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; that there are no heat losses; that the vapor flow rate at the inlet to the layer is constant and equal to Gv. Thus, the energy equation of the system [2], written for the condensation zone, takes the form

\[
\left(1 - \varepsilon \right) \rho_v c_v^P \frac{dT}{dT} + \varepsilon \rho_v c_v^P \frac{dT}{dT} = \varepsilon \rho_v \left( \frac{dS_v}{dP} \right)_T \frac{dP}{dT} - \left( \frac{dP}{dt} \right) \psi_v - \varepsilon \rho_c \psi_w \frac{dP}{dT},
\]

(1)

where

\[
\psi_v = T \left( \frac{dS_v}{dP} \right)_T; \quad \psi_w = T \left( \frac{dS_w}{dP} \right)_T.
\]

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

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

and the data of [3], values of the coefficients $\psi_w$ and $\psi_v$ may be obtained. Calculation shows that, in the pressure range 0.1-10 MPa, $\psi_w$ varies from $-0.293 \cdot 10^{-3}$ to $-3.28 \cdot 10^{-3}$ J/m$^2$/kg·N and $\psi_v$ from $-1.819$ to $-0.088$ J/m$^2$/kg·N.

Using the results obtained for $\psi_w$ and $\psi_v$, 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

$$\frac{\sigma_w \rho_w \psi_w}{(1 - \varepsilon) \rho_c c_p} + \frac{\rho_c c_p}{\sigma_w \rho_w c_p} \frac{dT}{dT} = \varepsilon,$$

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

$$\frac{\sigma_w \rho_w \psi_w}{(1 - \varepsilon) \rho_c c_p} + \frac{\rho_c c_p}{\sigma_w \rho_w c_p} \frac{dT}{dT} = \varepsilon.$$

Calculation of $\zeta$ shows that $\zeta = 5 \cdot 10^{-6}$ for $T = 373^\circ$K and $\zeta = 3 \cdot 10^{-2}$ for $T = 536^\circ$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

$$\left[\left(1 - \varepsilon\right) \rho_c c_p \rho_p \sigma_w \frac{dT}{dT} = g_p r_p.ight.\]

It follows from the continuity equation for the condensate flux that

$$\frac{d\sigma_w}{d\tau} = g_w.$$

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

$$\frac{d}{d\tau} \left(\frac{g_w}{\sigma_w}\right) = -g_p r_p = g_w.$$

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

$$\rho_w = \mu P / RT.$$  

Together with the relations

$$P = P_c \exp \left(-\frac{W_p}{RT}\right)$$

and

$$\sigma_v + \sigma_w = 1$$

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:

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

where $\sigma_w$ is the saturation of the medium with condensate,

$$\sigma_w = \frac{j_v x - \rho_w}{\varepsilon (\rho_w - \rho_v)}.$$

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