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QUASI-PERIODIC IN-SITU FOAMING IN PROCESSES OF SELECTIVE INSULATION OF HIGH-PERMEABLE CHANNELS OF THE POROUS MEDIUM

Abstract

Results of experimental and theoretical researches of in-situ quasiperiodic foaming in porous channels are presented under filtration of the concentrated water solutions of gas-yielding and gas-forming solutions with the purpose of shut-off of water-out layers. Filtration characteristic of injected water solutions of foam making chemical agents along flow tubes has been researched. The task in view has been shown to search space-time distribution of injected blocking solutions.

Selective insulation of water-out layers with barriers generated by high-viscous gels or insoluble sediments, not always leads to desirable results. Field experience confirms, that a barrier, generated on small distance from a well bottom, falls by fluid flow which restores the configuration and injected water moves to a layer on high-permeability channels once again.

Increase of flow diverting efficiency it is possible to reach by creation of not an individual barrier, but by the sequence alternating interpenetrating insulation barriers remote from each other on some distance in high-permeability zones.

Such barriers can be organized by consecutive injection of gas-forming and gas-yielding solutions with additives of water-soluble polymers and their delivery in water-saturated zones, providing conditions for pseudoperiodic foaming.

Let us suppose that into homogeneous horizontal interlayer it is consecutively injected chemical agents S and K, dissolved in a water phase, in-situ reaction between which leads to formation of foamy structure. Condition for periodic foaming is contact of agents in water solutions. We shall consider interaction of two dissolved substances (S and K) with foam formation.

Originally the boundary of contact between contacting substances S and K is maximal and formation of foamy structure is possible only at the presence of mutual contact.

Here speed of moving of foam formation boundary depends not only on factors of diffusion of two substances, but also on their initial concentration in solutions and stoichiometric ratio under gas generation reaction.

Foaming process is experimentally studied in the PVT cell due to stochiometric reactions of water solutions of chemical agents. In the laboratory researches (Fig.1) it is established, that dynamic mixing of solutions it is possible to achieve a various degree of intensity of agents contact leading to the new stages of foaming.

In [1, 2] periodic sedimentation is considered under misable solutions flow and the theoretical substantiation of this process is offered. Zeldovich and Todes, being based on this assumption, have shown existence of critical supersaturation value of a solution without achievement which settling out is impossible and sizes of dimension

of length and time, in a unique dimensionless combination $\dfrac{x}{\sqrt{Dt}}$. Thus n-th deposit is connected with dependence: $x_n = n\sqrt{Dt_n}$ [1]

Here it is the most natural to accept probability of formation of a gas bubble germs in the time unit on length unit (W_0) at the given concentration of reacting substances. Such probability has dimension of 1 cm/s.

Fig. 1.

Unlike it foaming process basically is characterized by adsorption value and interaction degree of the dissolved substances, rate of foam growth and intensity of foaming in the next element of porous space.

In the offered work polyacrylamide (PAA) adsorbed from the concentrated water solution of sodium carbonate is considered as a uniform polymer solution since the sodium carbonate will be adsorbed jointly with a polymer solution.

While solving the given problem it is necessary to know the flow character of injected chemical agents along of flow tubes. The task is reduced to search space-time distribution of concentration of impurity in injected solution.

The equation for one-dimensional filtration under $V = V_0 = const$ in view of convective diffusions will be as [3, 4, 5]:

$$V\frac{\partial C}{\partial x} + \frac{\partial (m_0 C)}{\partial x} + \frac{\partial a_S}{\partial t} = D\frac{\partial^2 C}{\partial x^2}. \tag{1}$$

In mass transfer between a filtrate and a solid phase to the equations (1) it is necessary to add the kinetics equation and exchange isotherms.

$$\frac{\partial a_S}{\partial t} = \beta\left(C - C_*\right), \tag{2}$$

$$a_S = f\left(C_*\right), \tag{3}$$

where C is concentration of PAA solution with inclusions of a sodium carbonate it any point x in time t, a is mass concentration in volume unit of the porous medium; C_* is concentration of a solution of equilibrium adsorption a_S; β is kinetic factor of adsorption; m_0 is porosity depending on the content of adsorbed substances, "absorbed" by a solid phase in the porous media. Here we accept

$$\frac{\partial\left(m_0 C\right)}{\partial t} \approx m'\frac{\partial C}{\partial t}.$$

$$m' = m_0 + \frac{a_s}{\delta}$$

m_0 is initial porosity of breed; δ is density of sorbing substances in a solid phase.

If during displacement of a solution adsorption speed of substance is considerably higher than diffusion speed, in the equation (1) it is possible to accept $D = 0$.

And then it will be

$$V\frac{\partial C}{\partial x} + m'\frac{\partial C}{\partial t} + \frac{\partial a_S}{\partial t} = 0. \tag{4}$$

At a linear isotherm:

$$a_S = H \cdot C_*, \tag{5}$$

where H is Henry's factor. The equations (2), (4) and (5) are supplemented with the following initial and boundary conditions:

$$
\begin{aligned}
C\left(x,t\right) &= C_0 &&\text{at} && x = 0,\\
C\left(x,t\right) &= 0 &&\text{at} && t = 0,\\
a\left(x,t\right) &= C_0 &&\text{at} && t = 0,\\
m'\left(x,t\right) &= m_0 &&\text{at} && t = 0,
\end{aligned}
\tag{6}
$$

where C_0 is solution concentration at entry of layer.

The solution of system (2), (4) and (5) under condition of (6) is similar to one presented in [4]

$$\frac{C}{C_0} = 0,5\left[1 + F^*\left(\varphi\right)\right], \tag{7}$$

where $F^*\left(\varphi\right) = 1 - F\left[\varphi\right]$; $F\left(\varphi\right) = \dfrac{2}{\sqrt{\pi}}\displaystyle\int\limits_0^x e^{-u^2}\,du$ is integral of probability and

$\varphi = \sqrt{\dfrac{\beta}{\Gamma}\left(t - \dfrac{mx}{V}\right)} - \sqrt{\dfrac{\beta x}{V}}.$

Adsorption of concentrated PAA solution with soda ash on layer length will be defined by width of a transitive part which changes in an interval $C = \left(0,01 \div 0,99\right)C_0$. From these conditions it follows $0,02 \le F^*\left(\varphi\right) \le 1,98$. By table [6] for function $F\left(\varphi\right) = -0,98 \div 0,98$ the area of argument change $-1,65 \le \varphi \le 1,65$ or adsorption zone $\sqrt{x_{0,01}} - \sqrt{x_{0,99}} = 3,3\sqrt{\dfrac{V}{\beta}}$ are found.

Possible value of width of PAA solution with soda ash adsorption zone on sandstone, where the values of porosity $m_0 = 24\%$, permeability $k = 4,0$ D, Henry's

factor $H = 0,582$ according to [4] found $\beta = 0,36 \cdot 10^{-3}$ 1/min. And speed of a filtration under solution injection $V = 0,5$ m/day $= 0,347 \cdot 10^{-3}$ m/min, equals $l = 3,2$ m.

In the obtained adsorption zone generation of barriers for selective isolation of water out interlayer is necessary. Solution adsorbed across the layer leads to formation of the non-uniform alternating barriers remote from each other on some distance. Foam on zone size will be formed as a result of mutual diffusion of solutions under the contact of water solutions of chemical agents.

The given process of mutual diffusion in view of processed reaction is described as:

$$\frac{\partial C_{SK}}{\partial t} = D_{SK}\frac{\partial^2 C_{SK}}{\partial X^2} - f\left(C_S, C_K, C_\Pi\right), \tag{8}$$

$$C_S\left(x,0\right) = \begin{cases} C_S = 1, & x = 0, \\ e^{-x}, & 0 < x < l, \end{cases}$$

$$C_K\left(x,0\right) = \begin{cases} 0, & x = 0, \\ e^{x}, & 0 < x < l. \end{cases}$$

Foaming $(C_f \geq 0)$ takes place at size $\xi = C_S C_K$ as well.

So, foam is formed at any values of ξ at contact C_S and C_K. In case when $C_f > 0$ foaming speed is slowed down, and at $C_n \leq 0$ it is accelerated.

As is seen from expression, near to border of contact of gas-yielding solutions S and K (at $X = 0$) it is formed plentiful foam, and then "quasiperiodic" foaming is observed.

At the point $\xi = (C_C C_K) = 0$ speed of foam formation will be maximal. The process can be illustrated as it is presented in Fig. 2.

Foaming kinetics depends on quantity of allocated gas bubbles, simultaneously promoting delay of allocated new gas bubbles.

Fig. 2.

$$f\left(C_\Pi\right) = \frac{\partial C_\Pi}{\partial t} = \vartheta_1 - \vartheta_2 C^2$$

ϑ_1 is speed of gas generation;

ϑ_2 is speed of gas liberation delay.

Having accepted that there is a linear correlation between bubbles concentration in water solution and pressure :

$$P = kC_n$$

where k is rate of pressure change;

$$\frac{\partial P}{\partial t} = a_1 - a_2 P^2,$$

$$P|_{t=0} = 0,$$

where $a_1 = k\vartheta_1$ (k is rate of gas bubbles generation); $a_2 = \vartheta_2$ is the factor considering influence of before allocated gas germs on speed of new bubbles formation.

Solution of the given equation can be found in the form of:

$$kC_\Pi = P = \sqrt{\frac{a_1}{a_2} \left(1 - \frac{2}{e^{2\sqrt{a_1 a_2 (t+c')}+1}} \right)},$$

where c' is integral constant.

The received results can form a basis for development of method of water cutting regulation under flooding of oil saturated layers. In due time this leads to sweep efficiency increase and displacement front alignment.

Under the acid solution flow in the porous media where there are PAA solution with soda adsorbed, immovable foam films forms. These films can collapse either under big pressure drop, or owing to "ageing".

In the next injection stage liquid is blocked by foam films which has practically long life span. Liquid flow thus occurs on small number of channels, sufficient for formation of through ways of course.

In such system at the given pressure drop on borders gradually it is established quasi-steady mode at which a part of films periodically collapses and recycles injected solutions in high pores of a layer.

The degree of flow blocking depends on speeds of in-situ foam generation and simulation process is that similar to the filtration law with a limiting gradient and it is described as [6, 7]:

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

$G (S, r^*)$ is limiting gradient;

$K_f (S, r^*)$ is relative permeability for foam. These parameters depend on a water-saturation of medium's micro geometry, where r^* is the minimal radius of capillaries, which are blocked by foam films.

System of equations describing liquid flow in view of PAA with ash soda adsorption, and acid solution in view of diffusion, foaming reaction in an one-dimensional case look like:

$$m_1 \frac{\partial}{\partial t} \left(\rho_{B,H} S_{B,H} \right) + \frac{\partial}{\partial x} \left(\rho_{B,H} V_{B,H} \right) = 0,$$

$$\frac{\partial}{\partial t} \left(m' S_p C_{s,k} \right) + \frac{\partial}{\partial x} \left(V_{s,k} C_{s,k} \right) = \frac{\partial}{\partial x} \left(D_{s,k} \frac{\partial C_{s,k}}{\partial x} \right) - \frac{\partial a_S}{\partial t} - f \left(C_S, C_K, C_f \right),$$

$$\frac{\partial C_{\Pi}}{\partial t} = f\left(C_S, C_K, C_f\right),$$

$$\vartheta_{b,H} = -\frac{K_{Hu\zeta}\varphi_{d,H}\left(s_b\right)}{\mu_{b,H}}\frac{\partial P}{\partial X},$$

$$\vartheta_{s,k} = -\frac{K_b K_f\left(S_f, r^*\right)}{\mu_k}\left(\nabla P - \frac{G\left(S_f, \gamma^*\right)\nabla P}{|\nabla P|}\right).$$

m_1 is porosity of low-permeable interlayers;

m_0 is porosity of foam saturated high-permeable interlayer.

From parameters of problem it is possible to choose the dimensionless complex $\xi = K_0 G/\left(\mu_2 V_{S,k} l\right)$ describing stability, of foamy system generated in the layer.

In a limit of steady foamy systems there is a blocking of high-permeability interlayer on length l, therefore injected water starts to move on low-permeable interlayer.

There may exist the values of this parameter at which displacement fronts move in both interlayers with the same average speed that leads to increase in oil recovery factor.

At another limiting case adequating to unstable foamy systems, essential decrease of water mobility in high-permeable interlayer will not occur, as the parameter b enters into $V_{S,k}$ speed of water injection, the received result can be treated to as the fact of existence of optimal injection speed and increase of adsorbed layer width l for the foaming, leading as much as possible full oil recovery from inhomogeneous layers.

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