1] has experimentally established a relationship between the quantity of moist pores and moisture content for a number of solid materials, in the form of an equation

$$b = 1 - \exp(-7\omega). \tag{5}$$

As follows from Eqs. (3) and (5), with increase in moisture content the concentration V_l/V of pores completely filled by liquid increases while the concentration V_d/V of dry pores decreases. With increase in moisture content the concentration of moist pores V_m/V increases from zero to approximately $V_m/V = 0.7$ for $\omega \simeq 0.2$, then falls to zero. The variation in the fraction of various pore types with change in ω is shown in Fig 2, these changes leading to a complex dependence of thermal conductivity on moisture content, as will be shown below.

If the walls of the pores are wetted, then within the volume of air occupying these pores a partial vapor pressure gradient develops in the presence of temperature differences. Evaporation of moisture occurs at the hotter points of the wall with condensation at colder points. Then we must add heat transport by diffusing vapor λ_d upon its condensation in those portions of the pores where the temperature is lower to the heat transport due to molecular thermal conductivity λ_g. Neglecting radiant and convective thermal conductivity within the pore we will term the sum of the conductivities $\lambda_g + \lambda_d$ the thermal conductivity λ_m of a moist pore:

$$\lambda_m = \lambda_g + \lambda_d \tag{6}$$

The value of the diffusion component of the thermal conductivity is usually calculated from an expression found for an infinite slot bounded by parallel planes [1]:

$$\lambda_d = \frac{D}{R_0 T} \frac{P}{P - P'} \frac{dP'}{dT} r, \quad R_0 = \frac{R}{M}. \tag{7}$$

It was shown in [2] that in dispersed materials the diffusion transport will be reduced somewhat due to curvature of the pores. The same study also presented experimental and calculated values of the diffusion resistance coefficients for several dispersed materials $\mu = D/D'$, equal to the ratio of the diffusion coefficient D of the vapor in air to the vapor diffusion coefficient D' in the porous body. Depending on porosity, structure, and other factors this coefficient μ can vary from 2.5 to 10, i.e., the diffusion component of thermal conductivity decreases by a factor of μ times, and Eq. (6) takes on the form

$$\lambda_d = \frac{D}{\mu R_0 T} \frac{P}{P - P'} \frac{dP'}{dT} r, \quad R_0 = \frac{R}{M}. \tag{8}$$

We will now turn to selection of a model of oil-bearing ground simpler than that shown in Fig. 1. We will represent the soil as a solid skeleton of cemented grains penetrated by continuous pores, i.e., a structure with interpenetrating components [3]. The pores of the skeleton contain gas, vapor, liquid (petroleum, water, petroleum emulsion, etc.). The thermal conductivity of the grains (SiO_2) and cement ($CaCO_3$) are approximately the same — 3 W/(m•K), so that the thermal properties of the skeleton will be considered homogeneous. We note that basic information on oil-bearing soils is obtained by laboratory analysis of grains of the soil, with determination of the total porosity Π and moisture content ω. These data will be considered as a basis for calculating thermal conductivity of the oil-bearing soil. The remaining parameters necessary for the calculation depend on these basic ones and are determined from the geometric structure of the model.

Thus, the model is one of a multicomponent system with mutually penetrating components: a solid skeleton (with volume V_s) and pores filled by liquid (V_l), gas (V_g), and liquid with vapor (V_m). A method for exact calculation of the thermal conductivity of such a multicomponent system was presented in [4]. In the first approximation the calculation can be performed by reducing the multicomponent system to a two-component one with mutually penetrating components i and j, the thermal conductivity of which λ_{ij} is equal to [3]:

$$\begin{gathered} \lambda_{ij} = \lambda_i \left[c_j^2 + (1 - c_j)^2 \nu_{ij} + 2\nu_{ij} c_j (1 - c_j)/(\nu_{ij} c_j + 1 - c_j)\right], \\ \nu_{ij} = \lambda_j/\lambda_i, \quad m_i + m_j = 1. \end{gathered} \tag{9}$$

The parameter c_j is determined by solution of the cubic equation:

$$2c_j^3 - 3c_j^2 + 1 = m_j. \tag{10}$$

Equation (9) is the fundamental calculation expression which will be used to determine thermal conductivity for various components i and j in various stages of the calculation.

In accordance with this approach in the first stage we will find the thermal conductivity λ_{ml} of a binary mixture of interpenetrating components — the liquid $j = l$ and moist air $i = m$. It is then necessary to find the volume concentration of liquid m_l, equal by definition to $m_l = V_l/(V_l + V_m)$. Using Eq. (2), with the aid of identical transformations we write

$$m_\ell = \frac{\omega}{\omega + b(1 - b)}. \tag{11}$$

We perform the calculation of the thermal conductivity λ_{ml} of binary moist (ml) mixture with Eq. (9), taking

$$\nu_{m\ell} = \lambda_\ell/\lambda_m,\ c_\ell = f(m_\ell),\ \lambda_m = \lambda_g + \lambda_d \tag{12}$$

and defining the thermal conductivity λ_d by Eq. (7).

Now the structure of the moist material can be represented as a three-component one: the solid skeleton, dry and moist pores. We reduce this system to a two-component one in the form of two mixtures, one of which consists of a mixture of a portion of the solid skeleton (with volume V_{sA}) with moist pores, and the other the portion of the solid skeleton (with volume V_{sB}) with dry pores (Fig. 2). Each mixture is then a system with mutually penetrating components with effective thermal conductivities λ_{1m} and λ_{1g}, calculation of which is done with Eq. (9) in the second and third stages of the analysis.

Thus, we turn to the second stage and define the thermal conductivity λ_{1m} of the first mixture using the thermal conductivity of the solid skeleton $\lambda_1 (i = 1)$ and the moist pores $\lambda_{ml} (j = ml)$. By definition the volume concentration of the latter is equal to $V_{ml} = (V_l + V_m)/V_{sA}$; using definition (2) we obtain for m_{ml} the expression:

$$m_{m\ell} = \Pi. \tag{13}$$

In the second stage of the analysis in Eq. (9) we use the following notation:

$$i = 1,\ j = m\ell,\ \nu_{ij} = \nu_{1m} = \lambda_{m\ell}/\lambda_1,\ c_{m\ell} = f(m_{m\ell}),\ m_{m\ell} + m_1 = 1. \tag{14}$$

In the third stage we define the thermal conductivity λ_{1g} of a mixture of solid skeleton ($i = 1$) and dry gas ($j = g$), the volume content of which is equal to $m_g = V_d/V_{sB} = \Pi$. In Eq. (9) we then use the values:

$$i = 1,\ j = g,\ \lambda_{ij} = \lambda_{1g},\ \nu_{1g} = \lambda_g/\lambda_1,\ c = f(\Pi). \tag{15}$$

The fourth and final stage consists of using Eq. (9) to calculate the thermal conductivity λ of a binary system with interpenetrating components having thermal conductivities λ_{1m} and λ_{1g}, with values

$$i = 1_g,\ j = 1m,\ \nu_{ij} = \nu = \lambda_{1m}/\lambda_{1g},\ c = f(m_{1m}), \tag{16}$$

The volume concentration of component j is equal to

$$m_{1m} = (V_\ell + V_m + V_{sA})/V = \omega + b(1 - \omega). \tag{17}$$

Comparison of results of calculations with the proposed method and experiment reveals that use of Eq. (7) for the diffusion component of the thermal conductivity leads to elevated values for the effective thermal conductivity of the soil over the entire range of variation of moisture content ω, aside from the limits of completely dry $\omega = 0$ and completely saturated $\omega = 1$ material (curve 1, Fig. 4).

The proposed model and calculation method together with experimental results were used to solve the converse problem: the temperature dependence of the diffusion component of thermal conductivity was found: $\lambda_d = f(t)$. The experimental data were obtained for several model materials simulating oil-bearing soils: glass filters, and pored masses of quartz spheres. Figure 3 shows the dependence of the diffusion component of thermal conductivity λ_d on temperature t. As is evident from the figure, the divergence between curves 1 and 2 reaches ∿ 100%, while curves 2 and 3 practically coincide. Below, the function λ_d, curve 2, will be used to calculate the effective thermal conductivity of the grainy material — quartz spheres at various temperatures and moisture contents. A comparison of calculated and experimentally determined thermal conductivity values is presented in Figs. 4 and 5, with differences not exceeding ∿10%. Results of a comparison for oil-bearing soils are presented in Table 1.

As is evident from Figs. 4 and 5, the dependence of effective thermal conductivity of the model materials on moisture content for temperatures below approximately 60°C is monotonic in character, increasing with increase in moisture content, with limiting values of the effective thermal conductivity corresponding to dry $\omega = 0$ and totally saturated $\omega = 1$ materials. At temperatures above 60°C the curves have a maximum, more clearly expressed the higher the temperature. This character of the dependence can be explained by the fact that at temperatures below 60°C the thermal conductivity of moist pores is less than that of the liquid (curve 4, Fig. 3), so that the major contribution to effective thermal conductivity is produced by the liquid, the volume of which increases with increase in moisture content. At temperatures above 60°C the thermal conductivity of moist pores λ_m becomes greater than that of the liquid and now produces a significant contribution to the effective thermal conductivity of the material. It was noted above that the volume of pores V_m having a thermal conductivity λ_m (moist pores) initially increases with moisture content, reaches a maximum, then begins to decrease (see Fig. 2). Therefore, the dependence of the effective thermal conductivity of the moist material on moisture content is of an extremal character. Thus, to estimate the thermal conductivity of moisture-bearing materials such as soils and oil-bearing strata one can use a simple model. If it is necessary to refine the effect of individual parameters (grain diameter, granulometric composition, etc.) on effective thermal conductivity, a more complex model of a bound polydispersed medium must be created.

Example. Calculation of a glass filter with water at a temperature of t = 94°C, filter porosity $\Pi = 0.54$, moisture content 50% ($\omega = 0.5$).

From handbook data [5] at a temperature of t = 94°C the thermal conductivity of glass is equal to 0.90; that of water, 0.68; and air, 0.04 W/(m·K).

Stage I. We use Eq. (9) to determine the thermal conductivity λ_{ml} of a binary system of moist air $i = m$ and liquid $j = l$, $\lambda_l = 0.68$ W/(m·K). We find the thermal conductivity of the first component with Eq. (6), in which $\lambda_g = 0.04$ W/(m·K) and $\lambda_d = 2.00$ W/(m·K), and use curve 3 (Fig. 3) to find $\lambda_m = 0.04 + 2.00 = 2.04$ W/(m·K). Then from Eq. (5) with the known moisture content $\omega = 0.5$ we find $b = 0.96$ and use Eq. (11) to calculate the volume concentration $m_l = 0.5/[0.5 + 0.96(1-0.5)] = 0.51$. With Eqs. (9), (10), (12) we obtain $\nu_{ml} = 0.68/2.04 = 0.33$, $c_l = 0.49$, $\lambda_{ml} = 2.04[0.49^2 + (1-0.49)^2 \cdot 0.33 + 2 \cdot 0.33 \cdot 0.49(1-0.49)/(0.33 \cdot 0.49 + 1-0.49)] = 1.18$ W/(m·K).

Stage II. We determine the thermal conductivity λ_{1m} of a binary mixture consisting of the solid skeleton $i = 1$, $\lambda_1 = 0.90$ W/(m·K) and the component $j = ml$, $\lambda_{ml} = 1.18$ W/(m·K) with Eqs. (9)-(11), (13), (14) $\nu_{1m} = 1.18/0.9 = 1.31$, $c_{ml} = 0.47$, $\lambda_{1m} = 0.90[0.47^2 + (1-0.47)^2 \cdot 1.31 + 2 \cdot 1.31 \cdot 0.47(1-0.47)/(1.31-0.47 + 1-0.47)] = 1.04$ W/(m·K).

Stage III. We calculate the thermal conductivity λ_{1g} of a binary mixture consisting of the solid skeleton $i = 1$, $\lambda_1 = 0.90$ W/(m·K) and the dry gas $j = g$, $\lambda_g = 0.04$ W/(m·K), with Eqs. (9), (10), (15) $\nu_{1g} = 0.04/0.09 = 0.04$, $c_g = 0.47$, $\lambda_{1g} = 0.90[0.47^2 + (1-0.47)^2 \cdot 0.04 + 2 \cdot 0.04 \cdot 0.47(1-0.47)/(0.04 \times 0.47 + 1-0.47)] = 0.22$ W/(m·K).

Stage IV. We calculate the effective thermal conductivity of a binary mixture consisting of a first component $i = 1m$, $\lambda_{1m} = 0.22$ W/(m·K) and a second component $j = 1m$, $\lambda_{1m} = 1.04$ W/(m·K) and use Eqs. (9), (10), (17), with the volume concentration of the second component defined by Eq. (16), $m_{1m} = 0.5 + 0.96(1-0.5) = 0.98$, $\nu = 1.04/0.22 = 4.73$, $c = 0.08$, $\lambda = 0.22[0.08^2 + (1-0.08)^2 \cdot 4.73 + 2 \cdot 4.73 \cdot 0.08(1-0.08)/4.73 \cdot 0.08 + 1-0.08)] = 1.00$ W/(m·K).

For comparison, the experimental value of thermal conductivity of a moist glass filter at t = 94°C with moisture content $\omega = 0.5$ is $\lambda_{ex} = 0.98$ W/(m·K). The divergence between these values comprises $(\Delta\lambda/\lambda)\% = (0.98-1.00) \cdot 100/0.98 \simeq -2\%$.

NOTATION

V, unit volume of material; V_p, pore volume in material; V_d, dry pore volume; V_l, liquid volume; V_m, moist pore volume; V_s, skeleton volume; Π, porosity; ω, moisture content; b, parameter describing quantity of moist pores; λ_1, λ_g, λ_d, λ_m, thermal conductivities of solid skeleton, gas, diffusion component, and moist pore, W/(m·K); D, D', diffusion coefficients for vapor and air in smooth slot and porous material, m^2/sec; R, universal gas constant, J/(mole·K); T, absolute temperature, K; P, total pressure of gas mixture; P', partial pressure of liquid vapor, N/m^2; r, heat of vapor formation, kJ/kg; molecular mass, kg/mole; λ_{ij}, thermal conductivity of binary mixture of components i and j, W/(m·K); m_i, m_j, volume concentrations of components i and j; c_j, parameter dependent on volume concentration of component j.

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THE GENERALITY OF EQUATIONS FOR MIXED-CONVECTIVE HEAT TRANSFER TO LIQUIDS AT SUPERCRITICAL PRESSURE IN VERTICAL PIPES

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UDC 536.24

Using experimental data for helium at supercritical pressure which were obtained for ascending and descending flow in a vertical pipe, we verified the validity of a number of known equations for mixed-convective heat transfer.

Several equations are being recommended today for calculating mixed-convective heat transfer to liquids at supercritical pressure in vertical pipes; these equations are essentially based on experimental data obtained for water and carbon dioxide:

for descending flow [1]

$$\mathrm{Nu} = \mathrm{Nu}_c f(K), \tag{1}$$

where $\mathrm{Nu}_c = \mathrm{Nu}_0 (\bar{c}_p/c_{p\ell})^n (\rho_w/\rho_\ell)^{0.3}$ [2]; $f(K) = 1$ for $K = (1 - \rho_w/\rho_\ell)\,\mathrm{Gr}/\mathrm{Re}^2 < 0.15$, $f(K) = 2.75 K^{0.46}$ for $0.15 < K < 6$,

for ascending and descending flow in the region $\mathrm{Gr}/\mathrm{Re}^2 < 0.6$ [3]

$$\mathrm{Nu}_c = \frac{\mathrm{Re}\,\mathrm{Pr}\,\xi_1/8}{1 + 12.7\sqrt{\xi_1/8}\,\{[\mathrm{Pr}^*\,\rho_\ell/\rho_1 (1 + K)]^{0.66} - 1 - 0.1 K^2\}}, \tag{2}$$

where ξ_1, Pr^*, ρ_1 and K are the parameters defined in [3],

for ascending flow [4]

$$\mathrm{Nu} = \mathrm{Nu}_c f(K), \tag{3}$$

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