EXPRESS ASSESSMENT OF THE INTERACTION BETWEEN THE PRODUCTION AND INJECTION WELLS IN THE TOURNAISIAN-FAMENNIAN DEPOSITS OF OZERNOE FIELD

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The paper discusses Ozernoe oil field, dedicated to the Solikamsk depression and located in the north of the Perm region. Lithofacies of Ozernoe field are divided into four zones: reef slope, lower back reef, upper back reef and border. Efficiency of the implemented flooding system is evaluated according to the level of interaction between the production and injection wells. The elements of math statistics such as Spearman’s and Kendall’s rank correlation methods are used in order to determine strength and direction of correlation relation between two features. In accordance with these methods, the evaluation of the influence of injection well on production one is carried out based on available field data that include amount of injected and produced water per month for studying wells. Statistical methods based on the calculation of Spearman’s and Kendall’s rank correlation are not direct methods of evaluation of hydrodynamic connection between wells. In this regard, it is relevant to assess the reliability of its results using conventional methods such as pressure interference test. Noted that the accuracy of statistical methods based on available field data that include amount of injected and produced water per month for studying wells. Sta-

Ключевые слова: карбонатный коллектор, сложностроенная залежь, отложенная трещиноватость, раскрытие трещин, гидродинамические ис-
следования скважин, ранговая корреляция Кендэлла, гидропрослушивание пластов, литолого-
фациальные зоны.

 article

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Introduction

Ozernoe oil field is dedicated to the Solikamsk depression and located in the north of Perm region. An operator is LUKOIL-PERM LLC. Oil reserves are assigned to the Upper Visean-Bashkirian and Upper Devonian-Tournaisian carbonate complexes.

Oil deposits in the Upper Devonian-Tournaisian (Fransian (Fr), Famennian (Fm) and Tournaisian (T) deposits) are the main in terms of number of dedicated geological reserves. Tournaisan and Famennian are the most representative out of three united to the deposits. Upper Devonian-Tournaisian complex is formed in sharply differentiated sedimentation during formation of Kama-Kinel deflection system, which is the major cause of significant complexity of internal structure and variability of reservoir properties. The reservoir properties are associated with structural facies zones.

The results of analysis of core from Tournaisian-Famennian deposits on the territory of interests are summarized by A.P. Vilesov [1]. As a result of summary, the scheme of lithofacies zonation including reef crest (RC), inner reef (IR) and outer reef (OR) was proposed. Later in [2] data from the core study were complexed with data from 3D-seismic using the method of stepwise linear discriminant analysis. Litho-facies scheme was adjusted with following zones: reef slope (RS), lower back reef (LBR), upper back reef (UBR) and bioherm (B). Comparison of lithofacial schemes considered by [1] and [2] is shown on Fig. 1.

Research of fracture and spatial distribution of different types of reservoirs on the deposits of interest [3-5], revealed that lithofacial zonation made by I.S. Putilov correlate with field data, in particular with well test interpretation. Authors found that in lithofacies of upper back reef and adjoined areas crack-porous type of reservoir is dominant. The rest of reservoir is porous. These findings confirm the assumption of considerable complexity of structure. It is obvious that, recovery becomes more complex in such conditions and reservoir pressure maintenance in particular. It is known that displacement of oil by water from pore channels and crack-matrix system occurs under variety of hydrodynamic principles [6-8]. In this regard, study of waterflooding features complex deposits presented by reservoirs of different void types is relevant.

Fig. 1. Comparison of lithofacial schemes of Tournaisian-Famennian deposits of Ozernoe field
Evaluation of hydrodynamic link between producer and injector with use of statistical methods

One of the indicators for evaluation of efficiency of implemented flooding system is a level of interaction between producer and injector. There are different ways to evaluate interaction between producers and injectors in reservoir pressure maintenance system, such as tracer studies and interference test. However, they are expensive and unsuitable for express-assessment of interaction between producer and injector.

In such circumstances, be regarded as relevant statistical methods, such as Spearman's and Kendall's rank correlations [9-10], allowing to determine strength and direction of correlation between the two sign. According to these methods diagnosing the injection well influence on production is carried out on the basis of available field data of monthly volume of water injected and liquid produced from the wells of interest.

Spearman's rank correlation coefficient is non-parametric method used to study statistical relationship between phenomena. In this case, level of parallelism between two qualitative rows of studied signs is determined and strength of this relationship is given based on quantitative coefficient. The values of each sign is ranked according to the level of increase (from 1 to \( n \)), then the difference between the ranks (\( d \)) corresponding to one observation is determined. Sign \( X \) is well injectability, \( m^3/\text{day} \), factor \( Y \) is well production, tons/day. For sign \( X \) and factor \( Y \) there are grades assigned. The sequence and results of calculating of Spearman's rank correlation coefficients are considered by the example of wells located in northwestern part of the field and representing a certain element of implemented system development: injection wells № 452 and 453; production wells № 451, 454 and 455 (Fig. 2).

Table 1 below presents data and calculated Spearman's rank correlation coefficient for the pair of wells 453-455 located on a dedicated section of the deposit.

Spearman's rank correlation coefficient is calculated according to the formula

\[
p = 1 - 6 \sum \frac{d^2}{n^2 - n} = 1 - 6 \frac{424.5}{13^2 - 13} = -0.166.
\]

Spearman’s rank correlation coefficients between wells № 453 and 454 (0.221) and between the wells № 451 and 452 (\( \rho = 0.683 \)) are calculated in the same way.

Ranges of possible numerical values of Spearman’s rank correlation coefficient and the corresponding strength characteristics are presented in Table 2.

Table 2 shows almost none hydrodynamic link between the wells № 453 and 455; weak strength between wells № 453 and 454 and medium strength between wells № 451 and 452.

According to [11], the value of Spearman’s rank correlation coefficient is often underestimated. In this regard, the results of calculations must be checked using the method of Kendall's rank correlation. Presence of link between wells has to be diagnosed on the basis of the two statistical methods.

Fig. 2. Deposit section to study interaction between the wells
For calculation of Spearman’s rank correlation coefficient

<table>
<thead>
<tr>
<th>n</th>
<th>X</th>
<th>Y</th>
<th>Rank X, dx</th>
<th>Rank Y, dy</th>
<th>(dx – dy)^2</th>
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<td>188</td>
<td>5,229</td>
<td>11</td>
<td>2</td>
<td>81</td>
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</tbody>
</table>

\[
\tau = \frac{P - Q}{\frac{1}{2}N(N-1)} = \frac{35 - 43}{13(13-1)} = -0,1, \quad (1)
\]

As a result, use of the formulas lead to P equals 30 (Table 3).

Kendall’s rank correlation coefficient can be calculated using exact (1) and simplified (2) formulas:

\[
\tau = \frac{4P}{N(N-1)} = \frac{4 \cdot 35}{13(13-1)} = -0,1. \quad (2)
\]

For calculation of Kendall’s rank correlation coefficient

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>Rank X, dx</th>
<th>Rank Y, dy</th>
<th>P</th>
<th>Q</th>
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<td>123</td>
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<td>175</td>
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<td>168</td>
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<tr>
<td>188</td>
<td>5,229</td>
<td>13</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

\[
\tau = \frac{35 - 43}{13(13-1)} = -0,1. \quad (2)
\]
In order to check the null hypothesis of the equality to null of general Kendall’s rank correlation coefficient with competing hypotheses \( H_1 : \tau \neq 0 \)

with \( \alpha \) level of significance critical point has to be calculated:

\[
T_{\alpha} = z_{\alpha} \sqrt{\frac{2(2n+5)}{9n(n-1)}},
\]

where \( n \) is volume recovery; \( z_{\alpha} \) is critical point of double side area that is defined by Laplace function table.

If \( \tau < T_{\alpha} \) means there is no reason to reject the null hypothesis. Rank correlation link between qualitative characteristics is insignificant. If \( \tau > T_{\alpha} \) then a null hypothesis has to be rejected. Between qualitative characteristics there is significant rank correlation link.

The critical point \( z_{\alpha} \) is found as:

\[
\Phi(z_{\alpha}) = 1 - \frac{1-\alpha}{2} = 1 - \frac{0.05}{2} = 0.475.
\]

From Laplace table \( z_{\alpha} = 1.96 \).

The value of critical point:

\[
T_{\alpha} = 1.96 \sqrt{\frac{2(213+5)}{9 \cdot 13(13-1)}} = 0.41.
\]

Since the condition \( \tau < T_{\alpha} \) accepts the null hypothesis rank correlation link between the parameters is not significant.

Thus, both the statistical methods used to evaluate the hydrodynamic link between the injection well \( \#453 \) and production well \( \#454 \), demonstrate its actual absence.

The other two pairs of selected reservoir area Kendall’s method confirm method of Spearman.

**Evaluation of authenticity of Spearman’s and Kendall’s statistical methods of rank correlation application**

Statistical methods based on the calculation of Spearman’s and Kendall’s rank correlation coefficients are not direct methods to estimate hydrodynamic link between wells. In this regard, it is relevant to assess authenticity of its results using conventional methods such as interference test (IT).

It is known that interference test is studying of the propagation of elastic pulse (disturbances) in reservoir between wells. On this purpose, one of the wells, called disturbing well, change performance mode – it may be well shut, its switch on production with constant flow rate or bottom hole pressure and flow rate change. After the pulse was trigged pressure change is observed in the neighbor wells. It is obvious that the change in pressure in observation wells is caused by both the impulse in disturbing well and reservoir parameters in the direction of each observation wells.

LUKOIL-PERM LLC performs interference test regularly on the fields with complex geological structure, including Ozernoe. An example of hydrodynamic link assessment by interference test on the section of Tournaisian-Famennian deposits, represented by three wells is presented below (see Fig. 2).

Interference test was applied to the north-west part of deposits. During the test wells \( \#451, 454 \) and 455 were disturbing wells, \( \#452 \) and 453 were observation wells. The regimes of surrounding wells were stabilized to improve result authenticity. Example of obtained in research interference curve showing the change in pressure in observation well, is presented on Fig. 3.

The processing of interference test was carried by graphoanalitical method (integral). The method represents analytical processing of experimental response of curves. According to analytically found relationships the charts with straight lines were plotted. From the slope of these lines to the horizontal axis and the intercept on the y-axis, formation properties are defined. Obtained interference curves were processed by this method. Processing results are presented in Table 4. To assess reliably of reservoir parameters from processed interference curves the results of interpretation of build-up and drawdown curves are presented in table 4 [12-16].

Presented in the Table 4 data shows permeability obtained by interference test around wells \( \#453-454 \)
Thus, the data analysis of interference test conducted on the north-western part of the Tournaisian-Famennian deposits of Ozernoe field confirm authenticity of calculations of the link between wells by Spearman’s and Kendall’s rank correlation which leads to the possibility of their use for express solution of this task.

**Evaluation of interaction between all the wells of deposit with use of statistical methods of rank correlation**

Proven by interference test authenticity statistical methods, based on calculations of Spearman’s and Kendall’s rank correlation coefficients allows to estimate the level of interaction between the wells on entire reservoir area and not only in the areas covered by the research.

For all pairs of wells of Tournaisian-Famennian deposits of Ozernoe field Spearman's rank correlation coefficients (confirmed by Kendall) were calculated and used for estimation of interaction between the wells. The calculation results are combined with lithofacial diagrams and graphically presented in Fig. 4.

Data presented in Fig. 4 allow selecting reservoir areas with maximal and minimal influence of applied pressure maintenance system on performance of neighbor wells. Wherein, combination of results with lithofacial scheme according to I.S. Putilov allows to say that the maximal interaction between injection

---

**Table 4**

<table>
<thead>
<tr>
<th>Well №</th>
<th>Test type</th>
<th>Piezo-conductivity, m2/s</th>
<th>Hydraulic conductivity, mcm2·cm/mPa·s</th>
<th>Permeability, mD</th>
</tr>
</thead>
<tbody>
<tr>
<td>453</td>
<td>Drawdown curve</td>
<td>0.29</td>
<td>26.3</td>
<td>14.8</td>
</tr>
<tr>
<td>454</td>
<td>Build-up curve</td>
<td>0.07</td>
<td>5.8</td>
<td>1.4</td>
</tr>
<tr>
<td>455</td>
<td>Build-up curve</td>
<td>0.92</td>
<td>84.4</td>
<td>18.9</td>
</tr>
<tr>
<td>453-454</td>
<td>Interference</td>
<td>0.27</td>
<td>1.3</td>
<td>7.2</td>
</tr>
<tr>
<td>453-455</td>
<td>Interference</td>
<td>0.69</td>
<td>14.8</td>
<td>17.2</td>
</tr>
<tr>
<td>451-452</td>
<td>Interference</td>
<td>1.08</td>
<td>162.4</td>
<td>75.4</td>
</tr>
</tbody>
</table>

of 7.2 mD is in a range of permeability values defined by drawdown and build-up curves (14.8 and 1.4 respectively). A similar situation is observed for a pair of wells № 453-455. Compliance of permeability values, defined by interpretation of the interference to the values determined by pressure build-up (drawdown) is a factor that confirms authenticity of interference test.

The existence of hydrodynamic link between the wells and its intensity were measured by the piezoconductivity coefficient. Analysis of this parameter shows that the level of interaction between the wells № 451 and 452 has to be considered as maximal for the sector of interest. Besides, wells hardly communicate. These conclusions are coherent with calculation results obtained by Spearman’s and Kendall’s statistical method of rank correlation.

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Fig. 3. Curve of pressure change in observation well № 453
and production wells is observed in their placement within the same lithofacial zone. The interaction between the zones is minimal. At first this conclusion has a practical benefit in terms of corrections of current development scheme. At second, it confirms lithofacies analysis authenticity based on results of integration of core study data and 3D-seismic.

Conclusions

1. Express-assessment of the interaction between producers and injectors can be performed with use of Spearman’s and Kendall’s rank correlation methods.

2. The authenticity of statistical methods of Spearman’s and Kendall’s rank correlation in the assessment of the level of interaction between the injection and production wells confirmed by interference test (on example of Tournaisian-Famennian deposits of Ozernoe deposits).

3. Maximal level of interaction is observed between the wells located in the same lithofacial zone, allocated according to the I.S. Putilov.

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