Refining Permeability Values for History-Matching of the Reservoir Simulation Model

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Уточнение значений проницаемости при адаптации гидродинамической модели

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Reservoir simulation models are used to design oil field developments, estimate efficiency of geological and engineering operations and perform prediction calculations of long-term development performances. A method has been developed to adjust the permeability cube values during reservoir model history-matching subject to the core-derived dependence between rock petrophysical properties. The method was implemented using an example of the Bobrikovskiy formation (terrigenuous reservoir) deposit of a field in the Solikamskian depression. A statistical analysis of the Bobrikovskiy formation porosity and permeability properties was conducted following the well logging results interpretation and reservoir modelling data. We analysed differences between the initial permeability obtained after upscaling the geological model and permeability obtained after the reservoir model history-matching. The analysis revealed differences between the statistical characteristics of the permeability values based on the well logging data interpretation and the reservoir model, as well as substantial differences between the adjusted and initial permeability cubes. It was established that the initial permeability was significantly modified by manual adjustments in the process of history-matching. Extreme permeability values were defined and corrected based on the core-derived petrophysical dependence $KPR = f(KP)$, subject to ranges of porosity and permeability ratios. By using the modified permeability cube, calculations were performed to reproduce the formation production history. According to the calculation results, we achieved convergence with the actual data, while deviations were in line with the accuracy requirements to the model history-matching. Thus, this method of the permeability cube adjustment following the manual history-matching will save from the gross overestimation or underestimation of permeability in reservoir model cells.
Introduction

Presently, oil and gas field developments are supported by geological and reservoir simulations of the deposits. A geological model that characterises a deposit geology and distribution of oil and gas reserves serves as a basis for building reservoir simulation models [1-7]. Development of a fluid-flow simulation model generally starts with its geological model upscaling, which results in the transfer of parameters (porosity, permeability, saturation) to an enlarged grid while retaining the formation vertical heterogeneity [8-10]. Following the upscaling procedure, the data on fluid properties [11-13], relative permeability, capillary forces and transition zone model [14-22] are prepared to set the initial state of the reservoir model [23]. After the historical data of the well operation have been prepared, the field development history-matching and the adjustment of the development parameters are performed [24-28]. In the process of the reservoir model history-matching, the impact of the aquifer is refined, permeability in the aquifer and within the oil zone, as well as relative permeability are corrected; the well productivity and injectivity indices are adjusted (the values of skin factor and reservoir-to-well connectivity) [29, 30].

In the model development process, the formation geological and physical attributes, permeability, relative permeability curves, etc. can be refined. [31]. The above parameters are determined using the core study and well logging data [32], as well as well testing methods [33-36]. That being said, the obtained information on reservoir properties is quite limited, while uncertainty in the porosity and permeability values distribution increases with each stage of the model development. Firstly, it happens when averaging the well data to the geological model grid cells and interpolating the measurement data in the interwell space. Secondly, it takes place upon upscaling of the geological model. Thirdly, it is true for the process of the reservoir model history-matching.

The initial permeability (obtained upon the geological model upscaling) can be significantly modified, as the fluid flow distribution in the model and, therefore, the dynamics of the development indicators depend on this parameter value. Given that the initial permeability adjustment, as well as the reservoir model history-matching are manually performed, the problem of retaining the distribution features of the reservoir initial geological and physical attributes and preventing incorrect porosity and permeability values in the cubes is arising.

Thus, the quality of the reservoir model history-matching [37-39] determines the efficiency of its application for predicting the development indicators and efficient designing of geological and engineering operations [40-43]. The crucial task is to elaborate a standardised approach to permeability adjustment in the process of the reservoir model history-matching [44-46]. Let us consider the problem using the Bobrikovian formation (terrigenous reservoir) deposit of a field in the Solikamskian depression as an example. The reservoir model of the formation is a model of a three-phase isothermal fluid flow in a pore medium (terrigenous reservoir). To identify the basic regularities, the heterogeneity of reservoir properties in the Bobrikovian formation was analysed based on the results of the well log data interpretation, and differences in the permeability cubes were revealed in the upscaled geological model and history-matched reservoir model. Based on the core-driven dependence of permeability on porosity, the permeability cube was modified after manual adjustments, and the reservoir-model calculations of the Bobrikovian formation development indicators were performed.

Statistical Characteristics of Reservoir Properties of the Bobrikovian Formation Based on the Well Log Interpretation Data

The reservoirs in the Bobrikovian formation are sandstone and siltstone. To assess reservoir properties and heterogeneity of the formation, the following parameters were analysed based on the well log interpretation data: KP is the porosity ratio, u.f.; KPR is the permeability ratio, mD; H_PR is the thickness of the permeable interlayer, m.

Table 1 gives the key statistical characteristics of the parameters.

| Parameter | Average value | Median | Mode | Min. value | Max. value | Standard deviation |
|-----------|--------------|--------|------|------------|------------|--------------------|
| KP, u.f.  | 0.1502       | 0.15   | 0.15 | 0.077      | 0.251      | 0.031              |
| KPR, mD   | 254.974      | 85.1   | 85.1 | 2.3        | 4,428.5    | 485.403            |
| H_PR, m   | 1.796        | 1.4    | 0.8  | 0.1        | 12.9       | 1.4667             |
Out of the entire sample array (for 327 wells), more than a half of the porosity ratio values falls between 0.13 and 0.18 u.f., and only very few values are below 0.08 and above 0.25 u.f. The average porosity value is 0.15 u.f. In the most cases (94 %), the permeability ratio varies between 2.3 and 1000 mD, while in 70 % of the cases, the permeability does not exceed 200 mD. The average permeable interlayer thickness is 1.8 m.

Based on the well log interpretation data analysis, it has been established that the Bobrikovian formation reservoirs are generally classified as medium porosity and permeability reservoirs as per A.A. Khanin classification (class III: porosity 11-18 %, permeability 100-500 mD; class IV: porosity 10-16.8 %, permeability 1-100 mD).

### Statistical Characteristics of Reservoir Properties of the Bobrikovian Formation in the Reservoir Model

To compare the porosity and permeability values of the Bobrikovian formation based on the well log interpretation data and the reservoir model, an analysis of porosity and permeability in the reservoir model containing 423,150 cells was performed. The key statistical characteristics for the cubes were determined: porosity (PORO), initial permeability after the geological model upscaling (PERMX_ish) and permeability in the history-matched reservoir model (PERMX_adapt).

Table 2 shows the key statistical characteristics of porosity and permeability in the model.

| Parameter     | Average value | Min. value | Max. value | Standard deviation |
|---------------|---------------|------------|------------|--------------------|
| PORO, u.f.    | 0.147         | 0.079      | 0.2483     | 0.0218             |
| PERMX_ish, mD | 157.375       | 2.311      | 9,771.3    | 246.013            |
| PERMX_adapt, mD | 114.066     | 0.025      | 1,719.0    | 222.756            |
| PERMX_delta, mD | –43.310     | –9,738.5   | 1,716.39   | 325.432            |
| PERMX_k, u.f. | 2.172         | 4.92510^-5 | 743.743    | 12.124             |
| PERMX_petro, mD | 115.982     | 0.150      | 1,719.0    | 211.47             |

The difference between the adjusted and initial permeability (PERMX_delta) varies from -9,738.5 to 1,716.39 mD, while the average value is shifted to negative values (see Table 2). It was determined that in 70.2 % of cases, PERMX_delta < 0 mD, i.e. the adjusted permeability is less than the initial value; in 29 % of the cases, PERMX_delta > 0 mD, i.e. the adjusted permeability is greater than the initial value; and in 0.8 % of the cases, the permeability in the reservoir model is equal to the initial value.

In most cases (80 %), the permeability in the history-matched model differs from the initial value by an amount from -220 to +110 mD. The permeability multiplier distribution (PERMX_k) is close to the exponential distribution, the median being equal to 0.367 u.f.

Thus, when comparing the results of the parameter analysis from the well log interpretation data and the reservoir model in general, a consistency in the statistical characteristics of distributions of the porosity values was determined, while the distributions of the permeability values exhibit differences. The average permeability value based on the well log interpretation data is generally higher than that in the models upon upscaling and history-matching (parameter values are 254.974, 157.375 and 114.066 mD, respectively).

### Adjustment of Permeability Ratio in the Reservoir Model

The option of adjusting the permeability values in the history-matched model as per porosity ratio ranges based on empirical data was considered. For this purpose, the core-derived petrophysical dependence $KPR = f(KP)$ was broken down into intervals by porosity, each of...
them corresponding to a certain range of permeability variation (Fig. 1).

From the initial field of values shown in Figure 1, the area with the highest data point density was selected, while single anomalous values outside the selected area were disregarded, as the modelling used averaged data. Four porosity ranges (I-IV) were determined; for each of them boundary values of permeability were set by equations (solid green lines in Fig. 1). The designated boundaries are outlier-independent, which results in a smoother permeability cube.

![Fig. 1. Core-derived dependence of permeability on porosity](image1.png)

Permeability values in the reservoir model cell

- \( \text{PERMX}_{\text{adapt}} > \text{PERMX}_{\text{petro}} \)
- \( \text{PERMX}_{\text{adapt}} = \text{PERMX}_{\text{petro}} \)
- \( \text{PERMX}_{\text{adapt}} < \text{PERMX}_{\text{petro}} \)

![Fig. 2. The cube representing the permeability deviation from the petrophysical dependence in the history-matched model](image2.png)

The method of the adjusted permeability cube correction consists in checking whether the adjusted permeability value falls within the specified boundaries, depending on the porosity value in the reservoir model cell. If the permeability value in the reservoir model cell is outside the given boundaries, it is assigned an upper or lower boundary value of the permeability ratio, which depends on the porosity. Such an approach to the adjusted permeability cubes eliminates the gross overestimation and underestimation of the permeability ratio in the reservoir model cells.

This approach stands on the fact that the core data scale is in centimetres, and the cell size in the reservoir model is 25 x 25 metres. Therefore, the core-derived permeability values cannot be fully assigned to the model cell, especially in the area of the high permeability ratio values.

Using the permeability boundary values, a permeability cube (\( \text{PERMX}_{\text{petro}} \)) was obtained and adjusted based on the cube after the manual history-matching of the model (\( \text{PERMX}_{\text{adapt}} \)). The resulting modified permeability cube (\( \text{PERMX}_{\text{petro}} \)) in the oil-water boundary has deviations corresponding to those from the petrophysical dependence. In the calculations, the aquifer permeability is set as equal to that in the adjusted cube to exclude the effect of various aquifer settings on the calculation results. In Figure 2, red and blue colours designate anomalous high and low permeability values in the history-matched reservoir model, which outline the boundaries of the main data point cloud for the dependence of permeability on porosity (see Fig. 1).

Table 2 shows the key statistical characteristics for the permeability cube (\( \text{PERMX}_{\text{petro}} \)) modified according to the petrophysical dependence. The data in Table 2 show that in the adjusted cube, the lower permeability boundary is 0.025 mD (\( \text{PERMX}_{\text{adapt}} \) cube), and after the exclusion of anomalous values by the proposed method, it was raised to 0.15 mD (\( \text{PERMX}_{\text{petro}} \) cube), with the upper boundary of 1,719 mD remaining unchanged and the average values almost identical.

For comparison, development indicators were calculated using the permeability cubes from Table 1 (\( \text{PERMX}_{\text{ish}}, \text{PERMX}_{\text{adapt}}, \text{PERMX}_{\text{petro}} \)). For the initial and modified permeability cubes, the oil and liquid production performance based on the computation results coincides with the actual performance - both for field domes individually and for the formation in general. The greatest convergence with the historical data was obtained at the initial development period. Figure 3 shows deviations in the calculation results from the actual...
deviation from the actual performance in the adjusted cube. This approach resulted in the accuracy of the Bobrikovian formation development using permeability indicators with the actual data was achieved as a consequence of the geological model cells. Cumulative oil production was reduced therewith.

**Fig. 3. Results of the reservoir model calculations for the productive formation in general over the entire development period**

Figure 3 shows that the greatest convergence with the actual performance was achieved through the manual history-matching of the model (PERMX adapt cube). When the permeability cube was adjusted to the core to core petrophysical dependence, the deviations from the actual performance were also consistent with the accuracy requirements to the model history-matching (PERMX petro cube), the deviation in the cumulative oil production was reduced therewith.

**Conclusions**

1. From the data analysis of the well log interpretation and the reservoir model, it was established that in most cases the Bobrikovian formation permeability does not exceed 200 mD.
2. In the history-matched reservoir model, the initial permeability obtained after the upsampling of the geological model was adjusted in most cases by an amount from -220 to +110 mD.
3. The approach under consideration provides for permeability adjustment after the manual history-matching of the model subject to the porosity ranges based on core-derived dependence $KPR = f(KP)$. The result is the adjusted permeability cube PERMX petro excluding gross overestimations and underestimations in the reservoir model cells.
4. A convergence of the development indicators with the actual data was achieved as a result of the calculations in the history-matching of the Bobrikovian formation development using the adjusted cube. This approach resulted in the deviation from the actual performance in the cumulative oil production of 0.2 thousand tons, the cumulative liquid production of 1.3 thousand tons, and watercut of 3.2%, which is in line with the model history-matching requirements.

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