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MUTUAL GAS DISPLACEMENT FROM A POROUS MEDIUM UNDER

CHEMICAL REACTIONS CONDITIONS

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Equations are derived that describe the technological process of natural underground sulfur-cleaning of natural gases containing hydrogen sulfide during their passage through a chemically active porous medium, and exact solutions are obtained of model problems.

One of the promising methods of developing low-sulfur natural gas deposits is the method of underground sulfur-cleaning [1, 2]. The crux of the method is to pass the gas containing the hydrogen sulfide through the stratum whose rock has iron oxide in its composition. Cleaning of the gas occur because of the chemical reaction between the hydrogen sulfide and the iron oxides. The quantity of extractive and bypassing boreholes assuring cleaning of the requisite quantity of gas in a given time, the distance between the boreholes and the depressions in the stratum must be determined to plan this development method. This is performed on the basis of mathematical modeling data [3].

Models of two-phase filtration under chemical reaction conditions between the phases and the skeleton are proposed in [4, 5], and self-similar solution are obtained for frontal displacement problems.

Filtration equations are derived in this paper for a gas containing hydrogen sulfide in a water-saturated medium under chemical reaction conditions with ferric and ferrous oxides in the rock. An exact solution is obtained for the one-dimensional problem describing the displacement of a sulfur-free gas by one containing hydrogen sulfide from a porous medium in whose composition are iron oxides. The problem of migration of the gas containing the hydrogen sulfide into the sulfur-free part of the deposits under chemical reaction conditions is solved.

Analogous problems occur in the investigation of underground leaching problems for metals [6], gypsum [7], underground extraction of sulfur [8], geochemistry and hydrogeology [9].

1. PHYSICOCHEMICAL TRANSFORMATIONS IN A POROUS MEDIUM

Upon injection of a low-sulfur gas into a porous medium whose rock contains iron oxides in its composition, dissolution of the hydrogen sulfide from the gas into the residual water and its chemical reactions with the ferrous FeO and ferric Fe_2O_3 oxides occur (Fig. 1).

The intensity of the hydrogen sulfide mass transfer between the gas and water phases q is given by the Gibbs law [10, 11]

$$q = \lambda(s_*) \left[\mu_g(c, p) - \mu_w(c, p)\right].$$ (1)

Water is the catalyst for the chemical reactions between H_2S and the iron oxides, these reactions do not occur unless it is present [2].

Reaction between the hydrogen sulfide and iron oxide results in the formation of iron sulfide and water

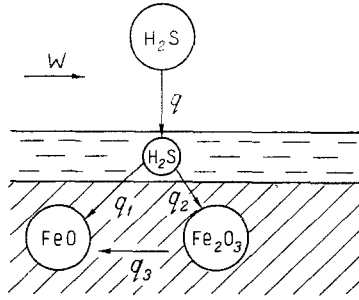$$FeO + H_2S \rightarrow FeS + H_2O.$$ (2)

Fig. 1. Physicochemical processes that occur during underground sulfur cleaning.

The chemical reaction between hydrogen sulfide and ferrous oxide proceeds in two stages. Ferric oxide, water and free sulfur form in the first stage

$$Fe_2O_3 + H_2S \rightarrow 2FeO + H_2S + S. \tag{3}$$

In the second the ferrous oxide being formed reacts with the hydrogen sulfide (2). The resultant reaction of both stages is described by the equation

$$Fe_2O_3 + 3H_2S \rightarrow 2FeS + 3H_2O + S. \tag{4}$$

The quantity of hydrogen sulfide going into chemical reaction with the iron oxide per unit time is computed from the law of effective masses

$$q_1 = A_1(s_*) \varphi c_1. \tag{5}$$

The quantity of the hydrogen sulfide reacting with the ferrous oxide per unit time is computed analogously

$$q_2 = A_2(s_*) \varphi c_2. \tag{6}$$

Since one mole of ferric oxide (2) is expended in a chemical reaction with one mole of hydrogen sulfide, then the quantity of ferric oxide expended in a chemical reaction per unit time equals $q_1\mu_1/\mu$. The quantity of ferrous oxide expended per unit time in the chemical reaction equals $q_2\mu_2/\mu$.

Since two moles of the oxide are formed from one more of ferrous oxide as a result of the first stage of the chemical reaction between hydrogen surfide and ferrous oxide (3), then the quantity of ferric oxide being formed per unit time equals $2\mu_1\mu_2/\mu$.

2. DERIVATION OF THE MOTION EQUATIONS

Since the hydrogen sulfide concentration in the gas is small, the physicochemical transformations of the hydrogen sulfide will not exert influence on the gas filtration process. The stratified pressure p and velocity W will be found from the solution of the nonstationary compressible gas filtration problem with the residual water saturation taken into account

$$m(1 - s_*)\frac{\partial \rho_g(p)}{\partial t} = \operatorname{div}\left(\frac{\hat{k}}{\mu(p)}\rho_g \nabla p\right). \tag{7}$$

The pressures of the mass flow rates in the extracting and bypassing boreholes are given for the problem of determining the stratified pressure.

We write the equation of mass balance for hydrogen sulfide. The quantity $m\rho_g(-s_*)$ hydrogen sulfide is contained per unit volume of the porous medium in the gas phase and $m\rho_w s_* \varphi$ in the water phase. Convective hydrogen sulfide transport occurs in the gas phase at the filtration rate, hence the hydrogen sulfide diffuses into the gas flow. Hydrogen sulfide absorption occurs with the intensity $q_1 + q_2$ because of the chemical reaction. Consequently, the hydrogen sulfide balance equation has the form
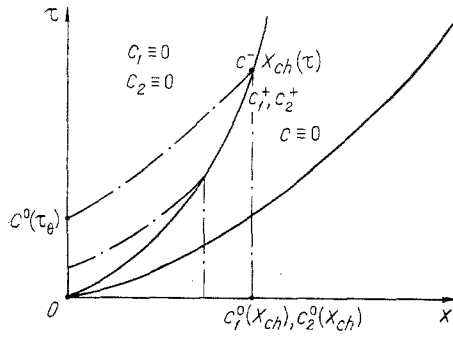
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Fig. 2   Fig. 3

Fig. 2. Dynamics of the displacement and chemical reaction fronts during injection of a gas containing hydrogen sulfide through a porous medium.
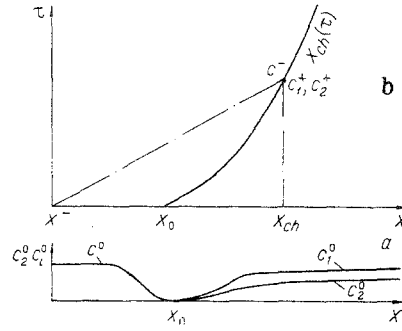
Fig. 3. Migration of a gas containing hydrogen sulfide into the sulfur-free part of a stratum: a) initial data; b) characteristic lines and discontinuities.

$$m \frac{\partial}{\partial t} \left[\rho_g (1 - s_*) c + \rho_w s_* \varphi \right] + \text{div} \left(\rho_g c \mathbf{W} \right) = \text{div} \left(D m \rho_g (1 - s_*) \nabla c \right) - q_1 - q_2. \tag{8}$$

Contained per unit volume of the porous medium is $(1 - m)\beta \rho_s c_2$ ferrous oxide which is expended in the chemical reaction with intensity $q_2 \mu_2 / \mu$. The ferrous oxide balance equation will be the following

$$(1 - m) \beta \frac{\partial}{\partial t} \rho_g c_2 = - \frac{q_2 \mu_2}{\mu}. \tag{9}$$

The quantity of ferric oxide per unit volume of the porous medium equals $(1 - m)\beta \rho_s c_2$. It diminishes with intensity $q_1 \mu_1 / \mu$ because of the chemical reaction with hydrogen sulfide and grows with intensity $2\mu_1 / _2\mu$ because of the chemical reaction between the ferrous oxide and hydrogen sulfide.

The ferric oxide mass balance equation takes the form

$$(1 - m) \beta \frac{\partial}{\partial t} \rho_s c_1 = - \frac{q_1 \mu_1}{\mu} + \frac{2 q_2 \mu_1}{\mu}. \tag{10}$$

Let us write the mass balance equation for the hydrogen sulfide in water. We shall consider the hydrogen sulfide to enter into the chemical reaction with the ferric oxides from a water solution. The quantity of hydrogen sulfide per unit volume of porous medium in the water phase equals $m \rho_w s_* \varphi$. It decreases because of chemical reactions with an intensity $q_1 + q_2$ and grows because of hydrogen sulfide dissolution in water from the gas phase (1):

$$m \rho_w s_* \frac{\partial \varphi}{\partial t} = \lambda \left[\mu_g (c, \ p) - \mu_w (c, \ p) \right] - q_1 - q_2. \tag{11}$$

After substituting the interphasal mass transfers (1), (5), (6) intensities into (8)-(11), we obtain a closed system of four equations in the unknowns c, φ, c_1 and c_2. In the dimensionless variables

$$X = \frac{x}{L}, \qquad \tau = \frac{W_0 t}{m L}, \qquad w = \frac{W}{W_0}, \qquad A_i = \frac{\rho_s}{\tau_i}$$

it has the form

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$$\frac{\partial}{\partial \tau} [\rho_g (1 - s_*) c + \rho_w s_* \varphi] + \frac{\partial}{\partial X} [\rho_g c w] =$$

$$= \frac{Dm (1 - s_*) \rho_g}{W_0 L} \frac{\partial^2 c}{\partial X^2} - \frac{L \rho_s}{W_0 \tau_1} \varphi c_1 - \frac{L \rho_s}{W_0 \tau_2} \varphi c_2, \tag{12}$$

$$\rho_w s_* \frac{\partial \varphi}{\partial \tau} = \frac{\lambda L}{W_0} [\mu_g (c, \ p) - \mu_w (\varphi, \ p)] - \frac{L \rho_s}{W_0 \tau_1} \varphi c_1 - \frac{L \rho_s}{W_0 \tau_2} \varphi c_2, \tag{13}$$

$$\frac{W_0 \tau_2}{mL} (1 - m) \beta \frac{\partial c_2}{\partial \tau} = - \varphi c_2 \frac{\mu_2}{\mu}, \tag{14}$$

$$\frac{W_0 \tau_2}{mL} (1 - m) \beta \frac{\partial c_1}{\partial \tau} = - \frac{\tau_2 \mu_1}{\tau_1 \mu} \varphi c_1 + 2 \varphi c_2 \frac{\mu_1}{\mu}. \tag{15}$$

3. LARGE-SCALE APPROXIMATION

For large L of the order of the stratum length the dimensionless complex in (14), equal to the ratio between the gas volume injected in the characteristic time of the chemical reaction (3) and the pore volume of the stratum, is small $W_0 \tau_2 / mL \ll 1$. Consequently, we have in a large-scale approximation

$$\varphi c_2 = 0. \tag{16}$$

There follows analogously from (15)

$$\varphi c_1 = 0. \tag{17}$$

Equations (15) and (17) mean that in a large-scale approximation the chemical reactions (2), (3) and (4) occur instantaneously, i.e., either hydrogen sulfide ($c_1 = c_2 = 0$, $\varphi \neq 0$) or iron oxides ($c_1 \neq 0$, $c_2 \neq 0$, $\varphi = 0$) are present at each point of the porous medium. For large L the ratio of the gas volume injected in the strata in the characteristic time of hydrogen sulfide dissolution in water is considerably less than the pore volume of the stratum $\rho_w W_0 / \lambda L \ll 1$. Consequently, in a large-cale approximation the hydrogen sulfide distribution between the phases corresponds to thermodynamic equilibrium

$$\mu_g (c, \ p) = \mu_w (\varphi, \ p), \quad \varphi = \varphi (c, \ p). \tag{18}$$

The Peclet number $Dm / W_0 L \ll 1$ is small in (12)

$$\frac{\partial}{\partial \tau} [\rho_g (1 - s_*) c + \rho_w s_* \varphi (c, \ p)] + \frac{\partial}{\partial X} (\rho_g c w) = 0. \tag{19}$$

Therefore, in the large-scale approximation we have four equations (16)-(19) in the variables (c, φ, c_1, c_2). To solve the system of equations obtained in the large-scale approximation it is necessary to obtaine the $H_2 S$ mass balance condition on the chemical reaction front. To do this, we take such a linear combination of (8)-(10), analogouusly to [4, 5], such that it would have the divergent form

$$\frac{\partial}{\partial \tau} [\rho_g (1 - s_*) c + \rho_w s_* \varphi (c, \ p) - 3 \mu (1 - m) \beta \rho_s c_2 / m \mu_2 -$$

$$- \mu (1 - m) \beta \rho_s c_1 / m \mu_1] + \frac{\partial}{\partial X} (\rho_g c w) = 0. \tag{20}$$

Equation (20) has a divvergent form. Conditions on the discontinuity of the concentration

$$\left\{ (1 - s_*) [c] + \frac{\rho_w s_*}{\rho_g} [\varphi (c, \ p)] - \frac{3 \mu (1 - m) \beta \rho_s}{\mu_2 m \rho_g} [c_2] - \right.$$

$$\left. - \frac{\mu (1 - m) \beta \rho_s}{\mu_1 m \rho_g} [c_1] \right\} V = w [c]. \tag{21}$$

can be obtained from it. Here $V = dX_{ch}/d\tau$ is the velocity of the chemical reaction front.

Let us note that the filtration rate in (12)-(21) is found from the solution of the problem (7) and is independent of the physicochemical transformations. Consequently, we will henceforth consider the velocity $w(X, \tau)$ given.

4. SOLUTION OF THE DISPLACEMENT PROBLEM

Let us consider the process of injection of a gas containing hydrogen sulfide into a stratum whose collector contains iron oxides. Under the assumption of incompressibility of the gas w = const the initial conditions correspond to disposition of the oxides in the stratum

$$\tau = 0: \; c_1 = c_1^0(X), \quad c_2 = c_2^0(X). \tag{22}$$

The boundary conditions correspond to a change in the composition of the gas being injected

$$X = 0: \; c = c^0(X). \tag{23}$$

Let us examine the simplest case when the solution of H_2S in water is subject to the Rowle-Dalton law $\varphi(c, p) = Kc$. Let ρ_g = const. As is seen from (16) and (17), either $c = 0$, $c_1 \neq 0$, $c_2 \neq 0$ or $c \neq 0$, $c_1 = c_2 = 0$. This corresponds to the assumption about the chemical reaction being instantaneous. We have $c \equiv 0$ ahead of the chemical reaction front for $X > X_{ch}(\tau)$ while $c_1 = c_2 = 0$ behind the front for $X < X_{ch}(\tau)$. The velocity of the c_1- and c_2-characteristics is zero, consequently, we have for $X > X_{ch}(\tau)$

$$c_1(X, \tau) = c_1^0(X), \quad c_2(X, \tau) = c_2^0(X). \tag{24}$$

As follows from (19), the relationships on the c-characteristics has the form

$$\frac{dX}{d\tau} = \frac{w}{(1 - s_*) + s_* K \rho_w / \rho_g}; \quad \frac{dc}{d\tau} = 0. \tag{25}$$

The trajectories of the chemical reaction front and the c-characteristics behind them are shown in Fig. 2. The c-characteristics yield the values of $c^-(X_{ch})$ with the line $X = 0$ at the rear of the discontinuity

$$c^-(X_{ch}, \tau) = c^0(\tau'), \tag{26}$$

where $[X_{ch}(\tau), \tau]$ is the point of the integral trajectory of the ordinary differential equation (25) passing through the initial point $(0, \tau')$, $\tau' = \tau'(X_{ch}\tau)$. The trajectory of the chemical reaction front motion $X_{ch}(\tau)$ is found from (21) as the solution of the ordinary differential equation

$$\frac{dX_{ch}}{d\tau} = wc^-(X_{ch}, \tau)\Bigg[(1 - s_*)c^-(X_{ch}, \tau) + \frac{\rho_w s_*}{\rho_g}Kc^-(X_{ch}, \tau) +$$
$$+ \frac{3\mu(1 - m)\beta\rho_s}{\mu_2 m \rho_g}c_2^0(X_{ch}) + \frac{\mu(1 - m)\beta\rho_s}{\mu_1 m \rho_g}c_1^0(X_{ch})\Bigg]^{-1}, \tag{27}$$
$$X_{ch}(0) = 0.$$

The function $c^-(X_{ch}, \tau)$ is determined from (24) and (26). Let us assume that this trajectory has been found. Let us draw $c-$, c_1, and c_2- characteristics from its arbitrary point (X_{ch}, τ) in the (X, τ) plane (Fig. 2) until they intersect the axes $X = 0$, $\tau = 0$, respectively, at the points τ_0 and $\dot{X}_{ch}$. To obtain the first integral of the ordinary differential equation (25), we integrate (20) over the closed domain D obtained with the boundary $\partial\Gamma$ and we use the two-dimensional Green's formula [13]. We then have

$$0 = \iint_D \left[\frac{\partial}{\partial\tau}A + w\rho_g\frac{\partial c}{\partial X}\right]dXd\tau = \oint(w\rho_g c d\tau - AdX) =$$
$$= w\rho_g\int_0^\tau c^0(\tau')\,d\tau + w\rho_g c^0(\tau_0)(\tau - \tau_0) + \int_0^{X_{ch}}A(c = 0, c_1^0(X),$$
$$c_2^0(X))\,dX - A(c^0(\tau_0), c_1 = c_2 = 0)X_{ch}. \tag{28}$$

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Here A is denoted by the expression

$$A = \rho_g (1 - s_*) c + \rho_w s_* \varphi (c, p) - \frac{3\mu (1 - m)}{m\mu_2} \beta \rho_s c_2 - \frac{\mu (1 - m)}{m\mu_1} \beta \rho_s c_1.$$

The quantities τ and τ_0 are connected by the relationship

$$X_{ch} = \frac{w}{1 - s_* + s_* K \rho_w / \rho_g} (\tau - \tau_0), \quad X_{ch} (0) = 0, \quad \tau = \tau_0 = 0. \tag{29}$$

We find the explicit dependence $X_{ch}(\tau)$, that is the solution of (27) from (28) and (29), where (24)-(28) describe the solution of the boundary value problem (22) and (23). They are simplified substantially under the assumption that the filtration rate $W = W_0$ is constant (i.e., the gas is incompressible), as are the injected gas concentration c^0 and the oxide concentrations c_1^0, c_2^0 in the rock. Then we obtain from (27) or (28) that the velocity of the chemical reaction front is constant

$$V = \left[1 - s_* + \frac{\rho_w s_*}{\rho_g} K + \frac{3\mu (1 - m) \beta \rho_s}{\mu_2 m \rho_g} \frac{c_2^0}{c^0} + \frac{\mu (1 - m) \beta \rho_s}{\mu_1 m \rho_g} \frac{c_1^0}{c^0} \right]^{-1}. \tag{30}$$

5. ANALYSIS OF THE TECHNOLOGICAL INDICES

Starting from the above, the fundamental technological indices of the process of underground sulfur-chemically active porous medium are computed. The chemical reaction front reaches the extracting boreholes after injection of $1/V$ of the pore volumes of the gas in the stratum after $T = mL/VW_0 = mL^2\mu/Vk\Delta p$. Here L is the distance between the series of pressure and extraction boreholes, b is the distance between the boreholes in a series, and h is the stratum thickness. After this time, $Q = \rho_g W_0 TbhN = \rho_g mLbhN/V$ of gas will have been extracted. Therefore, the pore volume QV/ρ_g is required to cleanse the mass of gas Q. A number of boreholes $N = QV/m\rho_g Lbh$ is required for successive opening of strata by galleries of extracting and bypassing boreholes.

6. HYDROGEN SULFIDE MOTION IN A SULFUR-FREE PART OF THE DEPOSIT

The mineral composition of the rock over the area of a deposit can change substantially in low-sulfur gas deposits. Hydrogen sulfide is missing in the part of the deposit whose rock contains iron oxide. The following method of development is expedient: Gas is extracted only in the sulfur-free part of the stratum; upon filtration of a gas containing hydrogen sulfide in the sulfur-free part of the stratum, it is cleansed; as the hydrogen sulfide front advances into the sulfur-free part of the stratum, the boreholes traversed by the front are cut off. The following Cauchy problem for the system of equations (16)-(21) is solved to estimate the velocity of hydrogen sulfide front advancement:

$$\tau = 0: \quad c_1 = c_1^0 (X), \quad c_2 = c_2^0 (X), \quad c = c^0 (X).$$

The distributions of the initial concentrations are represented in Fig. 3a while the behavior of the characteristics is presented in Fig. 3b. In the incompressible case all the characteristics are straight lines. As is seen from (25) the velocity of the c-characteristic is $V_c = [1 - s_* + s_* K \rho_w / \rho_g]^{-1}$. At the rear of the discontinuity $X_{ch}(\tau)$ it yields the value $c^-(X_{ch}(\tau))$:

$$c^- (X_{ch} (\tau)) = c^0 (X^- (0)), \quad X_{ch} (0) - X^- (0) = V_c \tau. \tag{31}$$

On the front of the discontinuity $X_{ch}(\tau)$ the c_1-characteristic yield the values $c_i^+(X_{ch}(\tau))$, i = 1, 2;

$$c_i^+ (X_{ch} (\tau)) = c_i^0 (X_{ch}). \tag{32}$$

Substituting (31)-(32) into (21), we obtain an ordinary differential equation describing the motion of the chemical reaction front
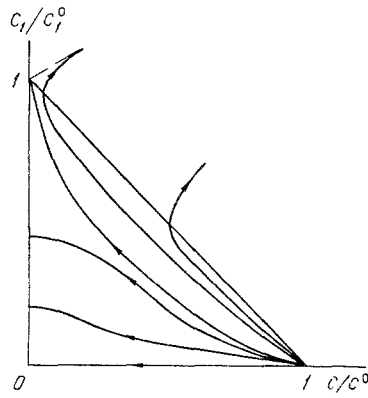
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Fig. 4. Stationary structure of
the concentration jump at the
chemical reaction front.

$$\frac{dX_{ch}}{d\tau} = \left\{(1-s_*) + \frac{\rho_w s_*}{\rho_g}K + \frac{\mu(1-m)\rho_s}{m\rho_g c^0(X_{ch}-V_c\tau)}\left[\frac{3c_2^0(X_{ch})}{\mu_2} + \frac{c_1^0(X_{ch})}{\mu_1}\right]\right\}^{-1}.$$ (33)

We obtain the first integral of (33). To do this, we integrate both parts of (20) over the domain D of the plane (X, τ), bounded by the contour Γ: $(X_{ch}, 0) \to (X_{ch}, \tau) \to (X^-, 0) \to (X_{ch}, 0)$ (Fig. 3) analogously to [13]

$$[\rho_g(1-s_*) + s_*\rho_w K]\int_{X_{ch}-V_c\tau}^{0} c^0(x)\,dx - \int_0^{X_{ch}}\left[\frac{3\mu(1-m)}{m\mu_2}\rho_s c_2(X)\beta + \frac{\mu(1-m)}{m\mu}\beta\rho_s c_1(X)\right]dX = 0.$$ (34)

The expression obtained is the desired first integral for (33). The dynamics of the front $X_{ch}(\tau)$ is shown in Fig. 3b. At the initial time the front velocity equals the velocity V_c since $c^+(X_{ch}) = c_i^-(X_{ch}) = 0$. As the front enters the domain of growing values of iron oxides concentration and the growth of the hydrogen sulfide concentration in the gas passing through the line of discontinuity, the velocity of front motion diminishes.

Let us note that upon considering the two-dimensional filtration flow with a stationary velocity field, the gas particle and hydrogen sulfide motion occurs along the identical trajectories but with a different velocity. Consequently, (31)-(34) are written down along each c-characteristic. On this basis the dynamics of the chemical reaction front and the hydrogen sulfide isoconcentrate is described.

7. STRUCTURE OF THE CONCENTRATION JUMP

The local effects of dissusion and nonequilibrium of the chemical reaction will be commensurate in order with large-scale convective effects in a small neighborhood of the discontinuity. This occurs for a characteristic dimension L of the order of the length of the transition zone from $c = c^0$ to $c = 0$ in (12)-(19).

Let us examine a continuous change in the concentrations in a small neighborhood of a jump. Let just ferric oxide be present in a porous medium, and H_2S dissolution in water let occur instantaneously. Then the equations of motion take the form

$$\frac{\partial}{\partial\tau}\left[1 - s_* + \frac{\rho_w s_* K}{\rho_g}\right]c + \frac{\partial c}{\partial X} = \frac{Dm(1-s_*)}{W_0 L\rho_g}\frac{\partial^2 c}{\partial X^2} - \frac{L\rho_s K}{W_0\tau_1\rho_g}cc_1,$$

$$\frac{W_0\tau_1}{mL}(1-m)\beta\frac{\partial c_1}{\partial\tau} = -\frac{\mu_1}{\mu}Kcc_1.$$

Two small numbers enter into the system, the Peclet number $Dm(1 - s_*)/W_0L$ and the relaxation number $\varepsilon = W_0\tau_1/mL$. External expansion with respect to them $(L \to \infty)$, the solution of the problem in a large-scale approximation, represents a jump in hydrogen sulfide moving over the stratum with the velocity V (30) for $c_2^0 = 0$. To construct the internal expansion, we go over to a reference system in (12) and (14) that moves with velocity V and we find the stationary solution, i.e., $c = c(\xi)$, $c_1 = c_1(\xi)$, $\xi = (X - V_\tau)/\varepsilon$. We obtain a system of two ordinary differential equations. From the condition that its solution tends to the discontinuous (external) as $\varepsilon \to 0$ we have the boundary value problem $\xi \to \infty$; $c = 0$, $c_1 = c_1^0$;

$$\xi \to -\infty: \quad c = c^0, \quad c_1 = 0.$$

After reducing the order, we obtain an autonomous system of final order in the plane $(c/c^0, c_1/c_1^0)$. Its phase portrait is presented in Fig. 4. The singular point (1.0) (as $\xi \to \infty$) in a nondegenerate node, while the singular point (0.1) (as $\xi \to \infty$) is a saddle point. The single integral trajectory connecting the singular points is shown in Fig. 4.

The existence of a structure for the concentration jump permits a multilateral description of the process under investigation. The form of the integral trajectory yields a representation of the continuous change in the concentration in the neighborhood of the jump because of the action of local processes.

NOTATION

c is the H_2S concentration in the gas phase; φ is the H_2S concentration in the water phase; p is the stratified pressure; t is the time; μ_g is the chemical potential of H_2S in the gas phase, μ_w is the chemical potential of H_2S in the water phase, λ is a proportionality factor; s_* is the residual water saturation; q_1 is the intensity of the chemical reaction of H_2S with FeO; q_2 is the intensity of the chemical reaction of H_2S with Fe_2O_3; A_1 and A_2 are reaction rate constants of H_2S with FeO and FeO_2O_3, respectively; μ_1 is the molecular weight of FeO, μ_2 is the molecular weight of Fe_2O_3; μ is the molecular weight of H_2S; W is the filtration rate; m is the porosity of the medium; ρ_g is the gas phase density; ρ_w is the water phase density; ρ_s is the porous medium density; k is the permeability of the medium; μ_0 is the gas phase viscosity; β is the volume fraction of rock whose iron oxides go into chemical reaction; c_1 is the FeO concentration; c_2 is the Fe_2O_3 concentration; L is the stratum length; x is a linear coordinate; Dm is the convective diffusion coefficient; $[\alpha] = \alpha^+ - \alpha^-$ is the sign of a jump in the physical quantity α equal to the difference in the values α ahead of α^+ and behind the discontinuity; X_0 is the boundary between the sulfur and sulfur-free parts of the deposit; α^0 is the initial value of any physical quantity α, and N is the number of boreholes.

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CALCULATION OF THE DENSITY OF VAPORIZATION CENTERS AT THE HEATING

SURFACE WITH AN ALLOWANCE FOR THEIR MUTUAL INTERACTION

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An expression is proposed for calculating the density of vaporization centers at the heating surface that accounts for the superheating, the roughness and material of the surface, the pressure, and the interaction between centers based on the Kenning model.

The monograph by V. F. Prisnyakov [1] provides an analysis of the known experimental and theoretical investigations of the density n_w of vaporization centers acting at the heating surface during boiling. This analysis has shown convincingly that one of the main reasons for the unsatisfactory results obtained in calculating n_w by using the well-known expressions is that the known theoretical considerations do not take into account the actual structure (roughness) of various surfaces and the method used for their treatment.

V. F. Prisnyakov assumed that the number of acting (active) vaporization centers is proportional to the total number of potential centers at the heating surface. The latter quantity depends on the roughness of the surface and the method used for processing it. As a result, an expression was derived in [1] for calculating the density of the acting centers at the heating surface:

$$n_w = n_{max}\Phi; \quad \Phi = A \int_{H_{max}}^{H_{min}} H \exp(-aH^2)\, dH, \tag{1}$$

where $A = 0.2865/\nu_h^3$ and $a = 0.2525/\nu_h^2$, ν_h is the fill factor indicating the extend to which the profile of the surface is occupied by troughs, which depends on the type of surface treatment [1] ($\nu_h = 0.2$-0.7), where $H = h/h_{me}$, where $h(\Delta T_w)$ is the trough height corresponding to the assigned superheat of the surface ΔT_w [1], h_{me} is the mean depth of troughs corresponding to the class of surface finish and n_{max} is the maximum density of centers at the onset of crisis:

$$n_{max} = 2\left\{\pi \sin^2\theta\,[1 + \pi\beta\,(Ja)]\right\}^{-1} R_{bo}^{-2}.$$

Using relationship (1), Prisnyakov was able to generalize the experimental data for different sets of conditions pertaining to saturated boiling. The difficulty in practical utilization of (1) and (2) is that, in most cases, the parameter θ is a quantity which is not known beforehand. If $\theta \approx 0$, expressions (1) and (2) lead to unlikely high values of n_w. Moreover, the solution of (1) does not account for the interaction between centers, which can be considerable for sufficiently large values of n_w and sufficiently large bubble dimensions. Interaction generally leads to both activation and deactivation of new vaporization centers. The mutual effect of two artificial centers in water boiling was investigated experimentally in [2]. It was found that for $\ell < 6R_{bo}$, the interaction is negative the centers deactivate each other), while, for $\ell > 6R_{bo}$, it is positive (the centers activate each other). If $\ell \gg R_{bo}$, there is no interaction. The work described in [2] was carried further in experiments performed by Judd and collaborators [3-5]. They investigated the interaction between natural vaporization centers at the surface in cases of saturated and underheated