SOCAR Proceedings

MATHEMATICAL MODELLING OF CARBONATE RESERVOIR DISSOLUTION AND PREDICTION OF THE CONTROLLED HYDROCHLORIC ACID TREATMENT EFFICIENCY

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A b s t r a c t

The article presents the theoretical studies results of hydrochloric acid compositions filtration in carbonate collectors porous media saturated with two-phase formation liquid. Solution of filtration problem in the process of carbonate rock leaching with possible regulation of process by hydrocarbon solvents is considered. Numerical algorithm of acid effect on oil-saturated formation is proposed and tested, which allows to determine the following parameters of filtration flow: concentration of hydrochloric acid, distribution of water saturation, pressure and other parameters. A mathematical model of the carbonate collector dissolution process using composite solvents has been developed, which allows predicting technological indicators of acid impact efficiency.

A significant part of the explored world oil reserves are within the carbonate reservoirs which can be attributed to the category of difficult to recover (complex macro- and micro-heterogeneity low productivity reservoirs, high-viscosity oil, significant content of asphaltenes, resins and paraffins) [1]. Carbonate reservoirs are characterized by a discontinuous structure, significant variability in properties, what makes their comparison difficult. When analyzing the physical and chemical properties of carbonate reservoirs that affect the filtration process, petrophysical properties are important: pore structure, specific surface porosity, permeability, fracture, cavernosity. Its scientific significance is thoroughly investigated in [1-9].

In general, a productive carbonate reservoir is classified as fractured, porous, cavernous.

Based on the research of the oil displacement process, the most significant parameter is the value of the specific filtration surface [2, 3]. The correlation dependence of the specific filtration surface area on the parameter (or pore radius) is described by the equation:

$$P_f = 380\sqrt{m/k} \qquad (1)$$

where k - permeability, μm^2; m - porosity, %.

Oil and water saturation is an important parameter of the reservoir rock. It is known that produced water can accumulate in pores in a free and a bound state. The thickness of the film water, according to current understanding, varies from 0.1 to 1 micron. Then, the water saturation of hydrophilic voids less than 0.25 microns in size should approach 100% [3].

The established statistical relationship between porosity and residual water saturation in the study of the filtration mechanism in carbonate reservoirs has the form:

$$S_B^* = \frac{c}{m}, \qquad c = const \qquad (2)$$

where, c = 66, 80, 85, 120, 128, 142, 225, 480 are the values established for carbonate reservoirs of various deposits [3].

So, based on the results of laboratory studies of the oil saturation of fractured-porous-cavernous carbonates of the Famennian age of the Rechitsa field, it was established that the oil saturation coefficient of limestones is 0.767-0.829, with porosity up to 23%. Most of the open voids in carbonates are caverns with an oil saturation of 100%. In hydrophobic reservoir rocks, oil occupies smaller pores, while water is dispersed in large pores [1].

It is known that the wettability of reservoir rock depends on the properties of water and oil, the structure of the pore space. For example, cavities have a hydrophobic surface. Currently, there are representative data on the predominantly hydrophobic nature of the surface of carbonate reservoirs [1, 3, 4]. Studies have shown that a decrease in the contact angle of wetting leads to a decrease in the residual oil saturation and

an increase in the residual water saturation of the porous medium [2-5]. Changes in the nature of oil wettability at the boundary with a porous medium can occur in the presence of surfactants contained in the displacing fluid [9, 10]. It is also known that formation oil contains surfactants and polar substances that can be adsorbed by the rock. Therefore, the integral wettability of reservoir rocks is a complex process that depends on the properties of the rock and the liquids that saturate the pore space [3, 10].

Some works [3, 4, 9, 10] state that at low permeability (less than 0.01 μm^2), the filtration mechanism is fully defined by the phenomenon of countercurrent capillary impregnation.

Hydrochloric acid exposure with regulation of the process by hydrocarbon solvents.

The use of hydrochloric acid treatments in carbonate reservoirs is a traditional and rather effective way to stimulate oil flow in production wells. Efficiency of hydrochloric acid is based on the chemical reaction of dissolution of carbonate rock (limestone, dolomite, dolomitized limestone varieties), as a result of which new voids are formed in the rock or existing pore channels and the cracks expand. The effectiveness of hydrochloric acid treatment on the bottom-hole formation zone largely depends on the depth of penetration of the acid composition into the formation and the aerial coverage of the formation [9, 10].

The condition of the bottom-hole zone formation has a great influence on the efficiency of the treatment. Depending on the degree of contamination, the type of bridging agents (pollutants) and the completeness of their dissolution in acid, the depth of penetration of the working agent and the degree of coverage by the action along the section of the formation will be different. It should be noted that the degree of coverage of the acidic impact of the heterogeneous carbonate reservoirs with conventional hydrochloric acid treatments is usually low [6, 9, 11].

During treatment, the acid moves mainly along the same channels and fractures, leaving a significant part of the reservoir unaffected. Therefore, the efficiency of hydrochloric acid treatments rapidly decreases with repeated treatments [12, 13].

Some characteristics of the mechanism and dynamics of hydrochloric acid treatments are given in [9]. By analyzing the results of a large number of treatments, he identified that the main reasons for a decrease in the effectiveness of acid treatments are:

1. During repeated treatments, the volume of injected acid solution remained the same;

2. The concentration of the hydrochloric acid composition decreased due to the diffusion effect of the displacement fluid (water with surfactants);

3. The use of separators during acid treatments provides additional resistance to fluid flow to the bottom of the well and does not provide the expected effect;

4. The presence of bridging agents (heavy oil components) prevents the acid from contacting with the rock surface and it has a negative effect on the dissolution efficiency of rock matrix.

Therefore, when carrying out treatments in wells producing paraffinic oil, some scientists have recommended a sequential scheme of hydrochloric acid treatments using hydrocarbon solvents rather than an emulsion consisting of an acid solution and a solvent [9-11, 14]. The obtained results of experimental work on the action of acid compositions showed a high increase in additionally produced oil per treatment, almost twice as much as in the implementation of the acid treatment without the use of solvents [9]. The success rate of hydrochloric acid treatments is 84%.

Theoretical studies of filtration process when using hydrochloric acid compositions have been carried out. Let us consider the case of interaction of an acidic solution with a carbonate reservoir saturated with oil. To solve the boundary value problem, a hyperbolic system of differential equations was used (the law of conservation of the mass) [2].

I. Water phase
a) the equation for the acid component:

$$\frac{\partial mS_w c_{w1}}{\partial t} + \frac{\partial QF_w c_{w1}}{\partial x} = -\frac{K_1 J}{\rho_w^0} \qquad (3)$$

b) the equation for the combined «salt-water» component:

$$\frac{\partial mS_w (1-c_{w1})}{\partial t} + \frac{\partial QF_w (1-c_{w1})}{\partial x} = \frac{K_{23} J}{\rho_w^0} \qquad (4)$$

II. Oil phase.

$$\frac{\partial mS_0 (1-c_{02})}{\partial t} + \frac{\partial QF_0 (1-c_{02})}{\partial x} = 0 \qquad (5)$$

a) the equation for the oil component:

$$\frac{\partial mS_0 c_{02}}{\partial t} + \frac{\partial QF_0 c_{02}}{\partial x} = \frac{J_0}{\rho_0^0} \qquad (6)$$

III. Gas phase.
a) the equation for gas component:

$$\frac{\partial mS_g}{\partial t} + \frac{\partial QF_g}{\partial x} = \frac{K_4 J}{\rho_g^0} - \frac{J_0}{\rho_g^0} \qquad (7)$$

IV. Rock. $$\frac{\partial (m^* - m)}{\partial x} = -\frac{J}{\rho_R^0} \qquad (8)$$

We get the following balance ratios:

$$S_g + S_w + S_0 = 1 \qquad (9)$$

$$F_g + F_w + F_0 = 1 \qquad (10)$$

As a result of determining these parameters, we obtain:

$$F_w = F_w (S_w, S_0, S_g) \qquad (11)$$

$$F_0 = F_0 (S_w, S_0, S_g) \qquad (12)$$

Functional dependence can be determined by

approximating experimental data. The resulting system is not enclosed, that is ten equations contain twelve unknowns (m, S_w, S_0, S_g, F_g, F_w, F_0, C_{w1}, C_{02}, J, J_0). Therefore, an additional correlation was introduced between the current porosity m and the concentration of the agent C_{w1}. The more reagent is released for response per unit of time, the faster the reagent contained in the rock is consumed, and hence, the higher the current porosity. This dependence can be described by the linear Darcy's law.

Assuming the conditions that in the absence of acid ($C_{w1}=0$) the porosity coefficient will be equal to the initial value $m=m_0$ and at the maximum concentration it will reach the porosity value of the rock we get the following mathematical expression:

$$m = \frac{c_{w1}}{c_{w\varnothing}}\left(m^* - m_0\right) + m_0 \qquad (13)$$

Using the conclusions of the analysis of the Gibbs thermodynamic correlation [2] which allows to relate the number of phases and components of the system with the number of independent parameters of this system, we introduce the following parameters - temperature and pressure. All other parameters are functions of these two parameters, including the concentration of gas dissolved in oil $c_{02} = c_{02}(p,T)$.

In this non-isothermal model, the temperature is assumed to be constant. And since the pressure gradient is extremely small, then its value is taken constant.

Conclusion: c_{02} = const. The experimental value c_{02} = 0.1 [12].

It is also assumed that there is no gas in the pore space $S_g = 0$, which means there is nothing to dissolve in oil, and, therefore $c_{02} = 0$. As a result, we get:

$$c_{w1} = 0.1 * \frac{S_g}{S_g + e} \qquad (14)$$

where, e – parameter of uncertainty.

Let us consider the process of hydrochloric acid impact on a carbonate oil-bearing reservoir in combination with hydrocarbon solvents. This case does not take into account the release of CO_2 into a separate gas phase. The problem was solved within the framework of a two-dimensional problem of non-stationary multicomponent fc_{wo} filtration, taking into account the above assumptions. The flow of a heterogeneous (multiphase) incompressible fluid during displacement is described by a system of differential equations for a one-dimensional flow obtained by K.M.Fedorov [12]:

$$\frac{\partial mS_w}{\partial t} + u\frac{\partial}{\partial x}F + v\frac{\partial}{\partial z}F = 0$$

$$\frac{\partial}{\partial t}mS_w c_{wk}(1+a_k) + \frac{\partial}{\partial x}F_w c_{wk} + v\frac{\partial}{\partial z}F_w c_{wk} = 0$$

$$\frac{\partial}{\partial t}m\left(S_w c_{wp} + S_0 K c_{wp}\right) + u\frac{\partial}{\partial x}\left(F_w + F_0 K\right)c_{wp} +$$

$$+v\frac{\partial}{\partial z}\left(F_w + F_0 K\right)c_{wp} = 0 \qquad (15)$$

$$u = -\Lambda\frac{\partial}{\partial x}p, \quad v = -\Lambda\frac{\partial}{\partial z}p \qquad \Lambda = k(x,z)\left(\frac{k_w}{\mu_w} + \frac{k_0}{\mu_0}\right),$$

$$\frac{\partial}{\partial x}\Lambda\frac{\partial}{\partial x}p + \frac{\partial}{\partial z}\Lambda\frac{\partial}{\partial z}p = 0, \qquad S_w + S_0 = 1$$

where, u, v – components of the mixture filtration velocity in the direction and respectively;

k, k_w, k_0 – absolute, relative phase permeabilities of water and hydrocarbon phases, respectively;

μ_w, μ_0 – dynamic viscosity;

α - quantities of adsorbed component.

The interaction of active components in the displacing fluid with the carbonate material of the rock is proposed to be taken into account by the linear change in porosity relative to the reduced concentrations of hydrochloric acid and solvent in the water phase [12].

$$m^{(i)}(a) = m_0^{(i)} + c_{wk}\left(b^{(i)}c_{wp} + \left(1 - c_{wp}\right)b_{min}^{(i)}\right) \qquad (16)$$

where the superscript i identifies zones of different initial porosity and absolute permeability ($i = 1$ is the main low permeability part of the filtration region; $i = 2$, are high permeability lenses), the subscript «0» indicates the value of the parameter corresponding to the initial one ($t = 0$);

in b_{min} - share of the rock that reacts with an acidic solution in the absence of a solvent with $c_{wp} = 0$;

in b_{max} - share of the rock that reacts in the presence of a solvent (in $b_{max} >$ in b_{min}).

These values are proportional to the initial values of porosity in the corresponding zones. Absolute permeability is considered a semi-empirical function of porosity:

$$k^{(i)} = k_0^{(i)}\left(\frac{m^{(i)}(a)}{m_0^{(i)}}\right)^n \qquad (17)$$

Correlations (15, 16) together with the Henry sorption isotherm and the assignment of the distribution constant K, encloses the system of equations (14).

The initial conditions at are set as follows:

$$S_w(x,z,0) = S_{w0} \qquad (18)$$

$$c_{wk}(x,z,0) = c_{wp}(x,z,0) = 0 \qquad (19)$$

$$m(x,z,0) = m_0^{(i)} \qquad (20)$$

Boundary conditions include impermeable bottom and top layer, which is mathematically expressed in the normal component of these borders filtration rate equaling to 0, and hence, by Darcy's law, the normal derivative of the pressure, as well as the injection and production modes. On the injection well at $x = 0$:

$$p(0,z,t) = \hat{p} \qquad (21)$$

$$S_w(0,z,t) = 1 - S_0^* \qquad (22)$$

$$S_w(0,z,t) = c_{wk}(0,z,t) = 1 \qquad (23)$$

On the production well, at $x = l$, the pressure is known:

$$p(l,z,t) = \tilde{p} \tag{24}$$

Dimensionless variables:

$$\bar{x} = \frac{x}{x_*}, \ \bar{z} = \frac{z}{z_*}, \ \bar{t} = \frac{t}{t_*}, \ \bar{k} = \frac{k}{k_*} \tag{25}$$

$$\bar{\mu} = \frac{\mu}{\mu_*}, \ \bar{p} = \frac{p}{p_*}, \ \bar{u} = \frac{u}{u_*}, \ \bar{v} = \frac{v}{v_*} \tag{26}$$

where the parameters with an asterisk at the bottom are characteristic values:

$$t_* = \frac{m_* \mu_* l_*^2}{k_* p_*}, \quad u_* = v_* = \frac{k_* p_*}{\mu_* l_*}, \quad l_* = l,$$

$$k_* = k_0^{(1)}, \quad \mu_* = \mu_0, \quad p_* = \tilde{p} \tag{27}$$

Then the mathematical model in dimensionless variables will have practically the same form. For porosity and absolute permeability, values are normalized with respect to $m_0^{(i)}$ and k_*.

Modeling filtration processes in a porous medium using methods of enhanced oil recovery, the determined values are usually expressed in terms of the functions of the dimensionless volume of the pumped liquid to the pore volume of the reservoir.

$$\tau = \frac{\iint_{0\ 0}^{t\ h} \hat{u} \, dz \, dt}{\iint_{0\ 0}^{1\ h} m_0 \, dx \, dz}, \hat{u} = u(0,z,t) \tag{28}$$

where h – the reservoir thickness [12-14]. The coefficient of current oil recovery has the form:

$$\eta = \frac{\iint_{0\ 0}^{t\ h} \hat{u} * \hat{F} \left(1 - \hat{c}_{wk} - \hat{c}_{wp}\right) dz \, dt}{\iint_{0\ 0}^{1\ h} m_0 S_0 \, dx \, dz} \tag{29}$$

Numerical studies solve this task. The finite difference approximation of the equations replaces the original differential formula with the following methods:

1) determination in alternating directions with a run-through for an elliptic equation with respect to pressure.

2) for equations having a non-divergent form with a central difference approximation of velocities in convective transfer terms of a hyperbolic type («corner against the flow» scheme) of the first order of accuracy.

Results of a numerical experiment of the process of underground leaching of layers.

The algorithm for solving the filtration problem of dissolution of a carbonate reservoir is as follows. We introduce the initial and boundary conditions to achieve a higher accuracy of the results described by differential equations in the area of two-phase fluid filtration.

Initial conditions: the reservoir system is in the initial state, $t = 0$, $x = 0$

1. The porosity of the reservoir is equal to the initial value $m = m_0$.

2. The reservoir is filled with formation water $c_{w3} = 0$.

3. There is no gas phase, the porous medium is filled with water $1 - S = 1$.

4. The concentration of the chemical is equal to the initial value $c_R = c_{R0}$.

5. There is no chemical reaction at the start of the simulation $c_i = 0$.

Boundary conditions: information about what is injected into the porous medium $t > 0$, $x = 0$.

1. The porosity coefficient is equal to the final value $m = m^*$.

2. The mineral part of the reservoir is completely dissolved $c_R = 0$.

3. The gas phase is absent in the pore space $1 - S = 1$.

4. The concentration of the acid in the solution is equal to the initial concentration $c_{w1} = c_{w0}$.

5. Initial fluid flow $Q = Q_0$.

Introducing the self-similar variable $\xi = x/t$ and assuming $S = S(\xi)$, we reduce the Buckley-Leverett equation:

$$m \frac{\partial S}{\partial t} + Q \frac{\partial F}{\partial x} = 0 \tag{30}$$

describing two-phase filtration to an ordinary differential equation:

$$\frac{\partial S}{\partial \xi}\left(\frac{\partial F}{\partial S}\frac{Q}{m} - \xi\right) = 0 \tag{31}$$

The equation has two solutions:
1) Trivial solution:

$$\frac{\partial S}{\partial \xi} = 0 \rightarrow \xi = const \tag{32}$$

2) Gradual solution:

$$\xi = \left.\frac{dF}{dS}\right|_{S=S^{\pm}} \frac{Q}{m} \tag{33}$$

To find out which of the solutions manifests itself in a particular area, it is necessary that it, being physically meaningful, satisfies the additional correlation of shock stability.

$$\xi = \left.\frac{dF}{dS}\right|_{S=S^{\pm}} \geq D \tag{34}$$

Having considered the algorithm for solving the problem in various filtration zones, there is still no way to combine these equations at the front of a chemical reaction. When analyzing the algebraic system of equations the balance ratio of substances participating in the reaction on the jump plane is described. The resulting system takes the form:

1. Acid balance

$$c_{w1}\left(Q^+\left(1-F^+\right) - m_* D\left(1-S^+\right)\right) - K_1\left(m_* - m_0\right)\frac{\rho_R^0}{\rho_w^0}D = 0 \tag{35}$$

2. Balance of salt and water

$$\left(1-c_{w1}\right)\left(Q^+\left(1-F^+\right) - m_* D\left(1-S^+\right)\right) + K_{23}\left(m_* - m_0\right)\frac{\rho_R^0}{\rho_w^0}D =$$

$$= Q^-\left(1-F^-\right) - m_0 D\left(1-S^-\right), \ K_{23} = K_2 + K_3 \tag{36}$$

3. Gas balance

$$Q^+ F^+ - m_* D S^+ + K_4\left(m_* - m_0\right)\frac{\rho_R^0}{\rho_w^0}D = Q^- F^- - m_0 D S^- \tag{37}$$

where $Q^+=Q_0$ – flow;

    m^* – final porosity;

    F^+ – Buckley -Leverett function for gas;

    S^+ – gas saturation - characterize the zone «after» the shock, and similar ones;

    Q^-, F^-, S^- – the zone «before» the jump.

The resulting algebraic system has two fundamentally different solutions:

1)

$$\frac{m_*D}{Q^-} = \frac{F^-}{S^- + \left(\dfrac{m_* - m_0}{m_0}\right)\dfrac{\rho_R^0}{\rho_w^0}\left(\dfrac{1-c_{w1}}{c_{w1}}\right)\left(K_1 + K_{23}\dfrac{c_{w1}}{1-c_{w1}}\right)} \quad (38)$$

2)

$$\frac{m_*D}{Q^+} = \frac{F^+}{S^+ + K_1\dfrac{\rho_R^0}{\rho_w^0}\left(\dfrac{1-c_{w1}}{c_{w1}}\right)\left(\dfrac{m_* - m_0}{m_0}\right)\dfrac{1}{c_{w1}}} \quad (39)$$

where m^* – final porosity;

    $Q^+=Q_0$ – describe the flow,

    S^+ – gas saturation - characterize the zone «after» the jump;

    F^+ – the Buckley-Leverett function for gas;

    Q^*, m_0, F^-, S^- – characterize the zone «before» the jump.

Based on a more detailed study of the results of numerical experiments, using graphical approach and analytical calculations a unique solution was obtained.

The results obtained during the research can be summarized as follows:

1. Based on the postulates and assumptions of the mechanics of multiphase media, general approaches to modeling the process of the effect of hydrochloric acid solutions on an oil-saturated carbonate reservoir are proposed. The analysis of enclosed models of the effect of hydrochloric acid on an oil and water-saturated reservoir and a two-phase filtration flow in a heterogeneous reservoir at a pressure above critical values is carried out.

2. The analysis of certain filtration modes of a hydrochloric acid solution in a porous medium of a carbonate reservoir has been carried out. It was determined that the problems of dissolution of carbonates have a pronounced frontal character during the movement of a liquid, allowing them to be solved analytically. The numerical solution of the processes of dissolution of carbonate rock with an acidic solution is noted in a narrow region of the porous medium. The released carbon dioxide as a result of the reaction forms a free-moving phase. At pressures above the saturation pressure, carbon dioxide dissolves in the oil phase, significantly reducing the viscosity of the oil and increasing the efficiency of its displacement. Another significant feature of the numerical solution of two-phase fluid flow in a porous medium is the stable movement of the displacement front not only in high permeability layers, but also in low permeability intervals of the productive formation.

3. With a single-phase fluid movement in a porous medium, analytical solution to the problem of acid displacement of formation water is obtained. A numerical algorithm for the acid action on an oil-saturated reservoir has been proposed and tested; it makes it possible to determine the parameters of the filtration flow: the concentration of hydrochloric acid, the distribution of water saturation, pressure and other parameters.

4. The mathematical model of the process of dissolution of carbonate reservoir rock using composite solvents allows predicting technological indices of the physical and chemical influence and their results on a bottom-hole formation zone.

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Математическое моделирование растворения карбонатных коллекторов и прогнозирование эффективности регулируемой солянокислотного воздействия

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Реферат

В статье представлены результаты теоретических исследований процесса фильтрации соляно кислотных композиций в пористых средах карбонатных коллекторов, насыщенных двухфазной пластовой жидкостью. Рассмотрено решение задачи фильтрации в процессе выщелачивания карбонатных коллекторов с возможным регулированием процесса углеводородными растворителями. Предложен и испытан численный алгоритм кислотного воздействия на нефтенасыщенный пласт, который позволяет определить следующие параметры фильтрационного потока: концентрацию соляной кислоты, распределение водонасыщенности, давление и другие параметры. Приведена математическая модель процесса растворения карбонатного коллектора с использованием композитных растворителей, позволяющая прогнозировать технологические показатели эффективности кислотного воздействия.

Ключевые слова: карбонатная порода; пористая среда; коллектор; пластовые флюиды; моделирование; кислотное воздействие; растворитель.

Karbonatlı kollektorların həllolmasının riyazi modelləşdirilməsi və tənzimlənə bilən xlorid turşusu ilə təsirinin effektivliyinin proqnozlaşdırılması

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Xülasə

Məqalədə, ikifazalı lay mayesi ilə doymuş karbonatlı kollektorların məsaməli mühitində xlorid turşusu kompozisiyalarının süzülmə prosesinin nəzəri tədqiqatlarının nəticələri təqdim olunmuşdur. Karbonatlı kollektorların yuyulması prosesində karbohidrogen həlledicilərinin vasitəsilə prosesin mümkün tənzimlənməsi ilə süzülmə məsələsinin həllinə baxılmışdır. Neftlə doymuş laya turşu ilə təsirin ədədi alqoritmi təklif olunmuş və sınaqdan keçirilmişdir. Bu isə süzülmə axınının parametrlərini – xlorid turşusunun konsentrasiyası, su ilə doymanın paylanması, təzyiq və digər parametrləri müəyyənləşdirməyə imkan verir. Kompozit həlledicilərin istifadəsi ilə karbonatlı kollektorların həllolma prosesinin riyazi modeli təqdim olunmuşdur. Riyazi model turşu ilə təsirinin effektivliyinin texnoloji göstəricilərini proqnozlaşdırmağa imkan verir.

Açar sözlər: karbonatlı süxur; məsaməli mühit; kollektor; lay flüidləri; modelləşdirmə; turşu ilə təsir; həlledici.