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HEAT AND MASS TRANSFER IN THE CONDENSATION REGION OF VAPOR FILTERING IN A DISPERSE LAYER

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A calculation of the process of water-vapor condensation as it filters through a disperse medium is given. Relations are obtained for determining the rate of growth and the magnitude of the heated zone.

Recently, there has been growing interest in the investigation of vapor condensation in the course of filtration in disperse media, in connection with the prospects for the use of vapor—thermal methods of intensifying petroleum and gas extraction. Various empirical and semiempirical relations for the calculation of the magnitude and growth rate of the heated (vapor-treated) zone of a petroleum deposit in the form of a disperse sphere have been widely used in practice.

In the present work, on the basis of physical and mathematical models of the vapor-condensation process in a disperse medium [1, 2], an attempt is made to obtain more general analytical relations for calculating the heating dynamics of vapor-treated petroleum deposits. The following assumptions are made: that filtration is one-dimensional; that the condensation region is of depth ΔH; that grad $T = 0$ and grad $P = 0$ over the whole region; hat there are no heat losses; that the vapor flow rate at the inlet to the layer is constant and equal to G_v. Thus, the energy equation of the system [2], written for the condensation zone, takes the form

$$[(1-\varepsilon)\rho_\mathrm{c}c_p^\mathrm{c}+\varepsilon\sigma_\mathrm{w}\rho_\mathrm{w}c_p^\mathrm{w}+\varepsilon\sigma_\mathrm{v}\rho_\mathrm{v}c_p^\mathrm{v}]\frac{dT}{d\tau}=g_\mathrm{p}r_\mathrm{p}-[\varepsilon\sigma_\mathrm{v}\rho_\mathrm{v}\psi_\mathrm{v}+\varepsilon\sigma_\mathrm{w}\rho_\mathrm{w}\psi_\mathrm{w}]\frac{dP}{d\tau}, \qquad (1)$$

where

$$\psi_\mathrm{v}=T\left(\frac{\partial S_\mathrm{v}}{\partial P}\right)_T;\quad \psi_\mathrm{w}=T\left(\frac{\partial S_\mathrm{w}}{\partial P}\right)_T.$$

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The left-hand side of Eq. (1) defines the amount of heat consumed in heating unit volume of disperse medium and the vapor–water mixture which it includes. The right-hand side characterizes the heat of phase transition liberated $g_p r_p$ and the heat on account of change in vapor and condensate pressure.

Using the thermodynamic relation

$$\left(\frac{\partial S_{sp}}{\partial P}\right)_T = -\left(\frac{\partial V_{sp}}{\partial T}\right)_P \tag{2}$$

and the data of [3], values of the coefficients ψ_w and ψ_v may be obtained. Calculation shows that, in the pressure range 0.1–10 MPa, ψ_w varies from $-0.293\cdot10^{-3}$ to $-3.28\cdot10^{-3}$ J·m²/kg·N and ψ_v from -1.819 to -0.088 J·m²/kg·N.

Using the results obtained for ψ_w and ψ_v, the amount of heat liberated on isothermal increase in the pressure of the vapor–water mixture may be estimated. It is expedient to use the relation

$$\frac{\varepsilon\sigma_w\rho_v\psi_v + \varepsilon\sigma_w\rho_w\psi_w}{(1-\varepsilon)\rho_c c_p^c + \varepsilon\sigma_w\rho_w c_p^w}\,\frac{dP}{dT} = \zeta. \tag{3}$$

In Eq. (3), the heat consumed in heating the vapor phase of the mixture is neglected, since $\psi_v \ll \rho_w$ over a considerable range of pressure variation (0.1–5 MPa). Using the Clapeyron–Clausius equation, Eq. (3) is brought to the form

$$\frac{\varepsilon\sigma_w\rho_v\psi_v + \varepsilon\sigma_w\rho_w\psi_w}{(1-\varepsilon)\rho_c c_p^c + \varepsilon\sigma_w\rho_w c_p^w}\,\frac{r_p}{T(V_v - V_w)} = \zeta. \tag{4}$$

Calculation of ζ shows that $\zeta = 5\cdot10^{-4}$ for T = 373°K and $\zeta = 3\cdot10^{-2}$ for T = 536°K. Thus, in the given range of temperature variation for the saturated water vapor, the heat liberated on increasing the pressure may be neglected, with an error of no more than 3%. Finally, Eq. (1) may be written in the form

$$[(1-\varepsilon)\rho_c c_p^c + \varepsilon\sigma_w\rho_w c_p^w]\,\frac{dT}{d\tau} = g_p r_p. \tag{5}$$

It follows from the continuity equation for the condensate flux that

$$\varepsilon\rho_w\,\frac{d\sigma_w}{d\tau} = g_w. \tag{6}$$

Since, according to the assumptions made, there are no heat losses, it follows that

$$\frac{d}{d\tau}\,(\varepsilon\rho_v\sigma_v) = -g_p + j_v. \tag{7}$$

To simplify the calculations, the Clapeyron–Mendeleev equation may be used as the equation of state:

$$\rho_v = \mu P/RT. \tag{8}$$

Together with the relations

$$P = P_0\exp\left(-\frac{\mu r_p}{RT}\right) \tag{9}$$

and

$$\sigma_v + \sigma_w = 1 \tag{10}$$

Eqs. (5)-(8) form a closed system describing the heat and mass transfer in the condensation region. The magnitude of the phase-transition matter flux is found from the solution of this system:

$$g_p = \frac{\rho_w}{\rho_w - \rho_v}\left\{j_v - \varepsilon(1-\sigma_w)\,\frac{d\rho_v}{d\tau}\right\}, \tag{11}$$

where σ_w is the saturation of the medium with condensate,

$$\sigma_w = \frac{j_v\tau - \varepsilon\rho_w}{\varepsilon(\rho_w - \rho_v)} \tag{12}$$

Using Eqs. (5)-(12), the temperature dependence of the heating time of the condensate zone may be obtained:

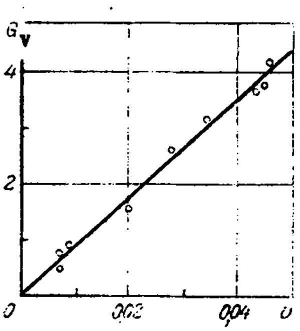

Fig. 1. Comparison of the calculated (straight line) and experimental (points) data on the velocity of isotherm propagation in the nonsteady filtration of saturated water vapor in a quartz-sand layer with $d_{equ} = 0.25$ mm as a function of the vapor flow rate at the inlet to the layer.

$$\tau = C_1 \exp\left(\frac{c_p^w}{r_p} T\right) - \frac{(1-\varepsilon)\rho_c c_p^c}{j_v c_p^w} \exp\left(-\frac{c_p^w T}{r_p}\right) + \frac{\varepsilon\mu P_0}{j_v RT} \times \exp\left\{-\left(\frac{c_p^w T}{r_p} + \frac{\mu r_p}{RT}\right)\right\} + \int \frac{\varepsilon\mu P_0 c_p^w}{j_v RT r_p} \exp\left\{-\left(\frac{c_p^w T}{r_p} + \frac{\mu r_p}{RT}\right)\right\} dT. \tag{13}$$

Taking into account that

$$g_p \approx j_v = \frac{G_v}{\Delta H} \tag{14}$$

results in considerable simplification of Eq. (13). The vapor reaching element ΔH condenses only partially; however, the amount of vapor condensing is considerably larger than the amount of uncondensed vapor. This follows from the relation

$$\frac{[(1-\varepsilon)\rho_c c_p^c + \varepsilon\varphi_w \rho_w c_p^w]\, dT}{r_p (1-\varphi_w)\, \varepsilon\, d\rho_v} = \delta \gg 1, \tag{15}$$

from which it follows, taking account of Eqs. (8) and (9), that $\delta = 62$ for $T = 373$°K and $\delta = 23$ for $T = 400$°K, i.e., $\delta \gg 1$. It follows from Eqs. (5) and (6), taking account of Eq. (15), that

$$T = \frac{\varepsilon r_p}{c_p^w} \ln\left|\frac{(1-\varepsilon)\rho_c c_p^c + \rho_w c_p^w\left(\sigma_0 + \dfrac{G_v \tau_0}{\varepsilon\rho_w \Delta H}\right)}{(1-\varepsilon)\rho_c c_p^c + \rho_w c_p^w \sigma_0}\right| + T_0, \tag{16}$$

$$\sigma_w = \sigma_0 + \frac{j_v \tau_0}{\varepsilon\rho_w}. \tag{17}$$

The rate of propagation of the isotherm is determined from Eq. (16):

$$\frac{\Delta H}{\tau_0} = \frac{c_p^w G_v}{\varepsilon(1-\varepsilon)\rho_c c_p^c + \rho_w c_p^w \sigma_0} \, \frac{1}{\exp\left[\dfrac{c_p^w}{r_p}(T - T_0)\right] - 1}, \tag{18}$$

where τ_0 is the heating time of element ΔH to temperature T.

For saturated vapor with P > 0.5 MPa, a correction factor Z, characterizing the deviation of the vapor properties from an ideal gas, must be introduced in Eq. (8), the equation of state.

As shown by calculation of δ, the amount of uncondensed vapor is no more than 10% of the vapor which condensed in this case at pressures up to 2 MPa. Thus, up to an initial pressure in the disperse medium of 2 MPa, it may be assumed that $g_p \approx j_v$ with an error of around 10%.

In Fig. 1, results of calculation from Eq. (18) for the velocity of isotherm propagation are compared with experimental data. As is evident from Fig. 1, the discrepancy is no more than 2-5%, which indicates that the assumptions made above are valid. The use of Eq. (18) with constant G_v offers the possibility of determining the heating of the zone H in the form

$$H = \frac{\Delta H}{\tau_0}\tau, \tag{19}$$

where $\Delta H/\tau_0$ is the velocity of isotherm propagation.

NOTATION

P, pressure, N/m²; T, temperature, °K; σ_v, vapor saturation of medium, m³/m³; σ_w, saturation of medium with water; r_p, heat of phase transition, J/kg; ε, porosity; c_p^c, specific heat of sand, J/kg·K; c_p^w, specific heat of medium, J/kg·K; c_p^v, specific heat of vapor; G_v, vapor flow rate, kg/m²·sec; ρ_v, vapor density, kg/m³; ρ_w, water density, kg/m³; v_v, specific volume of vapor, m^{-3}; g_p, flux-density of phase-transition material; kg/m³·sec; τ, time, sec; μ, molecular weight; τ_0, heating time of condensate up to T; v, rate of growth of heated zone, m/sec.

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A THEORY OF BINARY LIQUID MIXTURE EVAPORATION FROM CAPILLARIES

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A theory of binary liquid mixture evaporation from capillaries is developed. Expressions defining mixture composition and the law of meniscus motion during evaporation are obtained.

We will consider isothermal evaporation of binary mixtures from capillaries. Because of the brevity of the diffusion relaxation time in the gas phase as compared to the evaporation time, the component vapor flows will be regarded as steady state for any position of the moving meniscus. It is assumed that molecules of each mixture component can experience a phase transition on the liquid–gas boundary. The gas mixture into which evaporation occurs consists of molecules of the volatile mixture components and molecules of a gas which is chemically inert with respect to the components. The liquid surface is assumed impermeable to vapor–gas mixture molecules.

In the general case, during evaporation of liquid mixtures there is a constant change in mixture composition due to the differing volatilities of the components. We will assume that the volumes occupied by the components are additive:

$$V = \frac{M_1}{\rho_1^0} + \frac{M_2}{\rho_2^0}. \tag{1}$$

The content of the first component is defined by the law of conservation of mass in the form

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