Peculiarities of Excitation of Self-Oscillations in Geological Systems

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Abstract. Theory of self-oscillations in the filtration of gas-liquid mixtures in a porous media is presented. Self-oscillatory mode of filtration of hydrocarbon mixtures has described. The possibility of occurrence of similar modes without phase equilibrium (the effect of "gas bearing") is discussing. System of filtration equations, including energy equation, is also explored is able to reveal such effect in filtration of geothermal waters.

1. Introduction
Self-oscillations theory in the filtration of gas-liquid mixtures in a porous media is considered in this article. It has became possible to create common scheme describing any self-oscillation system. Self-oscillation system is an open system because emergence and maintenance energy is given by an external source. The system contains a nonlinear regulator and a source of permanent (non-periodic) exposure. Nonlinear regulator transforms constant impact in periodic (e.g. intermittent) and oscillations occur due to this transformation. It should be noticed that oscillator vibrations control regulator by means of feedback and determine a phase and a frequency of it. Dissipation (of energy) in the self-oscillatory system is recovered by energy, which comes from constant source of exposure, and therefore oscillations are save. It is important to mention that self-oscillations differ from forced oscillations in the following way: frequency and amplitude of the self-oscillations are specified by the parameters of the oscillating system itself whereas the same of forced oscillations are established by the external influence. Moreover an existence of nonlinear element is suitable for limiting the amplitude of the oscillation and making the oscillatory system stable.

2. Instability of solutions of the filtration equation (linear approximations)
The pulsations of pressure, composition and flow rate of mixture can sometimes be observed in nature and laboratory conditions during a research of filtration of multiphase multicomponent mixtures through the porous space [1,2]. However quantitative description of such effects is still absent. Inferences of a number of domestic researchers involving both the possibility of occurrence of pulsations while selecting fluids from the formation and the problem of stability of gas condensate currents caused a great discussion. The authors [3] describe similar effects within working filtration models without involving any additional physical mechanisms.
The following system of equations is considered [7]:

$$
m \frac{\partial}{\partial t} (NZ_i) = V (k \beta_i \nabla P) \quad i = 1, \ldots, l,
$$

$$
\beta_i = \frac{f_r \rho_c y_i}{\mu, M_c} + \frac{f_{sc} \rho_{sc} x_i}{\mu, M_{sc}}, \quad N = \frac{S \rho_{sc}}{M_{sc}} + \frac{(1-S)\rho_c}{M_c}, \quad z_i = Vy_i + (1-V)x_i
$$

\( P \) - pressure, \( \rho_{c,sc}, \mu_{c,sc}, f_{r,sc}, M_{c,sc} \) - densities, viscosities, relative permeabilities and molecular weights of the gas and liquid phases, \( S \) - fluid saturation of the medium, \( x_i, y_i, z_i \) - the fraction in the liquid, gas and in the mixture of the \( i \)-th component, \( V \) - mole fraction of the gas.

System (1) with the equations of phase states and theirs equilibrium condition describes the equilibrium isothermal filtration of the \( l \)-component mixture with phase transitions. In case of two-component mixture the authors [3] recommend to investigate the stability of the solution in the linear approximation. It also was proved that in case of single phase or immiscible fluids the solutions of the system (1) are always stable. Instability of stationary modes happens because the dependence between an effective density \( N \) and a pressure \( p \) tends to decrease sharply. A similar phenomenon can arise when filtering carbonated liquids and gas-condensate mixtures. Thus it was shown that appearance of the \( N(p) \) dependence with the falling branch in a large-scale approximation of the theory of multicomponent filtration leads to discontinuous oscillations in time in a distributed system. In [4] the period of self-oscillations \( T \) is assessed in the linear approximation:

$$
T \sim \sqrt{\tau_f \tau_r}
$$

\( \tau_r \) - relaxation time in a two-phase system and \( \tau_l \) - convective transfer time. The simplest example of density with the falling branch is a hypothetical two-phase system where the phase densities vary more slowly than saturation with liquid (both the phase density and the saturation with liquid depend on pressure).

The definition \( N = \frac{S \rho_{sc}}{M_{sc}} + \frac{(1-S)\rho_c}{M_c} \) and the condition \( \rho_{sc} > \rho_c \) correspond to sections of retrograde condensation during the filtration of gas-condensate mixtures and nonequilibrium evaporation during the filtration of carbonated liquids.

3. Simulation of the two-phase filtration in the porous media of mixtures with a retrograde section of the phase diagram

To understand basic physical laws, determining the processes of filtration of a mixture and their numerical estimates, the simplest two and three-component hydrocarbon systems, whose thermophysical and thermodynamic properties are well studied were used as the object of research in the JIHT RAS.

It should be noted that along with an atypical phase diagram (such sections on the phase diagram, where gas content increases with increasing pressure) some additional features in functions of the relative phase permeability could be found during the research of the filtration of a two-phase mixture through a porous media. The values of the relative phase permeability functions for both the gas and liquid phases are about zero for different gas contents. As a result, a range of filtration parameters, that
guarantees appearance of selfoscillatory mode at a constant pressure drop under isothermal conditions, was discovered.

4. Mathematical model

Mathematical model of filtration was created [8]. To perform numerical calculations special program "Plast" was used. Under the assumption of equal pressure in phases under the condition of phase equilibrium in a hydrodynamic block of the program one-dimensional nonstationary filtration of a two-phase multicomponent mixture of hydrocarbons under isothermal conditions was calculated (distinctive times of phase transitions significantly less than the hydrodynamics). When it comes to the thermodynamical block, it calculates the composition of the gas and liquid phases and the liquid gas ratio at each point of space. The filtration process under the assumptions of chemical neutrality of the components in the onedimensional case is described by the mass balance equations for each component represented in a divergent form with respect to the molar densities

\[
m \frac{\partial}{\partial t} \left( \sum_{j} c_{ij} n_j s_j \right) + \frac{\partial}{\partial x} \left( \sum_{j} c_{ij} n_j U_j \right) = 0
\]

(2)

\(m\) - porosity; the index \(i\) corresponds to the component of the mixture; the index \(j\) corresponds to the phase (1 - gas, 2 - liquid); \(c_{ij}\) - molar fraction of the \(i\)-th component in the \(j\) phase of the two-phase mixture; \(n_j\) - molar density of the \(j\)-th phase; \(s_j\) - volume fraction of the \(j\)-th phase in the mixture; \(U_j\) - velocity of the \(j\)-th phase; \(t\) - time; \(x\) - coordinate. Equations of conservation of momentum are written in the Darcy's law approximation:

\[
U_j = -k \frac{f_j(s_j)}{\mu_j} \frac{\partial P}{\partial x}
\]

(3)

\(k\) - absolute permeability; \(\mu_j\) - coefficient of dynamic viscosity of the \(j\)-th phase; \(P\) - pressure; \(f_j\) - function of the relative phase permeability of the \(j\)-th phase.

Equations of state for the gas and liquid phases expressed in terms of the compressibility coefficients are also needed.

\[
P = n_j z_j RT
\]

(4)

\(z_j\) are the compressibility coefficients of the \(j\)-th phase; \(R\) - gas constant; \(T\) - temperature of the mixture.

The equilibrium concentrations of the components in both phases depend on the pressure and satisfy the following condition:

\[
\sum_i c_{ij}(P) = 1
\]

(5)
The volume fractions of the phases are related as

\[ \sum_{j} \delta_j = 1. \]  \tag{6} 

The system of equations is supplemented by boundary and initial conditions.

The results of numerical calculations, the description of the experimental setup and the results of experiments with various hydrocarbon mixtures are given in [6,8,14].

It is necessary to consider possible filtration modes. The pressure drop is known to influence the movement of fluids. The exact pressure values determine the phase diagram section and all other properties of the oscillatory system. On the one hand the internal properties of the system are expected to reduce the consumption (loss of condensate in the retrograde section, decrease in the value of the phase permeability of the gas) or the conductivity. On the other hand this reduction can be caused by pressure gradient decrease. If the gas phase stops, the pressure in front of the condensed phase will rise. Although the density of liquid phase is higher than the gas one, its velocity is significantly less and therefore system energy decreases and reaches a certain minimum value, at the same time \( \Delta E_{\text{out max}} \) - the maximum amount of energy, given for the period. The condensate evaporates when the pressure in the retrograde section increases (the effective density of fluid N decreases as pressure increases). After that, condensate gradually evaporates, making flow rate increase (increase in gas phase permeability and increase in conductivity upstream). System energy starts to increase, when gas phase involves in movement again, and reaches a certain maximum value, at the same time \( \Delta E_{\text{in max}} \) - the maximum amount of energy, supplied from the external system during the period. If

\[ \Delta E_{\text{out max}} - \Delta E_{\text{in max}} > 0 \]  \tag{7} 

then during each oscillation period the energy of the system is taken away and damped oscillations occur. If on the contrary

\[ \Delta E_{\text{out max}} - \Delta E_{\text{in max}} < 0 \]  \tag{8} 

then both system energy and oscillations increase. When

\[ \Delta E_{\text{out max}} = \Delta E_{\text{in max}} \]  \tag{9} 

the system in steady state is under periodic oscillation conditions with a constant amplitude.

Thus, analyzed system is a self-oscillatory system of oscillatory type[9].

5. Modes of filtration of gas-liquid mixtures in a porous media. Filtration of the watervapor system

Investigating geyser mechanism one can also obtain self-oscillatory mode of the two-phase filtration. It is necessary to consider the water with no retrograde sections on the phase diagram, which has an
inhomogeneous temperature field as well as the filtration of such water. The inhomogeneous temperature field is an analogue of the retrograde region, since when the mouth of the geyser is filled with water, the liquid under the ground near the hot part of the stream evaporates and self-oscillations are become possible. Inhomogeneous temperature field along the path of filtration of geothermal waters can cause self-oscillatory mode as a result of an increase in gas saturation at the site, where the temperature rises. In case of isothermal filtration of a two-phase gas-liquid mixture in a porous media an inverse relationship appears due to the nonlinearity of the phase permeability coefficients. However this inverse relationship is not negative: in a two-phase section with increasing pressure at a constant temperature the amount of liquid increases and, accordingly, the filtration resistance increases. This leads to a permanent flow rate of only the liquid phase (with insufficient gradient of pressures) in a stationary mode or to the stationary flow rate of gas and liquid phases at a sufficiently large pressure drop at an inlet and outlet of an experimental setup. In the presence of local sources of heat along the path of filtration and, consequently, a local increase in temperature, sections with the falling branch of dependence of the density of the fluid on the pressure appear. Self-oscillations depend on length of filtration path, formation permeability, viscosity of a liquid and its mineralization. In order to take into account the influence of each of these parameters, a numerical solution of the filtration equations is necessary. (Energy equation for the filtered flow should also be taken).

Solutions for the geothermal reservoir area around a productive well are given in [10-12]. The article [12] is the closest to the subject. It deals with axisymmetric non-stationary problem of the inflow of a steam-water mixture into a well with a fixed pressure drop, taking into account the heat exchange of the formation with the roof and the sole. It is shown that at the non-stationary stage of evolution the distribution of water saturation can vary nonmonotonically. Near the well to a certain distance heat exchange leads to a decrease in water saturation and then, on the contrary, to an increase in water saturation. This is due to the fact that, on the one hand, the flow of heat is expended on increasing the temperature (pressure) of the phase transition, which leads to the condensation of part of the vapor, and on the other hand - to vaporization. However calculations show that at the stationary stage heat exchange in the entire region leads to decrease in the water saturation, despite on slight increase in the temperature and, correspondingly, the pressure of the phase transition. The aim of the cited work wasn't to reveal a self-oscillatory mode, but received stationary solutions indicate that such mode is possible in a certain region of the parametric space. The identification of all possible modes of heat and mass exchange in the geothermal reservoir remains relevant, as it will promote the development of coolant recovery technologies.

6. Self-organization processes in gas-liquid systems near the saturation pressure

The latest experimental and theoretical studies of gas-containing liquids [13] have shown the rheological and relaxation properties of gas-liquid system in pre-transitional conditions to be determined by "micro balls" - the smallest gas bubbles, cooperation action of which manifests itself by approaching the saturation pressure. The balls of a new phase are obviously formed not only in liquids with dissolved gas. It also takes place in gas-condensate mixtures: balls, significantly affecting the filtration characteristics of porous media, are generated as the system moves to condensate precipitation pressure. In such conditions by means of adsorption on the surface of a porous media stable micro balls are formed. The appearance of such layer results (due to the effect of the "gas bearing") in reducing the filter resistances and increasing the flow rate of the fluid, reaching its maximum at a pressure, which is slightly higher than the saturation pressure. In the immediate vicinity of the saturation pressure, an increase in size of the balls leads to the appearance of additional hydraulic resistances due to the clogging of the micropores with liquid, so the fluid flow begins to decrease. Reducing the pressure to levels lower than the saturation pressure leads to a sharp increase in
the filter resistances. Self-oscillations of flow rate in such case are possible under the condition that the lifetime of micro balls of a gas has the same order as the characteristic filtering times.

The effects of nucleation are most clearly manifested in the filtration of multicomponent media in porous media. It is evident that with a two-phase filtration of geothermal waters in an inhomogeneous temperature field such effect can also take place.

7. Conclusions

Self-oscillatory processes during filtration in porous media can have a different physical nature, but most of them can be described by a system of equations including the equation of continuity and the equation of motion. Modes of self-oscillations and filtering parameters at which a self-oscillatory mode is possible have been detected.

An investigation of the complete system of filtration equations, including the energy equation and the effect of formation of gas micro balls, can reveal the effect of self-oscillations during the filtration of geothermal waters.

The identification of self-oscillating regimes of heat and mass transfer in the geothermal layer can contribute to the development of coolant recovery technologies.

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