GAS INFILTRATION INTO AN ELASTICALLY COMPRESSIBLE JOINTED POROUS MEDIUM

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Equations are derived for gas infiltration in a jointed porous stratum whose effective parameters are substantially dependent on the state of strain and the liquid pressure. An example is considered of driving a gallery with constant backup pressure.

A theory has been given [1, 2] for the infiltration of a homogeneous fluid into a jointed porous rock, and the main assumptions in that theory have been used [3] in deriving the corresponding gas infiltration equations. Nonlinearly elastic states occur in the entry of a liquid or gas into a jointed or jointed porous medium, which have been considered in [4-7]. A modified model has been suggested [8] for the infiltration of a liquid into an elastic jointed porous material. A distinctive point was that the infiltration region may be divided into zones having closed and open joints. The conditions for equal pressures and fluxes in the blocks are met at the boundary between the zones, while the pressure in the joints is equal to some critical value and the flux is zero. Here we consider gas infiltration in the [8] model, where we restrict consideration to a material in a state of hydrostatic compression with stress σ.

The joint porosity and permeability are defined by the elastic strain [8]:

$$m_1 = \overset{\circ}{m}_1\varphi_1, \quad k_1 = \overset{\circ}{k}_1\varphi_1^3, \quad \varphi_1 = (p_1 - \sigma)/(p^\circ - \sigma), \tag{1}$$

in which the joints exist (are open) for $p_1 > \sigma$. (1) applies also when the joints lie in one plane (e.g., sedimentary rocks), in which case σ is the compressive stress normal to that plane.

The (1) formulas have been derived previously [4] without invoking a critical pressure in a study on the infiltration of liquid into a purely jointed stratum.

We assume that the gas infiltration follows Darcy's law and that the block porosities vary in the usual fashion:

$$m_2 = \overset{\circ}{m}_2\,[1 + (p_2 - p^\circ)/K_m]. \tag{2}$$

We use (1) and (2) with the relationship between the density and pressure for the gas $\rho = \gamma p$, $\gamma = \rho^\circ/p^\circ$ to get from the continuity equations for the joints and blocks that

$$\begin{aligned} \gamma\overset{\circ}{m}_1\partial(p_1\varphi_1)/\partial t &= (\gamma\overset{\circ}{k}_1/\mu)\,\nabla(p\varphi_1^3\nabla p_1) + \psi, \\ \gamma\overset{\circ}{m}_2\partial p_2/\partial t &= (\gamma\overset{\circ}{k}_2/\mu)\,\nabla(p_2\nabla p_2) - \psi. \end{aligned} \tag{3}$$

The mass transfer ψ between the joints and blocks in [3] described by

$$\psi = \delta(p_2^2 - p_1^2), \quad \delta = (\alpha\rho^\circ)/(\mu p^\circ),$$

in which α is a dimensionless coefficient.

We introduce the dimensionless parameters

$$\xi = x/L,\ \omega = t/\tau,\ b = \overset{\circ}{m}_1/\overset{\circ}{m}_2,\ g = \varkappa\tau/L^2,\ \beta = \sigma/(p^\circ - \sigma),$$
$$\varkappa = \overset{\circ}{k}_1(p^\circ - \sigma)/(\mu\overset{\circ}{m}_2),\ \tau = \mu\overset{\circ}{m}_2/[\alpha(p^\circ - \sigma)],\ \varepsilon = \overset{\circ}{k}_2/\overset{\circ}{k}_1.$$

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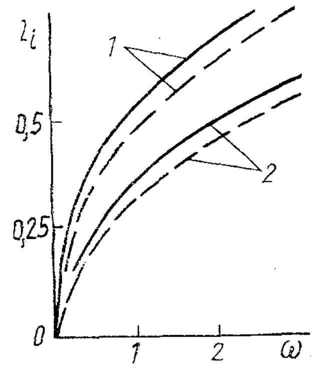

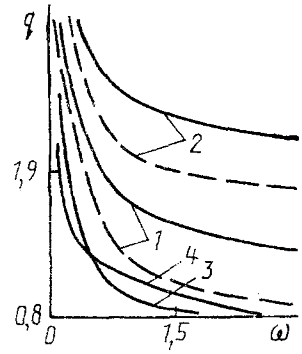

Fig. 1 Fig. 2

Fig. 1. Motion of perturbation front (solid lines for joints, dashed lines for blocks), $\beta = 1$; $\nu = 0.5$ (1), 0.8 (2).

Fig. 2. Fall in flow rate: $\beta = 3$ (1), 9 (2); $\nu = 0.2$ (solid lines), 0.8 (dashed lines); $\beta = 3$, $\nu = 0.2$ (3-solution to linear system; 4-numerical solution to (4)).

Equations (3) in dimensionless form are

$$b\partial(\varphi_1^2+\beta\varphi_1)/\partial\omega = g\nabla[\varphi_1^3(\varphi_1+\beta)\nabla\varphi_1]+\lambda,$$
$$\partial\varphi_2/\partial\omega = \varepsilon g\nabla[(\varphi_2+\beta)\nabla\varphi_2]-\lambda,\quad \lambda=(\varphi_2+\beta)^2-(\varphi_1+\beta)^2. \tag{4}$$

In (4), in practice $b \ll 1$, $\varepsilon \ll 1$, which means that the perturbations are singular. Then one can neglect the corresponding terms, as is usually done in the [1] model, to determine only the external solution. As an illustration, we construct an approximate solution to (4) by an integral method [9] for one-dimensional infiltration in a gallery. For comparison, we use the same method to solve (4) with $\varphi_1^3 = 1$ in the first equation, which corresponds to gas infiltration [3] in a linear jointed porous medium [1]. The accuracy is checked from the numerical solution to (4), where the difference scheme has been based on the [10] recommendations.

The boundary conditions are $\xi = 0$, $\varphi_i = (p_0 - \sigma)(p^\circ - \sigma) = \nu$, $0 < \nu < 1$, $\xi = \ell_i$, $\varphi_i = 1$, $\partial\varphi_i/\partial\xi = 0$, $i = 1, 2$, in which $\ell_i = \ell_i(\omega)$ are the perturbation fronts in the joints and blocks, and which satisfy the pressure profile

$$\varphi_i = \nu + (1-\nu)(3\xi/l_i - 3\xi^2/l_i^2 + \xi^3/l_i^3). \tag{5}$$

The functions $\ell_i(\omega)$ are derived from the second integral formulas corresponding to (4):

$$l_i^2(\omega) = c_i[1-\exp(-d\omega)] + n\omega, \tag{6}$$

where the positive constants c_1, d, and n and $c_2 < 0$ are defined by the coefficients of (4) and the backup pressure $\varphi_1 = \varphi_2 = \nu$

We write the flow from the gallery

$$q = [\varphi_1^3(\varphi_1+\beta)\partial\varphi_1/\partial\xi + \varepsilon(\varphi_2+\beta)\partial\varphi_2/\partial\xi]_{\xi=0}$$

on the basis of (5):

$$q = 3(1-\nu)(\nu+\beta)(\nu^3/l_1 + \varepsilon/l_2). \tag{7}$$

A series of numerical calculations from (6) and (7) was performed for the following initial data: $k_1^\circ = 10^{-13}$ m², $k_2^\circ = 10^{-15}$ m², $p^\circ - \sigma = 1$ MPa, $m_1^\circ = 1\%$, $m_2^0 = 10\%$, $\tau = 3600$ sec, L = 600 m, $\mu^\circ = 10^{-15}$ Pa·sec.

In accordance with the definition, we assume $0 < \nu < 1$. The range in β was determined from theoretical and experimental evidence [12, 13] that gives $\sigma \approx (0.75\text{-}0.9)p^\circ$, so $\beta = \sigma/(p^\circ - \sigma) \approx (3\text{-}9)$.

Figures 1 and 2 show numerical results from (6) and (7), where dimensionless parameters have been sued. The conclusions may be formulated for a fixed initial stratal pressure $p°$. The increase in β is governed by the increase in the critical pressure σ, which indicates more rapid crack compression as the backup pressure is reduced. Stationary infiltration shows [11] that the flow rate increases as the cracks are compressed and attains a state of saturation at the instant of closure in a borehole. Therefore, the $q(\omega)$ curves for large β lie higher (Fig. 2). Any increase in ν for constant $p°$ and σ denotes reduction in the depression in the stratum and retards the infiltration (Fig. 1) and lowers the flow rate (Fig. 2). For intermediate values of β and ν not given in Fig. 2, the pressure curves can be derived by approximation.

Similar calculations have been performed for a linear jointed porous medium [1] (an example is curve 3 in Fig. 2). The pressure drop in a linear medium is much more rapid than in a nonlinear one, and the corresponding curves may differ very substantially.

The accuracy of the results from approximations (6) and (7) was checked by numerical integration of (4) (example: curve 4 in Fig. 2). The deviations did not exceed 30% in any case for $\omega \gtrsim 1$.

NOTATION

x, t, p dimensional coordinate, time, and pressure; ξ, ω, φ dimensionless coordinate, time, and pressure; k, m, and $\varkappa$ permeability, porosity, and pressure transmission coefficient; σ critical pressure; p_0 backup pressure; K_m elastic modulus; ρ and μ gas density and viscosity; τ and L time and length scales; ℓ perturbation front; q flow rate. Superscripts and subscripts: $°$ initial values, 1 and 2 refer correspondingly to joints and blocks.

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