Research and improvement of statistical prediction methods of efficiency of hydrochloric acid treatments

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Abstract. The paper studies the apparatus of mathematical statistics for predicting the technological efficiency of hydrochloric acid treatments. The apparatus of mathematical statistics is quite widely used to process the results of measurements of field data, for example, during the assessment of the effectiveness of various methods of oil recovery increase. As a result, we developed a method to predict the efficiency of the HAT for injection wells using power-law regression equations. With an accuracy satisfactory for field purposes (even in the presence of a sparsely representative sample of actual data), which ensures the prediction of the technological efficiency of production wells in terms of the amount of additional oil production and the value of its duration after the HAT on the adjacent injection wells, it was proposed to use regression equations of the second degree.

1. Introduction

The apparatus of mathematical statistics is widely used to process the results of measurements of field data, for example, when assessing the effectiveness of various methods of enhanced oil recovery (EOR) [1, 2]. However, the field experience of the use of this apparatus shows that to obtain a good convergence of the calculation results with the actual data, a sufficiently large sample of measurements is required, which can not always be ensured in real production conditions. We attempted to improve the methods of processing experimental data in the presence of a small sample. The way of constructing a regression equation in the form of a polynomial of the second degree was chosen as the main method for solving this problem.

The technological effect of hydrochloric acid treatments of the formation is influenced by the geological-physical and technological parameters and factors of the objects of influence. On the basis of paired correlation dependences, parameters were selected that, in terms of their significance, had a greater influence on the efficiency of hydrochloric acid treatments (HAT). These parameters were used to predict the HAT results.

2. Materials and methods

As a research tool, we used the standard Microsoft Office (MS Excel) software package. Functions implementing statistical methods of data processing and analysis were used in MS Excel in the form of special software - an add-on called “Analysis Package” and to solve optimization problems - add-ons called “Search for a solution”.

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3. Results and Discussion

It is known that the stability of the injection capacity of wells is significantly influenced, on the one hand, by the degree of purification of the injected water from solid suspended particles and oil emulsion, and, on the other hand, by the compatibility of its chemical composition with the chemical composition of the formation water of the injection objects. In both cases, the role of the HAT technology is reduced to cleaning the bottom hole formation zone of injection wells from solid bridging agents of various origins and restoring its initial injection capacity.

In carbonate reservoirs, the decolmatation process is accompanied by the formation of deep drainage channels due to the dissolution of the lime component of the rock skeleton by acid.

In order to rationalize the choice of objects for hydrochloric acid treatments and prediction of their effectiveness based on the results of the field experience in the use of HAT in the regions of the Urals-Volga region, the studies of correlation and statistical relationships were carried out between:
- the characteristics of various productive reservoirs, including several layers or interlayers (the number of layers or interlayers, their porosity and permeability before and after treatment, changes in injection capacity, characteristics of formation fluids, etc.);
- the conditions for the HAT, including specific volumes of solution and pressure drops in the well and in the reservoir (injection pressures);
- the efficiency of water treatment in the fields (increase in injection capacity and its duration after treatment, impact of water treatment on the productivity of nearby observation wells and on their fluid loss, volumes of additionally produced oil) and a number of other factors.

The obtained results allow concluding that the geological, physical and reservoir properties of carbonate deposits have a significant impact on the efficiency of HAT and dictate the need for appropriate adjustment of its technology and methods for selecting targets of impact.

The observations of the reaction of nearby observation production wells after the operation of the HAT in each focal injection well has shown that for some time after the HAT, the total water production increases significantly while the oil production remains unchanged. However, few time after the increase in water production decreases by a certain amount and is accompanied by an increase in oil production, which continues for some time, after which the value of the total production for both oil and water reaches the initial (before HAT) level.

The influence of hydrochloric acid treatments on the operation of deposits is characterized by the following factors:
1. Additional oil production from nearby observation wells is directly proportional to the reservoir porosity coefficient, the reservoir permeability coefficient, the size of the perforation interval and is inversely proportional to the water cut and distance from the injection well.
2. The duration of additional oil production in the observation wells is directly proportional to the reservoir porosity coefficient, the reservoir permeability coefficient, the size of the perforation interval and is inversely proportional to the water cut value.
3. The water content of the reacting wells is directly proportional to the porosity coefficient and inversely proportional to the permeability coefficient, the thickness of the perforation interval and the distance from the injection well.
4. The amount of additional oil production from adjacent observation wells is inversely proportional to the injection capacity of the injection wells, and its duration, on the contrary, is directly proportional to the injection capacity of the injection wells.

Studying pairwise correlations, the following statistical patterns were determined, namely:
1. The additional injection capacity of the injection wells after the HAT increases significantly with the increase in the porosity and permeability of the reservoir.
2. The duration of additional injection capacity, on the contrary, decreases with increasing porosity and permeability of the reservoir;
3. The additional injection capacity of injection wells increases significantly with the increase in injection pressure compared to reservoir pressure and eth increase in the value of specific injection of reagent.
Since the revealed patterns had clear signs of multiparametric statistical relationships between reacting and influencing factors, it was decided to use them for the purpose of a possible forecast of the final technological effect using mathematical statistics in the form of constructing and solving regression equations [3-7].

For this purpose, the geological and production results of the application of HAT for 12 wells were analyzed, summarized in Table 1, where the following parameters were presented in the form of a tabular function:

\[ Y_1 = \Delta Q_{inj} (\text{additional injection after HAT}), \quad X_1 = K_{por} (\text{reservoir porosity}), \quad X_2 = K_{perm} (\text{reservoir phase permeability}), \quad X_3 = h_{perf} (\text{perforation power}), \quad X_4 = V_{HCL} / h_{perf} (\text{specific reagent injection}), \quad X_5 = \Delta P (\text{difference between injection pressure and reservoir pressure}). \]

| №  | Y_1  | X_1  | X_2  | X_3  | X_4  | X_5  |
|----|------|------|------|------|------|------|
| 1  | -10.2| 20.1 | 145.7| 1.9  | 1.11 | 55   |
| 2  | 154.6| 22.9 | 233  | 2    | 2.15 | 63   |
| 3  | -1.9 | 18.5 | 147  | 1.8  | 1.83 | 35   |
| 4  | -35  | 23.4 | 217  | 8    | 1.09 | 9    |
| 5  | 65.6 | 23.9 | 231  | 5.4  | 0.78 | 65   |
| 6  | 63   | 19.6 | 42.7 | 1.2  | 2.83 | 70   |
| 7  | 145  | 23   | 275  | 2.8  | 1.21 | 62   |
| 8  | -20.6| 24.5 | 340  | 0.8  | 5.71 | 35   |
| 9  | -48.4| 24.9 | 378  | 11.8 | 0.28 | 21   |
| 10 | 86.9 | 22.7 | 210  | 4.8  | 1.35 | 61   |
| 11 | 14   | 23.8 | 294  | 8    | 1.60 | 12   |
| 12 | 139  | 23.9 | 297  | 4.6  | 0.85 | 85   |

The processing experimental data has shown that the results of the experiment in the form of a table function in most cases with a sufficient approximation are reflected by the full cubic polynomial. Usually the third degree is not only sufficient, but also excessive, i.e. the number of terms of the polynomial can be reduced without significant loss of accuracy [8-12].

For the reduced table function, in accordance with [1], we compose a polynomial of degree 2 of the form:

\[ Y_1 = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + b_5 x_5 + b_6 x_1 x_2 + b_7 x_1 x_3 + b_8 x_1 x_4 + b_9 x_1 x_5 + b_10 x_2 x_3 + \ldots + b_{25} x_1 x_2 x_3 x_4 x_5, \]

(1)

where \( x_1 = K_{por}, \ x_2 = K_{perm}, \ x_3 = h_{perf}, \ x_4 = V_{HCL} / h_{perf}, \ x_5 = \Delta P, \ Y_1 = \Delta Q_{inj} \).

Let us investigate the components of the polynomial by means of correlation analysis. Correlation is used to quantify the relationship between two datasets, presented in dimensionless form. The correlation coefficient of a sample is the covariance of two data sets divided by the product of their standard deviations [1].

Correlation analysis allows establishing whether datasets are associated in magnitude, that is, whether large values from one dataset are associated with large values from another (negative correlation), or the data of two datasets are not related in any way (correlation is close to zero).

After the calculations, the following regression equation was obtained to predict the injection capacity of an injection well:

\[ Y_1 = -0.023 - 2.24 x_1 + 0.4 x_3 - 0.52 x_4 - 3.3 x_5 + 0.079 x_1 x_2 - 7.35 x_1 x_3 - 0.19 x_1 x_4 + 1.96 x_1 x_5 - 0.004 x_2 x_3 + 1.96 x_2 x_4 + 0.46 x_2 x_5 + 3.72 x_3 x_5 + 0.2 x_3^2 - 0.011 x_4^2 + 4.42 x_5^2 - 1.83 x_1^2 + 0.021 x_2^2, \]

(2)

where \( x_1 = K_{por}, \ x_2 = K_{perm}, \ x_3 = h_{perf}, \ x_4 = V_{HCL} / h_{perf}, \ x_5 = \Delta P, \ Y_1 = \Delta Q_{inj} \).
We get the equation in the form (2) and a comparison table of calculated and actual values (table 2). It is seen that the maximum error does not exceed 2.24%, which is an acceptable result.

Table 2. Comparison of calculated and actual values to predict the injection capacity of injection wells in the Bavlinskoye field

| №  | Calculation | Fact  | Deviation | Squar. dev. | Error, % |
|----|-------------|-------|-----------|-------------|----------|
| 1  | -10.15      | -10.2 | 0.04672015| 0.002182760 | 0.46     |
| 2  | 154.69      | 154.6 | 0.089246171| 0.007964879 | 0.06     |
| 3  | -1.94       | -1.9  | -0.042511727| 0.00187247  | 2.24     |
| 4  | -35.02      | -35   | -0.0197173 | 0.00388772  | 0.06     |
| 5  | 65.59       | 65.6  | 0.000607979| 0.00036820  | 0.01     |
| 6  | 62.97       | 63    | -0.030265455| 0.000915998 | 0.05     |
| 7  | 144.91      | 145   | 0.092953753| 0.008640400 | 0.06     |
| 8  | -20.61      | -20.6 | -0.00705564| 0.000049782 | 0.03     |
| 9  | -48.41      | -48.4 | -0.006901884| 0.000047636 | 0.01     |
| 10 | 86.92       | 86.9  | 0.021005243| 0.000441220 | 0.02     |
| 11 | 14.04       | 14    | 0.036067547| 0.001300868 | 0.26     |
| 12 | 139.00      | 139   | 0.002182478| 0.000004763 | 0.01     |

The dependence of the duration of the effect ($t_{inj}$), on different parameters was also obtained:

$$Y_2=-2.16-18.75x_1+5.72x_3-5.0x_4-10.34x_5-1.13x_1x_3-26.42x_1x_4-1.21x_1x_5 +27.78x_1x_5+0.08x_2x_3+27.78x_1x_4+2.92x_3x_5+10.76x_4x_5+8.86x_4^2+0.05x_2^2-22.02x_1x_4^2-2.49x_2^2-0.015x_5^2,$$

where

$$x_1 = K_{por}, \quad x_2 = K_{perm}, \quad x_3 = h_{perf}, \quad x_4 = \frac{V_{HCL}}{h_{perf}}, \quad x_5 = \Delta P, \quad Y_2 = \Delta t_{inj}.$$

We compare the calculated and actual values of the parameter $Y_2=\Delta t_{inj}$ (Table 3). The maximum error does not exceed 0.45 %, which indicates good convergence of the actual values and values calculated using the equation (3).

Table 3. Comparison of the calculated and actual values of the dependence of the duration of the effect on various parameters for the wells of the Bavlinskoye field

| №  | Calculation | Fact  | Deviation | Squar. dev. | Error, % |
|----|-------------|-------|-----------|-------------|----------|
| 1  | -239.86     | -240  | 0.14314181| 0.020489580 | 0.06     |
| 2  | 29.99       | 30    | -0.005542081| 0.00030715  | 0.02     |
| 3  | -30.12      | -30   | -0.120700612| 0.014568638 | 0.40     |
| 4  | -180.09     | -180  | -0.094245091| 0.008882137 | 0.05     |
| 5  | 29.93       | 30    | -0.06715996 | 0.004510460 | 0.22     |
| 6  | 359.6       | 360   | -0.039811492| 0.00158228  | 0.01     |
| 7  | 300.05      | 300   | 0.053994282| 0.002915382 | 0.02     |
| 8  | -150.03     | -150  | -0.034856237| 0.001214957 | 0.02     |
| 9  | -240.01     | -240  | -0.041674944| 0.001736801 | 0.02     |
| 10 | 150.07      | 150   | 0.066919748| 0.004478253 | 0.04     |
| 11 | 30.13       | 30    | 0.133939072| 0.017936755 | 0.45     |
| 12 | 209.97      | 210   | -0.02613169| 0.00682865  | 0.01     |

4. Conclusion

As a result, we developed a method to predict the efficiency of the HAT for injection wells using power-law regression equations. Statistical processing of the HAT results for 12 wells (Bobrikovsky deposits of the Bavlinskoye field) showed:

- Convergence of the calculated values of increasing the injection capacity of injection wells from the actual to 2.24% or less;
Convergence of the calculated values of the duration of the additional injection capacity from the actual one to 0.45% or less. With an accuracy satisfactory for field purposes (even in the presence of a sparsely representative sample of actual data), which ensures the prediction of the technological efficiency of production wells in terms of the amount of additional oil production and the value of its duration after the HAT on the adjacent injection wells, it was proposed to use (for the same conditions) regression equations of the second degree.

Thus, it was possible to prove that the use of power regression equations, even in conditions of a sparsely representative sample of data, allows predicting the technological effect of the HAT with high accuracy in the conditions of the Bobrikovsky horizon of the Bavlinsky field, if they are constructed taking into account specific geological and production and technological data corresponding to these deposits within the specified productive area.

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