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A SYSTEM OF HEAT-MASS-TRANSFER EQUATIONS FOR VAPOR

FILTRATION IN DISPERSED MEDIA

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A system of heat-mass-transfer equations describing filtration of a vapor in dispersed media is presented. The cases of "local thermal equilibrium" and temperature difference between the filtering agent and medium particles are considered.

Interest in the study of vapor filtration in dispersed media has increased recently. This is primarily due to the promise of vapor-fuel methods for increasing petroleum and gas output.

To describe the filtration process, a number of studies have proposed use of the system of equations presented in [1], which is not a totally justifiable approach. That system was obtained on the basis of the following assumptions: the change in mass content of the medium was expressed by the formula

$$dU_i = \frac{\varepsilon \sigma_i M_0}{R} \left(dP - \frac{1}{T^2} dT \right) + \frac{\varepsilon P M_0}{RT} d\sigma_i; \qquad (1)$$

the saturation of the medium by the i-th component was assumed to change insignificantly, i.e., $d\sigma_i \approx 0$; the filtering vapor was regarded as an ideal gas. Thus, according to [2], the filtration equation was linearized, i.e.,

$$\frac{\partial P}{\partial \tau} = A \operatorname{div}(\operatorname{grad} P), \qquad (2)$$

where

$$A = \left(\frac{k_p}{c_p \rho_b} - \frac{\varepsilon a_m}{c_p} \delta_p \right). \qquad (3)$$

The total flux of the liquid component was defined as

$$j_b = -a_m \rho_b \nabla U - a_m^T \rho_b \nabla T - k_p \nabla P, \tag{4}$$

where the first term on the right of Eq. (4) determines the liquid transfer due to change in moisture content, the second, the transfer due to temperature change, and the third, the liquid transfer in gaseous form.

Inasmuch as

$$U = \frac{\sum\limits_{i=1}^{n} \rho_i \varepsilon \sigma_i}{\rho_T} \tag{5}$$

and for dispersed media

$$\sum\limits_{i=1}^{n} \sigma_i = 1, \tag{6}$$

the change in mass content occurs primarily due to change in the densities of the gases being filtered, and not change in their saturations.

But, as was demonstrated in [3], the mass of material absorbed by the medium is equal, within an uncertainty of $10^{-4}\%$, to the mass of the liquid. This indicates that even for very large changes in density of the vapor phase in the dispersed medium, with slightly changing saturations the moisture content will change insignificantly. Only dispersed media the particles of which themselves absorb condensate are an exception.

In filtration in a dispersed medium the liquid transfer in gaseous form and that due to moisture content and temperature gradients is much less than the filtration transfer. Thus, instread of Eq. (4) the flux should be specified by

$$j_b = -k_b \nabla P \tag{7}$$

under the condition that filtration obeys Darcy's law.

Thus, it is obvious that the use of the equations of [1] to describe the processes accompanying intense condensation and filtration of not only gaseous, but also liquid phases in dispersed media, the particles of which do not absorb condensate, is unjustifiable. Moreover, in [1] the intensity of phase conversion was defined by the phase conversion criterion ε_f, the value of which was specified a priori. For a regular drying regime, in which the quantity of liquid evaporated per unit time is constant, ε_f was taken equal to a constant. But for a condensation process, where the phase conversion material flux $g_b \neq \text{const}$, such an assumption is incorrect. In this case g_b must be defined from other considerations.

To describe vapor filtration in dispersed media, it is necessary to simultaneously consider filtration and heat transfer. In the case of a single component two-phase filtration, the system of equations must obviously consist of two equations of state, while the number of energy equations depends on the heat-transfer model chosen.

At the present time the most widely used model is that in which a "local thermal equilibrium" exists in multiphase filtration in a dispersed medium. Using this model, the method of [2] produces an energy equation for the two-phase flow of the following form:

$$[\varepsilon \sigma_b \rho_b c_p^b + \varepsilon \sigma_n \rho_n c_p^n] \frac{\partial T}{\partial \tau} = Q_{ex}^n + Q_{ex}^b + g_b(h_n - h_b) + \varepsilon \frac{\partial P}{\partial \tau} - [\varepsilon \sigma_b \rho_b v_b c_p^b + \varepsilon \sigma_n \rho_n v_n c_p^n] \operatorname{grad} T - \varepsilon \sigma_b v_b (1 - \alpha_b T) \operatorname{grad} P -$$

$$- \varepsilon \sigma_n \rho_n v_n \left[T \left(\frac{\partial S_{sp}^n}{\partial P} \right)_T + V_n \right] \operatorname{grad} P - \varepsilon \sigma_b (1 - \alpha_b T) \frac{\partial P}{\partial \tau} - \varepsilon \sigma_n \rho_n \left[T \left(\frac{\partial S_{sp}^n}{\partial P} \right)_T + V_n \right] \frac{\partial P}{\partial \tau} + \sigma_n \rho_n Q_n' + \sigma_b \rho_b Q_b'. \tag{8}$$

In Eq. (8) it is assumed that

$$\left[T \left(\frac{\partial S_{sp}^b}{\partial P} \right)_T + V_b \right] = (1 - \alpha_b T) V_b. \tag{9}$$

Equation (8) indicates that the total change in energy of the two-phase flow per unit volume per unit time (the left side of the equation) is equal to the external heat supplied to the flow, $Q_{ex}^n + Q_{ex}^b$, the heat of phase conversion $g_b(h_n - h_b)$, the change in potential energy of

the flow due to change in saturation and pressure (the fourth, sixth, seventh, eighth, and ninth terms on the right side), together with convective heat transfer with rate v_b and v_n (fifth term on right), and heat liberated by friction forces $(\sigma_n \rho_n Q_n' + \sigma_b \rho_b Q_b')$. In the case where the vapor phase being filtered can be considered as an ideal gas, Eq. (8) simplifies somewhat, since

$$\left[T \left(\frac{\partial S_{sp}^n}{\partial P} \right)_T + V_n \right] = 0. \tag{10}$$

For the other equations of the system, we may take the continuity equation for the vapor flow

$$\text{div} \, (\varepsilon \sigma_n v_n \rho_n) + g_b + \frac{\partial}{\partial \tau} (\varepsilon \sigma_n \rho_n) = 0, \tag{11}$$

the equation of state for the condensate

$$\rho_b = \rho_{bT_0} [1 - \alpha_b T], \tag{12}$$

the Clausius–Clapeyron equation

$$\frac{dP}{dT} = \frac{h_n - h_b}{T(V_n - V_b)} \, , \tag{13}$$

the Darcy equation for each phase

$$v_b = - \frac{k_b}{\eta_b} \, \text{grad} \, P, \quad v_n = - \frac{k_n}{\eta_n} \, \text{grad} \, P, \tag{14}$$

and the equation of state for the vapor phase, which, if the vapor can be considered an ideal gas, is written in the form

$$PV = \frac{m_n}{\mu} \, RT \tag{15}$$

or in the general case

$$PV_n = zRT, \tag{16}$$

where z is a compressibility coefficient, defined either from the equation [4]

$$\left(\frac{\partial S_{sp}^n}{\partial P} \right)_T = - \frac{R}{P} \left[z + T \left(\frac{\partial z}{\partial T} \right)_P \right], \tag{17}$$

or by calculations with the tables of [5], as was done in [6]. In Eqs. (8) and (11) the value of the phase conversion flux density can be defined with the use of chemical potentials:

$$g_b = \beta (\mu_n - \mu_b). \tag{18}$$

The question was considered in greater detail in [2]. An experimental study [7] has shown that for nonstationary filtration of a saturated vapor in a dispersed mass the main phase conversion material flux is concentrated at the boundary of the dry wet zones, so that the approximation $j_n \approx g_b$ is valid. In the wet zone the flux g_b is defined by thermal losses into the surrounding wet zone of the medium, i.e., $g_b(h_n - h_b) = Q_{pot}$.

Equations (6), (8), (11)-(15) comprise a closed system for the process of nonstationary filtration of a saturated vapor in a dispersed medium in the presence of "local thermal equilibrium."

Recently, the literature (e.g., [8]) has proposed that "local thermal equilibrium" may be disrupted in filtration in dispersed media, i.e., a significant temperature difference between the agent being filtered and the particles of the medium is possible.

To describe such processes, we will use the following assumptions: the liquid and gas phases being filtered are in thermal equilibrium, and heat exchange between the two-phase flow and the particles of the dispersed medium occurs by Newton's law:

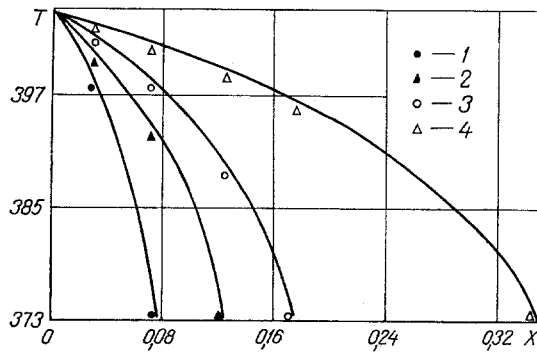$$Q_{ex}^n + Q_{ex}^b = - \alpha_n (T_n - T_r). \tag{19}$$

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Fig. 1. Comparison of calculated (solid
curves) and experimental (1-4) data on
temperature distribution over height of
a dispersed layer for filtration of satu-
rated water vapor at various positions
X = H of the phase transition boundary:
1) X = 0.075 m; 2) 0.125; 3) 0.175; 4)
0.350. T in °K.

In this case the energy equation for the two-phase flow will have the form of Eq. (8), but
with T replaced by T_n and the first term on the right in the form $\alpha_n(T_n-T_T)$.

The energy equation for the particles of the dispersed medium will be written in the
form

$$(1-\varepsilon)\,\rho_T c_T\,\frac{\partial T_T}{\partial \tau} = \lambda_T(1-\varepsilon)\,\mathrm{div}\,(\mathrm{grad}\,T_T) + \alpha_n\,(T_n - T_T) - Q_{\mathrm{pot}}.$$

(20)

If we neglect the quantity of heat expended in changing the potential energy of the two-
phase flow, then the flux density of phase conversion material will be given by

$$g_b = \frac{\alpha_n\,(T_n - T_T)}{h_n - h_b}.$$

(21)

Such an assumption is valid for processes in which the pressure changes slowly with time and
grad P has a low value, but a marked difference exists between the temperatures T_n and T_T.

Thus, in studying nonstationary filtration of a vapor in dispersed media in the absence
of "local thermal equilibrium" Eq. (20) must be included in the system of heat—mass-transfer
equations, and a correction included in Eq. (8) in accordance with the above. The remaining
equations, Eqs. (6), (11)-(15), are unchanged. To verify the validity of the assumptions
made above in deriving the system of equations, a calculation was performed for the case of
filtration of saturated water vapor through a layer of quartz sand for constant vapor pressure
at the input to the layer. The system of Eqs. (6), (8), (11)-(15) was solved by the method
of successive interchange of stationary states. It was assumed that heat liberation due to
friction was small in comparison to the heat of phase conversion. For the wet zone it was
assumed that all phase transition heat was applied to compensation of the heat losses into
the surrounding medium, the flux density of which Q_{flux} = const.

A comparison of calculated and experimental data is shown in Fig. 1, from which it is
evident that agreement is satisfactory (indicating the validity of the assumptions made).

It should be noted that the system of equations obtained is also more suitable than that
of [1] for description of the processes of high intensity drying, accompanied by significant
mass transfer related to multistage conversion of liquid into vapor in the evaporation zone
and vapor into condensate in the somewhat removed wet zone.

NOTATION

T, temperature; P, pressure; σ_i, saturation of medium by i-th phase; ε, porosity; U_i,
mass content of i-th phase; M_0, mass of vapor; k_p, liquid filtration transfer coefficient;
c_p, humid air capacity coefficient of dispersed medium; ρ_b, liquid density; δ_p, relative

liquid filtration coefficient; a_m, diffusion coefficient for moist bodies; a_m^T, thermal diffusion coefficient; $k_{b,n}$ filtration coefficient; h_n, specific enthalpy of vapor; h_b, specific enthalpy of liquid; S_{sp}, specific entropy of vapor; S_{sp}^b, specific entropy of liquid; c_p^n, specific heat of vapor; c_p^b, specific heat of liquid; σ_n, σ_b, saturation by vapor and liquid; V_n, V_b, specific volumes of vapor and liquid; ρ_n, vapor density; η_n, η_b, viscosity of vapor and liquid; k_n, k_b, permeability coefficients of vapor and liquid; μ, molecular weight of liquid; μ_n, μ_b, chemical potentials in vapor and liquid phases; β, mass transfer coefficient; α_n, heat-transfer coefficient.

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DENSITY OF ADSORBED WATER IN DISPERSE SYSTEMS

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On the basis of the existence of the effect of changing density of a dispersing medium and taking into account the crystal lattice deformation of the solid phase, the article determines the density of water adsorbed on kaolinite.

Among the wide-ranging investigations concerning the study of adsorbed water, there are relatively few works in which an attempt was made to determine the density of such water. This situation is due to the fact that the existing methods of experimentally measuring the density of adsorbed water, based on the use of various dispersing media (gases, liquids), did not take into account some phenomena (effects) originating in the surface layers of the disperse system. Among these effects are:

a) a change in the density of the dispersing medium under the effect of the solid phase and of the adsorbed water;

b) crystal lattice deformation of the solid phase under the effect of the water molecules and of the molecules of the dispersing medium;

c) the influence of the molecules of the dispersing medium on the structure of the adsorbed water.

We measured these effects and took them into account when devising a method of determining the density of adsorbed water.

The object of investigation was Glukhovetsk kaolin in its natural form.