Predicting the Effectiveness of Hydrochloric Acid Treatment in an Oil Field Using the Calculation of Changes in the Skin Factor and Hydrodynamic Modeling

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Abstract. The article provides an effectiveness assessment of the designed hydrochloric acid treatment at one of the wells of the Western field (Perm Krai). Efficiency was predicted with hydrodynamic modeling of measures to intensify the influx of oil based on a preliminary calculation of the change in the skin factor. Daccord and Lenormand’s experiments were used as the basis for improving the state of the bottomhole zone. These studies allow us to calculate the decrease in filtration resistance in the near-wellbore zone of the considered well formation. The calculation took into account key factors that affect the effectiveness of hydrochloric acid treatment. Using a hydrodynamic simulator, the procedure to stimulate oil production in the studied field is designed. Based on simulation calculations, an analysis of additional oil production was carried out in comparison with the base case for 10 years of operation of this development object. The methodology used in this work will allow oil companies to more reasonably approach the design of hydrochloric acid treatments, and also take into account key factors to find optimal solutions in order to maximize the effectiveness of measures.

1. Introduction

During the development of oil fields, deterioration of the bottomhole zone (BHZ) is observed. This is caused by numerous factors that lead to the mudding of the void space and, consequently, to a decrease in well productivity. Due to these complications, there is a need for geological and technical measures to intensify oil production.

Hydrochloric acid treatment (HAT) is the most common method for stimulating oil wells in the worsened condition of the BHZ today [1 - 6]. However, with the existing experience of using this technology and the simplicity of the method, the share of successful treatments is less than 50% [7 - 9]. This indicates an inadequate approach to planning and conducting the procedure, which consists in the insufficient study of the key factors affecting the HAT effectiveness.

The procedure success can be estimated by the skin factor, which takes into account the degree of contamination of the near-wellbore zone (NWZ). The skin factor is usually calculated using the Hawkins’ formula (expression 1) [10]:

\[ S = \left( \frac{k}{k_d} - 1 \right) \cdot \ln \frac{r_d}{r_w} \]  

(1)

S is skin factor;

k is permeability coefficient of the farfield zone, μm²;
2. Materials and methods

In this paper, we propose to evaluate the HAT effectiveness in one oil well of the Western field (Perm Krai) using the Tempest More hydrodynamic simulator, which is based on a change in the skin factor calculated by the Daccord and Lenormand’s formula (expression 2) [18, 19]:

$$\Delta S = -\frac{1}{d} \cdot l n \left( 1 + A c \cdot \left( \frac{q}{D \cdot h} \right)^{-1/3} \cdot \frac{1.7 \cdot 10^4 \cdot V}{\pi \cdot h \cdot m \cdot r_w^d} \right)$$

(2)

d is fractal dimension of pore space structure in bottomhole zone;

$A c$ is acid value;

$q$ is rate of acid composition injection, $m^3$/s;

$D$ is diffusion coefficient, $m^2$/s;

$h$ is perforated thickness of formation, m;

$V$ is volume of injected acid composition, $m^3$;

$m$ is porosity, %.

Daccord and Lenormand’s experiments made it possible to derive an empirical equation that allows us to estimate the change in the skin factor taking into account many factors, which include the geological features of the reservoir, the technological parameters of the injection of the acid composition and its properties, and also the well design.

This event is scheduled for 2021. The considered well has a standard diameter of 0.146 m and reveals the Tournaisian reservoir which has a porosity of 16%. Oil and water samples were taken from this development object to study the nature of the interaction with the acid composition to prevent complications in the form of highly viscous emulsions and sediments. Using hydrodynamic modeling, it is possible to analyze the procedure effectiveness when calculating the additional oil production obtained after 10 years of this facility operation.

3. Results

In order to determine the change in the skin factor, a number of laboratory works were carried out, as well as a review of scientific publications on HAT to ensure correct calculations.
The lithological and mineralogical composition of productive deposits plays a large role in the effectiveness of HAT since an increased content of terrigenous minerals reduces the effectiveness of the measure [20 - 22]. In this regard, expression 2 takes into account the quantitative contents of calcite and dolomite in the rock, which are expressed in the fractal dimension \( d \) (expression 3):

\[
d = \frac{1.6 \cdot x + 2 \cdot y}{x + y}
\]

\( x \) is limestone content in rock, %;
\( y \) is dolomite content in rock, %.

To determine the percentage of calcite and dolomite in the rock, laboratory tests were carried out with a carbonate meter KM-04M. This device allows you to ascertain the mass content of calcite, dolomite and insoluble mineral residue in the crushed rock sample. According to the study, it was determined that the content of calcite was 84 % and dolomite – 3 %.

In expression (2), the acid value is represented by the following relationship:

\[
Ac = \frac{m \cdot C_{HCl}}{C_{rock} \cdot \theta}
\]

\( C \) is molar concentration, mol/l;
\( \theta \) is stoichiometric coefficient.

The acid composition was FLUXOCORE-210 (grade P), which shows good performance in the field experience and in laboratory tests [23]. Several laboratory tests were carried out with this AC to study its interaction with reservoir fluids in various consistencies. The state of the obtained mixtures was evaluated visually for the presence of a precipitate and phase separation, and the amount of residue was examined when filtering through a 100-mesh sieve. Table 1 illustrates some results of the tests on the reservoir fluids and AC compatibility.

**Table 1.** Compatibility of formation fluids collected from the target well with the acid composition under test.
Prepared Mixture

Composition of interacting products

| Water         | 0 % |
|---------------|-----|
| Oil           | 50 %|
| AC            | 50 %|

According to the laboratory studies on compatibility, it has been found that the AC is suitable for these conditions since there are no complications when mixing and filtering. The molar concentration of hydrochloric acid in this AC is 32.39 mol/l.

The concentration value of the reservoir depends on the percentage of calcite and dolomite in the rock, as well as on their molar concentrations $C_{CaCO_3} = 27.08$ mol/l and $C_{CaMg(CO_3)2} = 15.40$ mol/l. The concentration value of the reservoir is calculated using the following equality:

$$C_{rock} = \frac{C_{CaCO_3} \cdot x + C_{CaMg(CO_3)2} \cdot y}{x + y} \quad (5)$$

The reservoir stoichiometric coefficient presented in expression (4) is calculated like a fractal value. The stoichiometric coefficient for calcite $\theta_{CaCO_3} = 2$, and for dolomite $\theta_{CaMg(CO_3)2} = 4$, then for the collector it is calculated using the following expression:

$$\vartheta = \frac{\theta_{CaCO_3} \cdot x + \theta_{CaMg(CO_3)2} \cdot y}{x + y} \quad (6)$$

The diffusion coefficient is estimated by the Stokes-Einstein equation [24]:

$$D = \frac{k_B \cdot T}{6 \cdot \pi \cdot \mu \cdot r} \quad (7)$$

$k_B$ is Boltzmann constant, J/K;
$T$ is absolute reservoir temperature, K;
$\mu$ is dynamic viscosity of acid composition, Pa⋅s;
$r$ is diffusing particle radius, m.

The dynamic viscosity of AC was determined with a Pinkevich Viscometer (VPZh-4) and it amounted to 1.37 mPa⋅s. The radius of the diffusing AC particles, as determined with a binocular microscope, was $1.0 \cdot 10^{-6}$ m. The temperature at the bottom of the considered well is 29°C, therefore $T = 302.15$ K.

Based on the hydrodynamic parameters of the target object and the technical characteristics of the Azinmash-30 pumping unit, it was decided to pump AC into the reservoir at a rate of 9.36 l/s. The BHZ is characterized by a deteriorated state, therefore it is planned to carry out large-volume hydrochloric acid treatment. Given the specific volumes of AC with this technology [25], it is planned to inject 40 m³ with a 9.7 m perforated formation thickness into this target well.

According to the calculations and recommendations, it has been found that after the planned HAT at the target site, the change in the skin factor will be -3.9. This value corresponds to a significant decrease in filtration resistance in the BHZ and an increase in oil flow to the wellbore. For a more accurate assessment of efficiency, hydrodynamic modeling is given, which will establish the increase in oil production. The hydrodynamic model of the development object, which is presented in Figure 1,
allows us to obtain data on the values of the well flow rate and accumulated production of interest for the base and forecast options, as given in Table 2. The calculations were conducted through 2030.

![Illustration of the hydrodynamic model](image)

**Figure 1.** Illustration of the hydrodynamic model.

**Table 2.** Simulation of the basic and design variants.

| Date    | Oil flow rate, m³/day | Cumulative oil production, thous. m³ | Water flow rate, m³/day | Cumulative water production, thous. m³ |
|---------|------------------------|-------------------------------------|-------------------------|---------------------------------------|
|         | Basic | Design | Basic | Design | Basic | Design | Basic | Design | Basic | Design |
| 01.2020 | 4.1583 | 4.1583 | 36.7074 | 36.7074 | 1.0667 | 1.0667 | 36.7074 | 36.7074 | 3.7342 | 3.7342 |
| 01.2021 | 4.0424 | 10.5711 | 38.0841 | 39.4028 | 1.1826 | 3.6789 | 41.6629 | 43.0817 | 4.1026 | 4.4446 |
| 01.2022 | 3.6541 | 8.9702 | 39.4996 | 42.9740 | 1.2104 | 5.2798 | 44.1547 | 46.5835 | 4.5456 | 6.0888 |
| 01.2023 | 3.2985 | 7.0429 | 40.7666 | 45.8541 | 1.2139 | 7.2071 | 46.9223 | 49.3511 | 4.9884 | 8.4100 |
| 01.2024 | 2.9957 | 6.2093 | 41.9128 | 48.2448 | 1.2132 | 8.0407 | 49.1185 | 51.5473 | 5.4314 | 11.2205 |
| 01.2025 | 2.7520 | 5.9245 | 42.9603 | 50.4548 | 1.2136 | 8.3256 | 51.2769 | 53.6757 | 5.8744 | 14.2119 |
| 01.2026 | 2.5522 | 5.3397 | 43.9298 | 52.5485 | 1.2109 | 8.4273 | 52.5485 | 54.6773 | 6.3182 | 17.2792 |
| 01.2027 | 2.3838 | 4.9750 | 44.8293 | 54.4287 | 1.2001 | 8.1239 | 53.7108 | 55.8396 | 6.7585 | 20.3116 |
| 01.2028 | 2.2261 | 4.6390 | 45.6699 | 56.1766 | 1.1883 | 7.4533 | 54.9607 | 57.2169 | 7.1945 | 23.1674 |
| 01.2029 | 2.0844 | 4.3402 | 46.4557 | 57.8119 | 1.1758 | 6.6629 | 56.1766 | 58.4268 | 7.6260 | 25.7426 |
| 01.2030 | 1.9680 | 4.0870 | 47.1967 | 59.3506 | 1.1659 | 6.1919 | 57.8119 | 60.0738 | 8.0544 | 28.0785 |
Analyzing the data presented in Table 2, it can be concluded that a significant increase in oil production is expected, approximately a 2.5-fold growth after HAT at the target oil producing well. Based on the conducted forecast with a hydrodynamic simulator, by the beginning of 2030 the cumulative oil production will have increased by 12.15 thousand m$^3$, and the cumulative water production - by 20.02 thousand m$^3$.

4. Conclusion
This work demonstrates unique approach to predicting the effectiveness of HAT in carbonate reservoirs. The technology allows us to estimate the increase in oil production using hydrodynamic modeling which takes into account a change in the filtration resistance in the BHZ calculated on the basis of key factors. These factors include the lithological and mineralogical composition of the rock, the technological parameters of the AC injection and its properties, as well as the design features of the well. Consideration of these factors will make it possible to predict the efficiency of oil production intensification measures most accurately. This paper provides a complete calculation cycle to change the skin factor for the target object and HAT design in the hydrodynamic model. The effectiveness of this technology is substantiated according to the results of oil production growth on the basis of laboratory work to study the properties and characteristics of the applied AC, analysis of the required technological parameters of the AC injection into the formation and the nature of its interaction with formation fluids, structural features of the developed formation, as well as a review of scientific publications on the methods of well stimulation. The methodology will allow oil companies to more competently approach HAT planning, design and conducting. This method can be used to make recommendations on the selection of AC and the technological parameters of its injection into the formation in order to obtain the greatest effect.

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