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

Margarita A. Smetkina<sup>1</sup>, Oleg A. Melkisev<sup>1</sup>, Maksim A. Prisyazhnyuk<sup>2</sup><sup>1</sup>Perm National Research Polytechnic University (29 Komsomolskiy ave., Perm, 614990, Russian Federation)<sup>2</sup>PermNIPIneft branch of LUKOIL-Engineering LLC in Perm (3a Permskaya st., Perm, 614015, Russian Federation)

### Уточнение значений проницаемости при адаптации гидродинамической модели

М.А. Сметкина<sup>1</sup>, О.А. Мелкишев<sup>1</sup>, М.А. Присяжнюк<sup>2</sup><sup>1</sup>Пермский национальный исследовательский политехнический университет (Россия, 614990, г. Пермь, Комсомольский пр., 29)<sup>2</sup> Филиал ООО «ЛУКОЙЛ-Инжиниринг» «ПермНИПИнефть» в г. Перми (Россия, 614000, г. Пермь, ул. Пермская, 3а)

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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 Bobrikovian formation (terrigenous reservoir) deposit of a field in the Solikamskian depression. A statistical analysis of the Bobrikovian 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 divergences 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.

#### Ключевые слова:

гидродинамическая модель, адаптация, фильтрационно-емкостные свойства, исходная проницаемость, адаптированная проницаемость, пористость, геологическая модель, ремасштабирование, результаты интерпретации геофизических исследований скважин, геолого-физические характеристики, статистические характеристики, куб проницаемости, керн, модифицированный куб проницаемости, показатели разработки.

Гидродинамическая модель (ГДМ) является инструментом для проектирования разработки нефтяных месторождений, расчета эффективности геолого-технических мероприятий (ГТМ) и выполнения прогнозных расчетов показателей разработки на долгосрочный период времени. Разработан метод корректирования значений куба проницаемости в процессе адаптации ГДМ с учетом зависимости между петрофизическими свойствами пород по данным исследования керна. Методика реализована на примере залежи бобриковского пласта (терригенный коллектор) одного из месторождений Соликамской депрессии. Проведен статистический анализ фильтрационно-емкостных свойств бобриковского пласта по результатам интерпретации геофизических исследований скважин и по данным ГДМ; рассмотрены различия между исходной проницаемостью, полученной после ремасштабирования геологической модели, и проницаемостью после адаптации ГДМ. В результате проведенного анализа выявлены несоответствия в статистических характеристиках значений проницаемости по данным интерпретации геофизических исследований скважин и в ГДМ, а также существенные различия кубов адаптированной и исходной проницаемости. Установлено, что в процессе настройки модели значительно модифицирована исходная проницаемость методом «ручной» адаптации. Выявление и корректировка экстремальных значений проницаемости выполнены на основе петрофизической зависимости  $KPR = f(KP)$  по керну с учетом диапазонов изменения коэффициентов пористости и проницаемости. С применением модифицированного куба проницаемости выполнены расчеты по воспроизведению истории разработки объекта. По итогам расчетов достигнута сходимость с фактическими данными, отклонения соответствуют требованиям точности настройки модели. Таким образом, данный способ корректирования куба проницаемости после «ручной» адаптации модели позволит избежать значительных завышений или занижений проницаемости в ячейках ГДМ.

Margarita A. Smetkina – Assistant at the Department of Geology of Oil and Gas (tel.: +007 342 219 84 11, e-mail: rsmet@mail.ru).

Oleg A. Melkisev (Author ID in Scopus: 55531674700) – PhD, Associate Professor at the Department of Geology of Oil and Gas (tel.: +007 342 219 84 11, e-mail: melkisev@pstu.ru). The contact person for correspondence.

Maksim A. Prisyazhnyuk (Author ID in Scopus: 56979292200) – Head of the Department for Creation and Monitoring of Hydrodynamic Models (tel.: +007 342 236 403, e-mail: Maksim.Prisyazhnyuk@pnn.lukoil.com).

Сметкина Маргарита Андреевна – ассистент кафедры геологии нефти и газа (тел.: +007 342 219 84 11, e-mail: rsmet@mail.ru).

Мелкишев Олег Александрович – кандидат технических наук, доцент кафедры геологии нефти и газа (тел.: +007 342 219 84 11, e-mail: melkisev@pstu.ru). Контактное лицо для переписки.

Присяжнюк Максим Александрович – начальник отдела создания и мониторинга гидродинамических моделей (тел.: +007 342 236 403, e-mail: Maksim.Prisyazhnyuk@pnn.lukoil.com).

**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<sub>PR</sub>* is the thickness of the permeable interlayer, m.

Table 1 gives the key statistical characteristics of the parameters.

Table 1

Key statistical characteristics of the parameters based on the well log interpretation data

Parameter	Average value	Median	Mode	Min. value	Max. value	Standard deviation
<i>KP</i> , u.f.	0.1502	0.15	0.15	0.077	0.251	0.031
<i>KPR</i> , mD	254.974	85.1	85.1	2.3	4,428.5	485.403
<i>H<sub>PR</sub></i> , 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.

The distributions of the porosity ratio values based on the well log interpretation data and the reservoir model are generally similar, with an average value of 0.15 u.f., permeability not exceeding 200 mD in most cases (80-90 %), for the initial and adjusted permeability cube.

During the reservoir model history-matching of the Bobrikovian formation, the initial permeability value has been adjusted to obtain the development estimates as close to the actual values as possible. The data in Table 2 shows that the permeability in the adjusted cube is generally lower than in the initial cube upon upscaling of the geological model.

A difference cube (*PERMX\_delta*) and a multiplier cube (*PERMX\_k*) were computed to determine the degree of difference between permeability in the history-matched reservoir model and in the upscaled geological model:

$$PERMX\_delta = PERMX\_adapt - PERMX\_ish,$$

$$PERMX\_k = PERMX\_adapt / PERMX\_ish.$$

Table 2

Key statistical characteristics of porosity and permeability of the reservoir simulation model

Parameter	Average value	Min. value	Max. value	Standard deviation
<i>PORO</i> , u.f.	0.147	0.079	0.2483	0.0218
<i>PERMX_ish</i> , mD	157.375	2.311	9,771.3	246.013
<i>PERMX_adapt</i> , mD	114.066	0.025	1,719.0	222.756
<i>PERMX_delta</i> , mD	-43.310	-9,738.5	1,716.39	325.432
<i>PERMX_k</i> , u.f.	2.172	4.925·10 <sup>-5</sup>	743.743	12.124
<i>PERMX_petro</i> , 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.

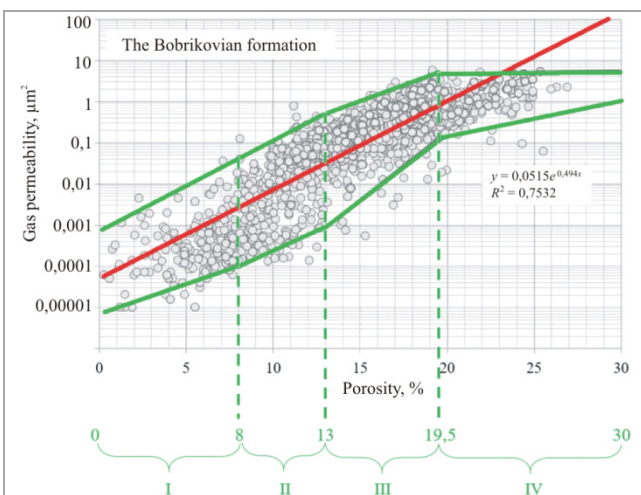


Fig. 1. Core-derived dependence of permeability on porosity

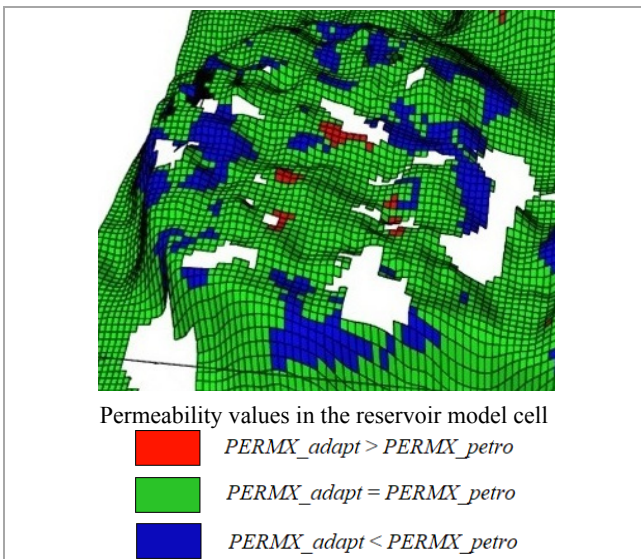


Fig. 2. The cube representing the permeability deviation from the petrophysical dependence in the history-matched model

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 (*PERMX\_petro*) was obtained and adjusted based on the cube after the *manual* history-matching of the model (*PERMX\_adapt*). The resulting modified permeability cube (*PERMX\_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 (*PERMX\_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 (*PERMX\_adapt* cube), and after the exclusion of anomalous values by the proposed method, it was raised to 0.15 mD (*PERMX\_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 (*PERMX\_ish*, *PERMX\_adapt*, *PERMX\_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

data for cumulative oil production, cumulative liquid production and watercut of the formation over the entire development period.

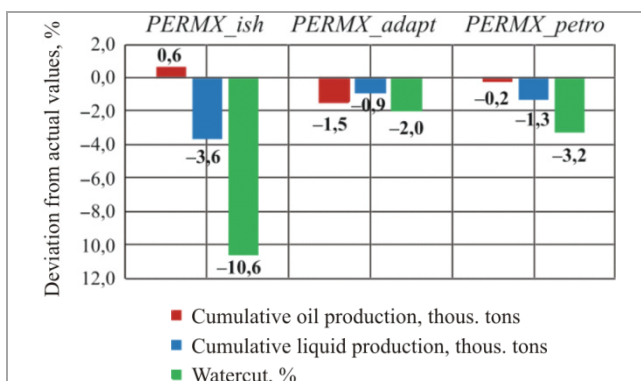


Fig. 3. Results of the reservoir model calculations for the productive formation in general over the entire development period

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 upscale 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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