Geological and technological justification of the parameters of acid-clay treatment of wells

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Abstract. The article shows that modelling and design definition of the impact requires the differentiation for a specific well-formation system. The authors found that the effective use of acid-clay exposure in terrigenous strata is possible in various geological and technological conditions considering the criteria for the impact applicability and the implementation of a specific impact design. They proposed to use selective acidic solutions of selective action to increase the efficiency of secondary acid treatments.

1. Introduction
Acid treatment technologies have a significant history of application as stimulating wells. The development of new approaches to wells stimulation and the development of new technologies and compositions can transfer them to the category of geological and technical measures (GTM) that will solve the problems of developing hard-to-recover reserves (HRR) of oil and gas associated with complex pore-fractured reservoirs. Oil and gas fields widely use hydrochloric acid treatments (HAT) and their modifications: various compositions and technological features [1–4]. So, the amount of HATs is so large that the total additional oil production from the reservoir due to hydrochloric acid treatment and their modifications is such that it is possible to compare the method with methods for enhanced oil recovery (EOR) of formations [5–7]. Acid-clay treatments are also widely used, and their corresponding application may occupy a more important position among well stimulation methods.

Recently, there has been an upward trend in the share of HRR in the global balance sheet, including in Russia. Significant volumes of HRR are associated with low permeability clayed terrigenous reservoirs with their own geological features. During well operation, the permeability and porosity properties (PPP) of the reservoir deteriorate in the bottom hole formation zone (BHFZ) in comparison with the remote zone. Since deterioration of the reservoir properties of BHFZ occurs during the primary and secondary drilling, as well as further during the well operation and due to objective
physical phenomena. Here, there are the main costs of reservoir energy used to move fluids in the formation.

The degradation of PPP results from the swelling of clay cement of reservoir rocks, the precipitation of salts and various reaction products (after injection of chemicals, etc.), an increase in the water saturation of the reservoir and a decrease in the phase permeability for oil, the penetration of the smallest mechanical particles into the BHFW as from a well, and from the remote zone of the formation, there is the compaction of rocks, the adsorption layers of various origin on the surface of the pore-fissure space. Most experts estimate the radius of the bottom hole zone from several tenths to several meters.

Proper operation of the wells implies keeping the PPP of BHFW close to the natural state, as well as the work on improving the PPP of BHFW. Thus, the need to restore and improve PPP arises from the task of maintaining and intensifying hydrocarbon production.

2. Materials and methods
Numerous influence factors that reduce permeability require an individual approach to the choice of technology and an active agent for influencing the BHFW. To correctly plan the impact on productive formations and to predict its effectiveness, it is necessary to understand the processes occurring in the BHFW and to determine possible responses to the impact. For this, there is a methodology for forecasting and designing impacts with modelling as a mandatory element [8–11].

To justify the choice of the stimulating oil production method, we analyzed the geological and physical characteristics and the current state of developing production facilities of the Langepass group of fields (West Siberian oil and gas production). All objects of this group have a high number of permeable intervals of formations with increased clay content (up to 14%), low carbonate content (less than 1%). There are differences in facies conditions and, as a consequence, differences in mineralogical composition and reservoir properties.

The effectiveness of acid-clay treatments (ACTs) for terrigenous strata is well known. We conducted modelling of the impact to forecast the effectiveness of ACTs for the conditions of the Langepass group of fields by the methodological approach of the methotechnology of physicochemical effects on the formations.

3. Results and Discussion
It should consider ACTs used to increase the injectivity of injection wells and the productivity of producing wells as a method aimed at cleaning the pore space from technogenic products brought into the BHFW during the opening or operation of wells. Thus, the success of the ACTs is largely dependent on the composition of cement, binding grains of the rocks of the reservoir and the composition of the clogging substances.

It is necessary to consider, first, the mineral composition of the rocks to build a mathematical model of the distribution of the acid-clay solution in a porous medium. The presence of minerals and compounds of elements which in the process of reaction with acid-clay can form an insoluble precipitate has a great influence. Sandy rock treated with acid-clay must have a very low content of carbonates, glandular compounds. While the high content of clay is not an obstacle to the success of ACTs. Therefore, we studied the mineralogical composition of the oil-bearing terrigenous stratum JV 1/1 of the Las Yeganskoye field. Table 1 shows the average composition of the rocks forming this formation.

Table 1 demonstrates that the formation contains a large amount of feldspar (up to 34%), clay (up to 11%) and carbonates (6%). It is possible to use well treatment with the acid-clay solution (HF + HCl) to increase the production rates of wells drilling in the JV 1/1 formation.
Table 1. The mineralogical composition of the formation rock JV1/1 of the Las Yeganskoe field

| Minerals         | Percentage, % |
|------------------|---------------|
| Quartz           | 43            |
| Feldspars        | 34            |
| Micas            | 6             |
| Clays            | 11            |
| Carbonates       | 6             |

The effectiveness of ACTs depends on the presence of minerals in the rock cement that are capable to dissolve. The main chemical reactions of the interaction of acids with rock minerals have the following formulas:

\[
\text{SiO}_2+6\text{HF}\rightarrow2\text{H}^++\text{SiF}_6^2++2\text{H}_2\text{O};
\]

Quartz

\[
\text{KAlSi}_3\text{O}_8+20\text{HF}\rightarrow\text{K}^++4\text{H}^++\text{AlF}_2^++3\text{SiF}_2^2++8\text{H}_2\text{O};
\]

K-Feldspar

\[
\text{NaAlSi}_3\text{O}_8+20\text{HF}\rightarrow\text{Na}^++4\text{H}^++\text{AlF}_2^++3\text{SiF}_2^2++8\text{H}_2\text{O};
\]

Na-Feldspar

\[
\text{Al}_3\text{Si}_2\text{O}_5(\text{OH})_2+16\text{HF}\rightarrow2\text{H}^++2\text{AlF}_2^++2\text{SiF}_2^2++9\text{H}_2\text{O};
\]

Kaoinite

\[
\text{KAl}_3\text{Si}_3\text{O}_10(\text{OH})_2+24\text{HF}\rightarrow\text{K}^++2\text{H}^++3\text{AlF}_2^++3\text{SiF}_2^2++12\text{H}_2\text{O};
\]

Ilite

\[
\text{CaCO}_3+\text{H}^+\rightarrow\text{Ca}^{2+}+\text{HCO}_3^-.
\]

Carbonate

The problems of processing secondary sedimentation reactions in the formation during acid treatments have a partial solution by introducing special additives into the working solution, as well as using various technological methods.

During processing, the feldspars and clays dissolve with hydrofluoric acid and the carbonates and some clays dissolve with hydrochloric acid. In these two stages of the dissolution of the reservoir rock, the feldspars and clays are completely dissolved by hydrofluoric acid and their concentration decreases, then the carbonates and some clays dissolve in another area and the hydrochloric acid concentration decreases. We conventionally divide the model layer into three flow areas of the injected solution: the 1st area corresponds to the flow of a solution containing hydrofluoric and hydrochloric acids (feldspars and clay dissolve); 2nd area corresponds to the flow of an acid solution containing hydrochloric acid and salts obtained as a result of a dissolution reaction (carbonates and part of clays dissolve); 3rd area corresponds to the flow of a solution of reaction products along with formation with initial filtration parameters.

We considered the process of equilibrium dissolution of a porous medium containing soluble minerals with an acid solution (a mixture of hydrochloric and hydrofluoric acids). The model neglects the diffusion transfer of components compared to the convective, gravitational pressure drop across the bottom of the well compared to the hydrodynamic one.

The system of equations describing the process of filtering a clay-acid solution and reaction products obtained as a result of dissolution consists of continuity equations for each component of the solution and the equation of motion:

\[
\frac{\partial m \rho_i c_{i\text{HF}}}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \cdot m \cdot \rho_i^{0} \cdot c_{\text{HF}} \cdot v \right) = -K_{sh} \cdot J_{sh} - K_{g1} \cdot J_{g1};
\]

\[
\frac{\partial m \rho_i c_{i\text{HCl}}}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \cdot m \cdot \rho_i^{0} \cdot c_{\text{HCl}} \cdot v \right) = -K_{k} \cdot J_{k} - K_{g2} \cdot J_{g2};
\]

\[
\frac{\partial m \rho_i c_1}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r \cdot m \cdot \rho_i^{0} \cdot c_1 \cdot v \right) = -K_{1sh} \cdot J_{sh} - K_{1g} \cdot J_{g1};
\]

(1)
respectively, obtained as a result of the reaction dissolution of water in the solution, are salts from the reaction and a changed amount of hydrochloric acid in the formation, quartz, feldspars and a part of clays, hydrochloric acid, where

\[ k_{g}, 1_{sh}, 1_{g}, 2_{k}, 2_{2g} \]

are threaded in hydrochloric acid there are salts obtained as a result of dissolution reactions, in the formation there are all the original minerals with hydrofluoric acid. hydrochloric acid in the solution due to the water released as a result of the dissolution of rock conditions, have the following form:

\[ \text{reactions under the condition of equilibrium of the process, considering the initial and boundary parameters at the break obtained from the conditions of mass balance at the fronts of chemical reactions.} \]

took the stoichiometric coefficients as the average in each group of minerals.

minerals, porosity is equal to the initial value.

It is assumed that feldspars include K-feldspar and Na-feldspar. The clay include kaolinite, smectite, illite, montmorillonite, bentonite. Carbonates include calcite and magnesite-dolomite. We calculated the change in the permeability of the treated zones of the formation according to the

where \( m \) is the porosity of the rock, \( \rho_{i,R,sh,g}, 0 \) are the densities of water, rocks, minerals of the rock, respectively, with \( HF, HCL, 1,2,5 \) are the concentrations of hydrogen fluoride, hydrochloric acid, and salts obtained as a result of the reaction dissolution of water in the solution, \( v \) is the fluid flow rate, \( K_{sh,g1,k,2g,1sh,g,2k,22g} \) are the stoichiometric dissolution reaction coefficients, \( J_{sh,g1,k,g2} \) are the reaction rates of the dissolution of feldspars, hydrogen fluoride clay acid and carbonates and parts of clays with hydrochloric acid, \( \alpha_{sh,g,k.sol,g} \) are volume content of feldspars, clay, carbonates and parts of clays that are threaded in hydrochloric acid \( (\alpha = c_{i}; \rho_{R}/\rho_{i}) \), \( r_{e} \) is the well radius, \( Q \) is the fluid flow rate, and \( h \) is the formation thickness.

For different flow areas, there are the following initial and boundary conditions: at the initial time, there is water in the formation, the concentration of acids in the solution is equal to the initial, the concentration of minerals in the rock and porosity are equal to the initial values; at the zero boundary, the concentration of acids in the solution is equal to the initial, the penetrations of the acid solution (hydrofluoric and hydrochloric, respectively), \( v_{sh}, v_{g}, k, g_{1}, g_{2} \), \( h_{sh}, h_{g}, k, g_{1}, g_{2} \) are the penetration depth of the acid solution (hydrofluoric and hydrochloric, respectively), \( c_{HF} \) are the concentrations of hydrogen fluoride, hydrochloric acid, and salts \( \alpha_{sh,g,k.sol,g} \) are volume content of feldspars, clay, carbonates and parts of clays that are threaded in hydrochloric acid \( (\alpha = c_{i}; \rho_{R}/\rho_{i}) \), \( r_{e} \) is the well radius, \( Q \) is the fluid flow rate, and \( h \) is the formation thickness.

The hyperbolic system of equations allows discontinuous solutions. The values of the unknown parameters at the break obtained from the conditions of mass balance at the fronts of chemical reactions under the condition of equilibrium of the process, considering the initial and boundary conditions, have the following form:

\[ r_{1}^{2} = \frac{V_{n} \cdot J(\pi \cdot \square) \rho_{i}^{0} \cdot c_{HF}}{m_{1} \cdot \rho_{i}^{0} \cdot c_{HF} + K_{sh} \cdot \rho_{n}^{0} \cdot \alpha_{sh} + K_{g1} \cdot \rho_{g}^{0} \cdot (\alpha_{g} - \alpha_{sol,g})}; \]

\[ V_{1} = (V_{0}/(\pi \cdot h) \rho_{i}^{0}(1 - c_{HF}) - r_{1}^{2}(m_{1} \cdot \rho_{i}^{0}(1 - c_{HF}) - K_{k} \cdot \rho_{k}^{0} \cdot \alpha_{k} + K_{vk} \cdot \rho_{k}^{0} \cdot \alpha_{k} - m_{2} \cdot \rho_{i}^{0} - K_{vsh} \cdot \rho_{sh}^{0} \cdot \alpha_{sh} - K_{vgl} \cdot \rho_{g}^{0} \cdot (\alpha_{g} - \alpha_{sol,g}) - K_{1sh} \cdot \rho_{sh}^{0} \cdot \alpha_{sh} - K_{11g} \cdot \rho_{g}^{0} \cdot (\alpha_{g} - \alpha_{sol,g}) - \frac{\pi h}{\rho_{i}^{0}}); \]

\[ c_{HCL} = \frac{r_{2}^{2}(m_{1} \cdot \rho_{1}^{0} \cdot c_{HCL} - K_{k} \cdot \rho_{k}^{0} \cdot \alpha_{k} - V_{0}/(\pi \cdot \square) \rho_{i}^{0})}{V_{1}/(\pi \cdot \square) \rho_{i}^{0} \cdot c_{HCL}}; \]

where \( r_{1,2} \) is the penetration depth of the acid solution (hydrofluoric and hydrochloric, respectively), \( V_{0,1} \) is the initial injection volume after the reaction, \( c_{HCL} \) is the decrease in the concentration of hydrochloric acid in the solution due to the water released as a result of the dissolution of rock minerals with hydrofluoric acid.

We calculated the change in the permeability of the treated zones of the formation according to the
Cozen-Karman law:

\[ \frac{k(r)}{k_0(r)} = \left( \frac{m}{m_0} \right)^n, \]

where \( k(r), k_0(r) \) is the permeability of the formation after and before acid treatment, \( n \) is an exponent \( (n = 10) \).

We calculated the relative productivity for the interlayers in the stratified formation according to the formula:

\[ Q_i / \Delta P = \frac{2 \pi h_i}{\mu_i} \left( \frac{1}{\int_{r_1}^{r_2} \frac{dr}{k_i(r)}} \right), \]

where \( Q/\Delta P \) is the productivity of the layer, \( k \) is the permeability of the layer after acid-clay treatment, \( i \) is the number of the layer in the stratified formation.

To assess the effectiveness of the impact, we considered a model well with a geological and statistical section built on the data from Table 2, shown in Table 3 and the composition of the rocks from Table 1.

**Table 2. Models of formations of typical objects used for mathematical modelling**

| Formation, field       | Interlayer | Thickness, m | Absolute permeability, mm² | Porosity, % |
|------------------------|------------|--------------|-----------------------------|-------------|
| JV 1/1, Las Yeganskoye | 1          | 3.0          | 0.014                       | 16          |
|                        | 2          | 1.5          | 0.005                       | 16          |
| AV 1/3, Yuzhno-Pokachaevskoye | 1  | 0.54        | 0.099                       | 19          |
|                        | 2          | 0.95         | 0.045                       | 19          |
|                        | 3          | 1.4          | 0.020                       | 19          |

**Table 3. Data on the structure and injectivity of wells selected for acid-clay treatment**

| Formation | Permeability interlayers, MD | Layer thickness, m | The maximum production rate of the well for the entire period of operation Q<sub>max</sub>, t / day | Well production rate Q, t / day |
|-----------|-----------------------------|-------------------|-----------------------------------------------|-------------------------------|
| JV 1/1    | 0.014                        | 3.0               | 40                                            | 8                             |
|           | 0.005                        | 1.5               |                                               |                               |
|           | 0.099                        | 0.54              |                                               |                               |
| AV 1/3    | 0.045                        | 0.95              | 120                                           | 80                            |
|           | 0.02                         | 1.4               |                                               |                               |

The main criteria for selecting wells for treatment are the following factors: a drop in fluid consumption during operation by more than twice, low injectivity/flow rates for the fluid at a given time (for injection wells below 200 m³/day, for producers below 40 m³/day), low formation heterogeneity of thickness (number of permeable intervals of at least 2–3). The data on the decrease in the flow rate of the wells allowed to estimate the size of the bottom-hole damage zone.

To calculate the effectiveness of acid treatments of selected wells, we used the following composition of the main reagent of the working solution: 1% HF + 7% HCl. We selected the concentration of acids in the solution based on the requirements to minimize corrosion of equipment and the design of the wells being treated. We chose the volume of injection of the acid solution depending on the productive formation thickness based on 20 m³ of solution per meter of thickness.

The results of forecasting the effectiveness of processing modelling well include the following: The total volume of the recommended injection of the acid-clay solution is 225 m³ and 144.5 m³ according to the facilities. Depending on the conductivity of the interlayers, this volume is distributed across the section of the layers according to the number of interlayers as follows: 205.14; 19.9 and 80.7; 45.5 and 18.26 m³. The estimated depths of the spread of pollution through the interlayers for the considered wells, considering the drop in their injectivity during operation, amounted to 0.66; 0.339; 0.66; 0.387.
and 0.261 m. The penetration radius of the acid solution through the interlayers in the analyzed wells, calculated by the proposed method, was 0.41; 0.231; 0.582; 0.355 and 0.23 m. We calculated changes in fluid flow after acid treatment of wells for each layer according to the generalized Dupuis formula considering the zonal heterogeneity of the bottom-hole zone of the wells (zones of rock leaching with acid and contamination). The figure represents the injectivity distribution of model wells in the interlayers before and after acid treatment.

The purpose of acid treatment of the production formation, as noted above, is to clean up the cremated filtration channels, create new channels and expand the existing ones by dissolving the rock matrix.

Fulfilment of the purpose leads to an increase in the effective diameter of the well and the bottom-hole formation zone. ACTs with proper planning and implementation, for the most part, contribute to increasing well productivity by reducing the skin factor in the BHFZ to negative values. Using the methotechnological approach, the correct planning of acid treatment requires modelling processes in the BHFZ and processing design.

When processing of BHFZ with acid without any modifiers, its maximum effect on the rock occurs in the wellbore zone of the formation. Acid loses most of its activity at the entrance to the formation, and the remote zones of the formation are practically not processed. This mechanism of acid exposure leads to the very intensive formation of the maximum number of new dissolution channels and expansion of old channels in the near-wellbore zone, and even at a small distance from the wellbore in the formation, the formation of dissolution channels and expansion of old ones practically does not occur. Laboratory experiments and field practice confirm that, during the process of being injected into the formation, the acid moves mainly along the same channels and cracks and leaves a significant part of the productive formation without impact. More permeable intervals are processed, and low permeability ones remain without improvement. Therefore, the efficiency of acid treatment drops rapidly during repeated treatments in one well.

![Figure 1. Charts of the distribution of injectivity in the interlayers before and after acid treatment of model wells of the formations: a) group I, b) group II](image-url)

(Figure 1. Charts of the distribution of injectivity in the interlayers before and after acid treatment of model wells of the formations: a) group I, b) group II)
The increase in the injection rate and a decrease in the diffusion rate, the time required for the acid to reach the rock surface, make it possible to control the process of creating new channels in the collectors during acid treatment. Russian and foreign practice use various methods aimed at reducing the diffusion rate. The basis of such methods includes compositions containing special chemicals, that cause a slowdown of the diffusion process when the acid front moves, these reagents are called decelarators. The deviation occurs simultaneously with the deceleration process when using such formulations. The decelerated composition retains its ability to dissolve the rock and can be pressed further into the formation, therefore, the active acid front deepens and deflects. This deviation effect will increase the coverage factor of the formation and increase the efficiency of acid exposure.

The acid with a decelerator of the reaction (ZSK-1M) reduces the rate of rock dissolution in the water-saturated part of reservoirs, and simultaneously increase the speed and efficiency of dissolution of hydrocarbon-saturated interlayers. The active reagent ZSK-1M allows hydrophobization of the surface of the pore-fissure space of the reservoir. The developed technology using an integrated selective reagent (CRID) based on an acid decelerator (ZSK-1M) has the above-described properties of deflecting the acid front and decelerating down the rate of its reaction with the rock. Researchers successfully tested the technology, which showed the promise of its use in various geological and physical conditions.

The technology allows to intensify the work of the following categories of wells:
- wells operating terrigenous and carbonate formations with poor reservoir properties;
- wells characterized by a weak reaction to repeated acid treatments.

The effects of CRID have the following features:
- the speed and degree of dissolution in the waterflooded part of the formation reduces by about 3 times;
- increases the speed and degree of dissolution of the oil-saturated reservoir by 1.5 times;
- the composition has a low viscosity, up to 2 MPa · s;
- does not form persistent emulsions;
- the composition has a reduced corrosion activity [0.293 g / (m² · h)];

The objects of influence include:
- wells operating terrigenous formations with low reservoir properties;
- wells characterized by a weak reaction to repeated acid treatments;
- CRID used for wells with water cutting in production of not more than 40%;
- ZSK-1 solution in a solvent for wells with water cutting in production of more than 40%.

The use of CRID reagent for a static or hydrodynamic bath in a well with a wave action or an implosive effect will increase the processing efficiency. It is possible to use the CRID technology with an additional flow-deflecting or waterproofing gel screen.

4. Conclusion
1. The specific well-formation system requires the individual modelling and design of the impact.
2. The effective ACTs use in terrigenous formations is possible in various geological and technological conditions, considering the criteria for the applicability of the impact and the implementation of the correct design of the impact.
3. It is possible to use composite acid solutions of selective action to increase the efficiency of the process of secondary acid treatments.

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