NOTATION

ρ is mass concentration, kg/m^3; t is time; x is the coordinate along the Ox-axis, m; D is the diffusion coefficient, m^2/sec; ℓ is the coordinate of the moving boundary, m; n is the number of mixture components; G is the vapor flux, kg/(m^2·sec); T is temperature, K; k is Boltzmann's constant, $k = 1.38 \cdot 10^{-16}$ J/deg; P is pressure, Pa; m is the molecular weight, kg; D'_{ij} is the binary diffusion coefficient in the gas phase, m^2/sec; L is the coordinate of the mouth of the capillary, m; γ is the activity coefficient; subscript 0 is for the initial moment of time; superscript 0 is for the pure component; s refers to saturated vapor; n + 1 refers to the external gas.

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FEATURES OF PERIODIC TEMPERATURE PROFILES IN FILTRATING CAPILLARY POROUS MEDIA

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The behavior of temperature profiles is examined in filtrating capillary porous media which are subjected to periodic heating. Reasons are described for amplitude shift in the temperature oscillations versus the fluid filtration rate.

The presence of a filtration flow in capillary porous media which are subjected to periodic heating changes their spatial and time-dependent temperature profiles. Thus, a previously unknown relationship was established experimentally [1] between increased heat and mass exchange rates with the earth's surface and increased amplitude of temperature oscillations with depth. This relationship was confirmed by investigations on filtering samples of reservoir rock by imposing periodic heat on one of its ends and measuring the periodic components of the temperature near the other [2]. Here in particular it was found that the amplitude of the temperature oscillations depended on the dimensionless filtration rate in a complex fashion. Thus, if the filtration and heat flows are in the same direction, the amplitude of the temperature oscillations will have a maximum at a given point in the porous medium, which maximum depends on the frequency of the imposed heat flow.

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Our goal is to analyze the previously discovered features of the periodic temperature profiles and the reasons why they arise.

An available solution for the propagation of heat and filtration flows in capillary porous media [2] shows that, in the absence of filtration, the amplitude of the temperature wave decays exponentially as it propagates along the X-axis, but its phase shift grows. If there is mass transport (in the approximation of a uniform temperature with a solid matrix), the temperature profile changes in the capillary porous medium. The filtering fluid causes an additional (convective) thermal energy transport.

Under conditions of an imposed periodic heat flow, temperature oscillations occur in the moving fluid. If we only consider convective heat transfer, then [2] we can obtain an expression for the dimensionless temperature of the moving fluid in the following form

$$\Theta = A^{*}\cos\omega\left[\mathrm{Fo} - \frac{\Lambda}{\mathrm{Pe}\,A}X\right]. \tag{1}$$

It follows from [1] that the amplitude of the temperature oscillations in the flow do not depend on the coordinate X; that is, the oscillations are not attenuated (in the one-dimensional approximation).

The phase shift decreases as Pe increases. Increasing the filtration rate of the fluid in the porous medium (in the same direction as the heat flow) decreases the relaxation of the temperature oscillations in the medium and increases the oscillation amplitude compared to oscillations in an immobile medium. At the same time, increasing the fluid velocity makes it such that the fluid cannot be heated, and this leads to a decrease in the amplitude of the temperature oscillations in a saturated porous medium, when the filtration is in the direction of the heat flow. These opposing tendencies lead to an extremum in the curve of the temperature oscillation amplitude versus the dimensionless filtration velocity Pe. This behavior has been confirmed experimentally [2].

Table 1 shows results calculated by solving the problem [2] for values of Pe, which correspond to the maximum amplitude A^{*}_{max} for various frequencies, the values of A^{*}_{max} itself, and also the ratio of A^{*}_{max} to A^{*}_{0}, the amplitude in the absence of filtration. The table shows that the range of oscillation frequencies of the heat flow with mass transport can be divided into two regions. At low frequencies (to ω = 0.7), the maximum amplitude of temperature oscillations A^{*}_{max} is observed in the absence of fluid filtration (Pe = 0) and decreases as the filtration rate is increased. At high frequencies (starting from ω = 0.7), A^{*}_{max} occurs in the presence of mass flow (Pe > 0), and the value of Pe, which corresponds to the largest values of the variable component of the temperature, increases with increasing frequency. As ω increases, the relative growth in the magnitude of the temperature oscillations increases because of the mass transport. Thus

TABLE 1. Pe Number, Corresponding to the Largest Amplitude of Temperature Oscillations A^{*}_{max}, the Value of A^{*}_{max}, and the Ratio A^{*}_{max}/A^{*}_{0} for Various Oscillation Frequencies of the Heat Flow. Calculation Parameters [2]: Λ = 1.52; A = 1.1; R = $1\cdot10^{-3}$; C = $1\cdot10^{-3}$; X = 1; $L^{*} = 0.3\cdot10^{-3}$ m

ω	Pe	A^{*}_{max}	A^{*}_{max}/A^{*}_{0}
0,5	0,000	0,423	1,000
0,6	0,000	0,369	1,000
0,7	0,001	0,327	1,000
0,8	0,008	0,295	1,002
0,9	0,015	0,269	1,007
1,0	0,024	0,248	1,013
2,0	0,099	0,149	1,135
3,0	0,161	0,112	1,295
4,0	0,219	0,092	1,475
5,0	0,267	0,080	1,668
6,0	0,312	0,071	1,873
7,0	0,355	0,064	2,090
8,0	0,397	0,059	2,319
9,0	0,438	0,054	2,561
10,0	0,492	0,051	2,815

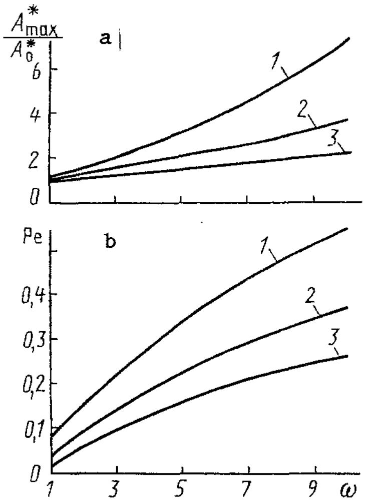

Fig. 1

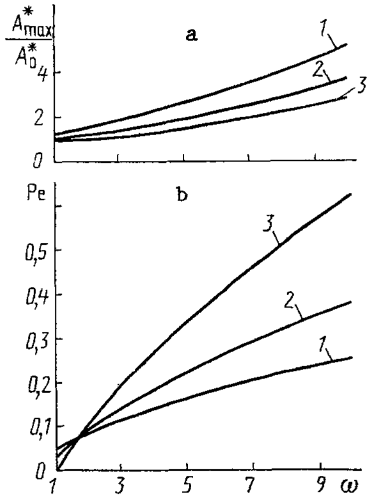

Fig. 2

Fig. 1. The ratio of the maximum amplitude of temperature oscillations A^*_{max} for Pe > 0 to the amplitude A^*_0 for Pe = 0 (a) and the value of Pe corresponding to A^*_{max} (b) versus the frequency ω of the heat flow oscillations. Thermal parameters: Λ = 1.0 for various values of A: 1) 0.5; 2) A = 1.0; 3) A = 2.0. All values are dimensionless.

Fig. 2. The ratio of the maximum amplitude of temperature oscillations A^*_{max} for Pe > 0 to the amplitude A^*_0 for Pe = 0 (a) and the value of Pe corresponding to A^*_{max} (b) versus the frequency ω of the heat flow oscillations. Thermal parameters: A = 1.0 for various values of Λ: 1) Λ = 0.5; 2) Λ = 1,0; 3) Λ = 2.0. All values are dimensionless.

while the ratio A^*_{max}/A^*_0 = 1.002 for ω = 0.8, A^*_{max}/A^*_0 reaches 2.815 for ω = 10 (for Pe = 0.492). Thus, the phenomenon of increasing the temperature oscillations in capillary porous medium subjected to periodic heating with simultaneous fluid filtration along the heat flow direction is largest in the range of high frequencies. The reason is that in this range the filtering fluid is heated faster, because the propagation rate of the temperature wave in the medium is proportional to $\sqrt{\omega}$. The temperature oscillations in the solid skeleton is strongly attenuated with increasing frequency, and the heat transfer process to a large degree is determined more by the flow of thermal energy in the moving fluid (convective transfer) than it is by conduction.

The closeness of the curves of the temperature oscillation amplitude versus filtration velocity for various frequencies at large Pe values in [2] and [3] indicates that heat transfer in this region is basically by forced convection.

The increase in the temperature oscillation amplitude due to mass transport depends on the parameters A and Λ of the porous medium, which is saturated by an immobile fluid. As A (Fig. 1) and Λ (Fig. 2) decrease, the ratio A^*_{max}/A^*_0 increases; that is, filtration in the direction of heat flow is largest when the solid skeleton of the porous medium only weakly participates in the heat transfer. The lower the value of A, the larger the velocity (Pe) for the maximum temperature oscillation amplitude (Fig. 1) and, conversely, as Λ is decreased, the magnitude of the dimensionless velocity corresponding to the maximum temperature amplitude decreases (Fig. 2).

The presence of an extremum in the curve of the temperature oscillation amplitude versus the dimensionless filtration velocity can be used to optimize the thermal and mass transfer in industrial processes [3]. The behaviors of the temperature profiles in filtrating porous media subjected to periodic heating, can also be found by using measurement techniques.

NOTATION

$X = x/L$ is the dimensionless coordinate; x is the coordinate, m; L is the thickness of the sample, m; $\theta = \lambda_0(t - t_0)/Lq_0$ is the dimensionless temperature; t is the sample temperature, K; t_0 is the temperature of the surround medium, K; λ_0 is the thermal conductivity of the standard, W/(m·K); q_0 is the amplitude of the heat flow oscillations, W/m^2; Fo is the Fourier number; Pe is the Peclet number; $\omega = \omega_0 L^2/a_0$ is the dimensionless angular frequency; ω_0 is the angular frequency of the heat flow oscillations, rad/sec; a_0 is the thermal diffusivity of the standard, m^2/sec; $\Lambda = \lambda/\lambda_0$ is the dimensionless thermal conductivity; λ is the thermal conductivity of the sample, W/(m·K); $A = a/a_0$ is the dimensionless thermal diffusivity; a is the thermal diffusivity, m^2/sec; $R = r_c\lambda_0/L$ is the dimensionless thermal resistance; r_c is the contact thermal resistance of the gap, m^2·K/W; $C = C_c h a_0/\lambda_0 L$ is the dimensionless heat capacity; C_c is the heat capacity of the contact gap, J/(m^3·K); and L^* is the characteristic dimension of the structure of the porous medium, m.

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PERMEABILITY AND PERCOLATIONAL PROPERTIES OF SEDIMENTARY ROCK

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Formulas for calculating the absolute and relative phase permeabilities of rock are obtained, taking account of the percolational properties of the pore space.

INTRODUCTION

The absolute and relative phase permeabilities are among the most important characteristics of sedimentary rock, and are determined primarily by the structure of the pore space.

Until recently, a simple model consisting of a bundle of parallel noninteracting capillaries was widely used to calculate the permeability. Considerable effort has been expended in trying to understand the factors responsible for the rock permeability and to eliminate the deficiencies of the simple capillary model. Percolation-theory concepts and methods, taking account of the coupling between different capillaries, have been of particular importance here [1-6].

In the usual formulation of the percolation-theory problem for the description of processes occurring in rock, the pore space is represented as large pores (points) and thin channels (bonds connecting the pores) [2]. The permeability in this lattice is determined basically by the thin channels; with decrease in their number, the interconnection of the pore space is disrupted and fluid filtration is impossible.

In recent years, the idea that there is no closed porosity in collector rock (at least, in terrestrial rock) [7]. Hence it follows that, with any porosity values, there is an interconnected pore space through which the flow of various fluids is possible [8]. Therefore, the filtrational properties must evidently be associated not with the geometric coupling of the pore space but with the coupling of the conducting pores.

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