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Mobility control under selective water isolation of highly permeable reservoirs by in-situ quasi-periodic foaming

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Abstract. *The paper presents the results of studies of quasi-periodic foaming in order to mobility control under selective water isolation in highly permeable pore channels. The foam generation occurs due to in-situ reaction between concentrated aqueous solutions of gas-releasing and gas-forming solutions. The flow pattern of injected aqueous solutions of foaming chemicals along the flow tubes is investigated. The problem is reduced to finding the space-time distribution of reacting agents in the given porous media zones.*

Keywords. visco-elasticity · liquid · pipe · compression · pulsating flow · wave.

Mathematics Subject Classification (2010): 76S05

Background. Selective isolation of watered layers of oil saturated reservoir by forming blocking barriers with highly viscous gels or insoluble precipitates does not provide the desired results. Field experience confirms that at some distance from the formed barrier, the filtration flow restores its configuration and the injected water moves again through highly permeable channels [3, 8, 14].

Increasing the efficiency of flow diversion can be achieved by creating not a single barrier, but a whole sequence of alternating deep-penetrating isolation barriers, distant from each other for some distance in highly permeable pore channels [7, 14].

This type of scheme of barriers can be organized by pumping of gas-forming and gas-releasing solutions with additives of water-soluble polymers into water-saturated interlayers and create the conditions for quasi-periodic foaming.

Suppose that chemical agents S and A, dissolved in the aqueous phase, are successively injected into a homogeneous horizontal interlayer and in-situ reaction between which results in foam formation.

The reason for periodic foaming is the ability of solutions to supersaturation. Consider the interaction of two solutes (S and A) to form a foam. Initially, the contact boundary between the interacting substances S and A is minimal and the formation of a foam structure is possible only in the presence of mutual diffusion. In the absence of supersaturation of solutions, the chemical agents S and A could not exist simultaneously and foaming would occur only at the border of the two interacting zones.

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In this case, it is sufficient to know that the diffusion rate and, consequently, the foam formation boundary displacement velocity depends not only on the diffusion coefficients of the two substances S and A, but also on their initial concentrations and the stoichiometric ratio in the gas formation reaction.

1 Introduction.

In the problem presented here, gas formation takes place at the interface of regions in one of which (I) there is only a substance S and therefore ($A = 0$), and in the second (II) $A > 0$, $C = 0$.

Assuming, that to start a reaction of gas formation it is necessary to achieve a certain threshold of supersaturation $(SA)_{cr}$, then a new stage of gas release will occur at some distance from the interface, at the point of x_{cr}.

The objectives is to establish a relationship between the spatial distribution of the gas formation zone and the process dynamics on the one hand, and the concentration of the solution, the rate of diffusion (mutual diffusion) and the rate of gas formation on the other hand [9, 10, 13].

Some works [10, 19] are concerned with the periodic deposition under the mixing solutions flow and the summary of this process is proposed.

Based on the points of the theory, the authors [9] considered quasi-periodic precipitation under the heterogeneous solutions flow in porous media and theoretically justified this process. Authors proposed a model of quasi-periodic precipitation and described the possibility of practical use of that effects.

As an alternative way, we consider the process of quasi-periodic gas formation during the solutions flow in porous media. The problem of substances adsorption and interaction for a given distribution and gas generation is solved. Sorption process under flow of aqueous solution of sodium carbonate can be considered as a homogeneous solution, because sodium carbonate will be adsorbed. In this case, the porosity m_0 and permeability k depends on the content of substances absorbed by the phase of the porous medium a, as follows [1, 4, 5, 6]:

$$m_0 = m_0 \pm \frac{a}{\delta}$$

$$k = Ad^2 \frac{m_0^3}{(1 - m_0)^2}$$

where $m_0^{'}$ is the initial porosity of the rock, δ is the density of the sorbing substance in the solid phase, A is constant, d is the diameter of middle layer of sorption.

For stationary filtration in a homogeneous porous medium, the following system of equations is described by [2, 17, 18]:

$$v\frac{\partial C}{\partial x} + m\frac{\partial C}{\partial t} + \frac{\partial a}{\partial t} = D_0\frac{\partial^2 C}{\partial x^2} \tag{1.1}$$

$$\frac{\partial a}{\partial t} = \beta\,(C - C_1) \tag{1.2}$$

$$a = f(C_1) \tag{1.3}$$

The equations describe the following processes: (1.1) – balance of substances; (1.2) – sorption kinetics; (1.3) – sorption isotherm, where ν – filtration rate, x – distance, C – concentration of sodium carbonate solution at any point x at time t; C_1 – concentration of solution, a - equilibrium adsorption; β – kinetic coefficient of adsorption; D – molecular diffusion coefficient.

The molecular diffusion is extremely small for this process compared to the convective transfer of an aqueous solution of soda. Therefore, the right side of equation (1.1) can be neglected in the calculations.

The kinetic equation (1.2) is approximate, and the sorption rate at a given point of the reservoir at a given time depends on the values of a and C on the previous times and we use the apparatus of the sensitivity theory to assess these values [2, 16, 18, 19].

2 Problem statement.

1. If under solution displacement adsorption rate of the substance is much higher than the diffusion rate, then in equation (1.1) we can take D=0. And then it will be

$$V\frac{\partial C}{\partial r} + m_0\frac{\partial C}{\partial t} + \frac{\partial a}{\partial t} = 0 \tag{2.1}$$

Under stationary filtration mode

$$v = qr \tag{2.2}$$

where $q = Q_0/2\pi m_0 h;$ Q_0 is the flow rate of the solution; h is the reservoir thickness), and for a linear isotherm $a = H \cdot C$ (H is the Henry coefficient) [12].

Equation (1.2), (2.1) and (2.2) are supplemented by the following initial and boundary conditions:

$$\begin{aligned} C(r,t) &= C_0; \text{ under } r = 0 \\ C(r,t) &= 0; \text{ under } t = 0 \\ a(r,t) &= 0; \text{ under } t = 0 \end{aligned} \tag{2.3}$$

Solution of the system (1.2), (2.1) and (2.2) under condition (2.3) for some large value of x and t and in the case of a linear isotherm, the following approximate dependence [4]:

$$u(x,t) = \frac{C}{C_0} = 0,5(1 + erfx)$$

$$erfx = \frac{2}{\sqrt{\pi}}\int\limits_0^x e^{-z^2}dz,$$

where $F(\phi) = \frac{2}{\sqrt{\pi}}\int\limits_0^x e^{-u^2}du$ - probability integral;

$$\varphi = \sqrt{\frac{\beta}{\Gamma}\left(t - \frac{mx}{v}\right)} - \sqrt{\frac{\beta x}{v}};$$

Distribution of the concentrated solution along the bed strike will be determined by the width of the transition part. The transition part or adsorption zone is included in the interval $c = (0,01 \div 0.99)c_0$. The scope of the argument determined by the table for the function $F(\phi) = (-0,98 \div 0.98)$

$$\varphi = -165 \div 1,65$$

or adsorption zone $\sqrt{V_{0,01}} - \sqrt{V_{0,99}} = 3,3\sqrt{\frac{V}{\beta}}$.

The possible size of adsorption zone for PAA and soda solution on the sandstone surface, in which the porosity values $m = 0.24$, permeability $k = 4.0D$ and the Henry coefficient $H = 0.581$ at certain estimates values [4] of the kinematic adsorption coefficient

$1/min$, filtration rate under solution injection $V = 0.5m/day = 0.347 \times 10 - 3m/min$ is equal to $l = 3.2m$.

The distance between the injection and production galleries is not less than $200m$, from the obtained result it can be seen that the adsorption size of the layers occupies a small volume compared to the reservoir volume. The resulting adsorption zone further requires the formation of barriers for selective isolation of watered layers. The effectiveness of these solutions can be significantly increased if in the formation of adsorbed PAA and soda mixed solution with in the pores will be created not a single barrier, but a whole system of alternating barriers distant from each other by some distance. Such a barrier system can be controlled by injection of foaming chemical agent into the adsorption zones where the substance S is initially located.

$$\sqrt{T} = \sqrt{\frac{\Gamma}{V} x} + \phi(u) \sqrt{\frac{\Gamma}{\beta}} \tag{2.4}$$

where $T = t - m\frac{x}{V}$; $u = \frac{C}{C_0}$, - is the time counted since the front along the entire formation reach this section. Under a certain saturation $SA - S_\beta$, T will be equal to

$T = t - mS_\beta \frac{x}{V}$; - relative concentration

Equation (1.4) is a good enough approximation for an isotherm of nonlinear type, it means replacing the isotherm of some linear function in the concentration area from zero to the initial one (C_0).

If we take $u = C/C_0 = Const$, then equation (2.4) in coordinates is a straight line. Equation (2.1) for $u = 0.5$ takes the form:

$$\varphi = \sqrt{\frac{\beta}{\Gamma}\left(t - \frac{mx}{v}\right)} - \sqrt{\frac{\beta x}{v}} = 0,$$

from which

$$x_a = \frac{vt}{\Gamma + m}$$

$$\sqrt{t - \frac{mS_b}{V} x} = \sqrt{\frac{\Gamma \cdot x}{V}}$$

S_β - saturation of CA in the washed zone of the reservoir.

At the beginning of the injection, the relative concentration $u(x,t) = C/C_0 = 1$, then equation (2.4) takes the form:

$$1 = 0,5(1 + erf\phi);\ 2\frac{2}{2\sqrt{\pi}} erf\phi$$

$$2 = \frac{1}{\sqrt{\pi}} \int_0^x e^{-z^2} dz$$

$$2\sqrt{\pi} = \int \left[z - \frac{z^3}{3} + \frac{z^5}{10}\right] dz$$

$$2\sqrt{\pi} = \frac{z^2}{2} + \frac{z^4}{12} + \frac{z^6}{60}\bigg|_0^x$$

2. The mutual diffusion of reactants taking into account the reaction is described as [4,9]:

$$\frac{\partial C_{sa}}{\partial t} = D_{CK} \frac{\partial C_{sa}}{\partial x} - f(C_S, C_X, C)$$

$$C_S(x,0) = \begin{cases} C_0 \; x \leq 0 \\ 0, \; x \geq 0 \end{cases} \; C_K(x,0) = \begin{cases} 0 \;\; x \leq 0 \\ k_0, \, x > 0 \end{cases}$$

Foaming $(C_g \leq 0)$ takes place at the value $\xi = C_s \cdot C_a$. Thus, the foam is formed at any values ξ, thus, in the case when $C_g \leq 0$ - the rate of foaming slows down, and at $C_g \geq 0$ there is an increase in the rate of foam formation [15].

$$f(C_C, C_a, C_g) = \sigma(\xi, C_g)$$

As can be seen from the expression, near the boundary of contact of solutions S and A (at $X = 0$), abundant foam is formed, and then there is a "periodic" foaming.

The kinetics of foaming is determined by the intensity of the release of gas bubbles, the next "portion" of which in turn slows the release of new bubbles, and this process is sinusoidal:

$$f(C_f) = \frac{\partial C_f}{\partial t} = v_1 sint - v_2 C^2$$

v_1 - the rate of gas production; v_2 - gas release delay rate.

Dependence of the chemicals concentration change in time is given on Fig. 1 and 2.

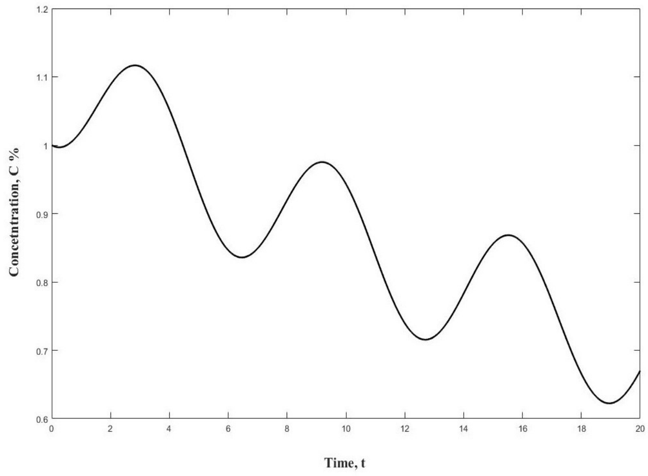

Fig. 1. Full-scale time-varying dependence of mixture concentration

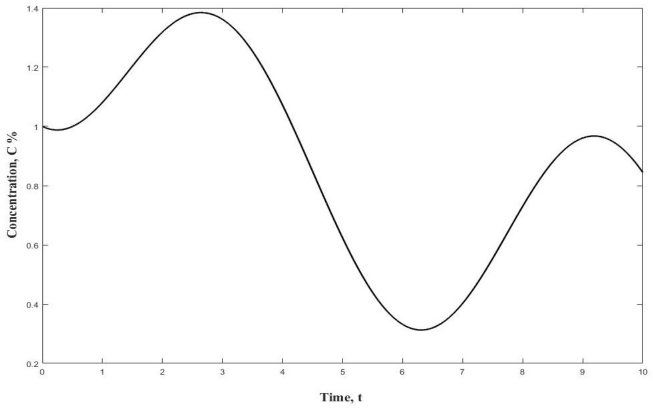

Fig. 2 Expanded scale of time-varying dependence of mixture concentration

As can be seen, the process of formation of the foam structure occurs according to the periodic law. As a result of mutual diffusion, foam is formed. This process mutual diffusion of reagents taking into account the reaction of foaming is described as:

$$\frac{\partial C_{sa}}{\partial t} = D_{CK}\frac{\partial C_{sa}}{\partial x} - f(C_S, C_X, C)$$

$$C_S(x,0) = \begin{cases} C_0 \ x \le 0 \\ 0, \ x \ge 0 \end{cases} \ C_K(x,0) = \begin{cases} 0 \ \ x \le 0 \\ k_0, \ x > 0 \end{cases}$$

Foaming $(C_f \ge 0)$ takes place at the value $\xi = C_s.C_a$.

Thus, foam is formed at any values ξ, while in the case when $C_f \le 0$ the speed of foaming slows down, and at $C_f \ge 0$ it accelerates.

$$f(C_s, C_a, C_f) = \sigma(\xi, C_f)$$

The degree of flow blocking depends on the rate of intra-layer foam generation and the simulation is that it is similar to the law of filtration with a limiting gradient and is described as [10, 11, 18, 17, 6]:

$$\left.\begin{array}{c} \overline{V} = \frac{k_0 k_f(s,r^*)}{\mu}\left[\nabla P - \frac{G(S,r^*)\nabla P}{|\nabla P|}\right], |\nabla P| > G(S,r^*) \\ \overline{V} = 0, \quad |\nabla P| < G(S,r^*) \end{array}\right\}$$

$G(S, r^*)$ - limit gradient,

$K_f(S, r^*)$ - relative permeability for foam. These parameters depend on the water saturation and microgeometry of the medium, where is r^* the minimum radius of capillaries blocked by foam films.

The system of equations describing the fluid flow taking into account the adsorption of polyacrylamide and soda mixture and acid solution with regard of the diffusion and foaming reaction in the one-dimensional case have the form:

$$m_1\frac{\partial}{\partial t}(\rho_{0,w}, S_{0,w}) + \frac{\partial}{\partial x}(\rho_{0,w}, V_{0,w}) = 0,$$

$$\frac{\partial}{\partial t}(m_0, S_f C_{s,a}) + \frac{\partial}{\partial x}(V_{s,a}C_{s,a}) = \frac{\partial}{\partial x}\left(D_{s,a}\frac{\partial C_{s,a}}{\partial x}\right) - \frac{\partial a_s}{\partial t} - f(C_s, C_a, C_f),$$

$$\frac{\partial c_f}{\partial t} = f(C_s, C_a, C_f),$$

$$v_{0,w} = -\frac{K_{0,w}\phi_{0,w}(S_w)}{\mu_{0,w}}\frac{\partial P}{\partial X},$$

$$v_{s,a} = -\frac{K_w K_f(S_f, r^*)}{\mu_a}\left(\nabla P - \frac{G(S_f, \gamma^*)\nabla P}{|\nabla P|}\right).$$

m_1 - porosity of low-permeability layers;

m_0 – porosity of foam saturated high-permeability layers.

Within the stable foam structures, the high-permeable interlayer is blocked along the length l, and as a result, the injected water begins to move along the low-permeable interlayer.

3 Conclusions

The results obtained can provides the basis for the development of a method for water content control under water flooding. This in turn results in a flattening of the displacement front and an increase in coverage.

When the acid solution passes through the pores, where the adsorbed PAA solution with soda is present, it forms fixed foam films. These films can break down either under the influence of a large pressure drop, or due to "aging".

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