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Development of a method for identifying zones to minimize fluid cross flows when modeling reservoirs using the material balance method

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Разработка методики выделения зон для минимизации перетоков жидкости при моделировании пластов методом материального баланса

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The digitalization of technological processes in recent decades spread to all sectors of the country's economy, and the oil and gas sector was no exception. Digital field models are increasingly used in engineering to substantiate development indicators and make technological and management decisions in order to increase the profitability of production. Full-scale geological and hydrodynamic models and simplified reservoir models differ in the amount of information taken into account, in detail and in the scope for solving engineering problems in conditions of limited time and technological resources. When modeling oil deposits, special attention is paid to the study of the mutual influence of wells, the dynamics of development indicators for individual sections of the deposit, the determination of possible cross flows between blocks or inflow from the aquifer. When moving to a more detailed level of modeling, the division of the reservoir into separate zones and their analysis allow in many cases to improve the quality of approximation and forecast of development indicators. For solving operational problems or modeling objects with high property uncertainty, simplified reservoir models have an advantage in terms of ease of setup and calculations efficiency. In the presented work, a method for differentiating a deposit into separate zones was proposed, taking into account the accumulated compensation for waterflooding centers, and it was tested on the example of a production facility in one of the fields in Western Siberia. With the help of stochastic modeling, statistical estimates were obtained for various options for combining flooding areas into single zones. The options were selected, which were characterized by close values of the accumulated compensation with a minimum standard deviation of the indicator in general for the object. Accounting and application of the obtained results with the subsequent use of calculations of development indicators based on the material balance method would ensure the minimum possible flows between the zones and, as a result, would allow obtaining optimal boundary conditions that minimized the influence of neighboring zones.

Ключевые слова:
очаг заводнения, накопленная компенсация, минимизация перетоков, граничные условия, ячейки Вороного, дифференциация залежи, метод Монте-Карло, среднеквадратическое отклонение, показатели разработки, коллекторские свойства, статистические характеристики, характеристики качества разделения залежи на зоны, геолого-гидродинамическая модель, упрощенная модель пласта, метод материального баланса.

Цифровизация технологических процессов в последние десятилетия распространилась на все отрасли экономики страны, исключением не является и нефтегазодобывающий сектор. Цифровые модели месторождений находят все большее применение в проектировании для обоснования показателей разработки и принятия технологических и управленческих решений с целью повышения рентабельности производства. Полномасштабные геолого-гидродинамические модели и упрощенные модели пласта отличаются объемом учитываемой информации, детальностью и областью применения для решения инженерных задач в условиях ограниченных временных и технологических ресурсов. При моделировании нефтяных залежей особое внимание уделяется исследованию взаимовлияния скважин, динамике показателей разработки по отдельным участкам залежи, определению возможных перетоков между блоками или притока из законтурной области. При переходе на более детальный уровень моделирования разделение залежи на отдельные зоны и их анализ позволяют во многих случаях повысить качество аппроксимации и прогноза показателей разработки. Для решения оперативных задач или моделирования объектов с высокой неопределенностью свойств упрощенные модели пласта обладают преимуществом с точки зрения простоты настройки и оперативности выполнения расчетов. В представленной работе предложен метод дифференциации залежи на отдельные зоны с учетом накопленной компенсации по очагам заводнения, выполнена его апробация на примере эксплуатационного объекта одного из месторождений Западной Сибири. С помощью стохастического моделирования получены статистические оценки различных вариантов объединения очагов заводнения в единые зоны. Выбраны варианты, характеризующиеся близкими значениями накопленной компенсации при минимальном среднеквадратическом отклонении показателя в целом по объекту. Учет и применение полученных результатов при последующем использовании расчетов показателей разработки на основе метода материального баланса обеспечат минимально возможные перетоки между зонами и, как следствие, позволят получить оптимальные граничные условия, минимизирующие влияние соседних зон.

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Introduction

Models that allow a comprehensive accounting of processes occurring in the reservoir-well-gathering system are becoming increasingly widespread in the oil and gas industry [1]. Particularly difficult is the creation of a reservoir model, where the construction is accompanied by significant uncertainty of the initial parameters [2–5]. There are various reservoir models types, from simple to more complex ones describing the nature of changes in the system during development. The choosing a particular method for modeling a reservoir system depends on the required tasks, constraints, volume of initial data as well as computational and time resources [6–8].

In addition to full-scale geological and hydrodynamic models, various types of simplified reservoir models are known: some represent the reservoir system as a single pore volume (material balance model), others consider the mutual influence of injection and production wells (CRM models), and others allow calculations to be performed on a two-dimensional grid with a more visual representation of the geological object structure (proxy models) [9–11].

While moving to a more detailed modeling level, it is important to take into account the mutual influence of wells and flows between deposit sections therefore the problem connected with identifying individual deposit zones is of particular interest. In many cases, in the practice of modeling, while constructing simplified reservoir models using the material balance method, large deposits are divided into a number of small sections. This approach allows a more detailed analysing the geological and technological indicators of individual sections (blocks) in the deposit or wells groups which in turn increases the reliability and predictive ability of the model. This paper proposes a method for differentiating a deposit into zones based on the calculation of accumulated compensation for flooding centers. The combination of flooding centers into single zones was carried out using the Monte Carlo method consiquently many different options for identifying zones within the deposit were obtained and their statistical characteristics were determined.

Formation models

As it is known the most detailed formation model is a geological and hydrodynamic one which creation requires a significant amount of initial data with their subsequent verification and coordination. The process of creating, initializing and setting up a geological and hydrodynamic model is iterative and labor-intensive as well as the calculations often require significant computing resources [12–14].

In conditions of the need to conduct more rapid assessing of a deposit or its individual sections as well as in the presence of uncertainty in the initial data or with their limited availability, simplified formation models have an advantage. Simplified formation models are of particular interest for problems related to the modeling complex formalized objects that, as a rule, do not have physical-mathematical and physical-chemical processes models or (and) there is no clear understanding the object geometry or (and) there is significant uncertainty in its properties but at the same time there are data on the actual hydrocarbons production. Examples of such objects may be hard-to-recover reserves, reservoirs with anomalous properties, non-structural deposits with complex geometrized boundaries. Modeling these objects with a high detail degree is impossible due to the complexity of assessing the necessary system parameters.

Among the simplified formation models, there are ones based on the material balance method, proxy models, CRM models, models based on the streamline method, and others [10, 11].

Grid types include a proxy model which is a two-dimensional single-phase simulator. There the development object is divided into elements according to an unstructured computational grid, performance indicators are reproduced for each well and adaptation to historical data is carried out. The proxy model allows you to assess the mutual influence of injection and production wells, conduct an analysis for individual deposit sections and predict formation pressure. This modeling method makes it possible to take into account the geological deposit features more clearly, unlike the models considered below. For example, the deposit contours are taken into account here, and clay zones or faults can be set as impermeable barriers.

A proxy model being an alternative to a geological and hydrodynamic model allows not only to reproduce the history of the developing the object, but also to solve the inverse problem based on actual selections data - to determine the distributing the formation pressure, restore the coefficients of hydraulic conductivity and useful injection and determine the parameters of the boundary area. The solution to the inverse problem is considered in the works [15, 16]. The main limitations in the use of proxy models are associated with the lack of the ability to conduct analysis for individual calculation cells in the three-dimensional space of the modeling area.

Another models class is the CRM (Capasitance Resistance Model) models based on the material balance equation and the Dupuit equation. The CRM model allows one to estimate the mutual influence of production and injection wells, take into account the relationship between the aquifer area and production wells as well as reproduce the development history [17–20]. The main area of model application is the operational analyzing the reservoir pressure maintenance system by calculating the well mutual influence coefficients based on production and injection data. There are several types of CRM models that take into account the control deposits volumes in different ways which is what the main assumptions and limitations of this method are associated with. The use of CRM class models is considered by the papers authors [21–25]. To describe the displacement of a multiphase flow in porous media, there is experience in using analytical models based on streamlines which are based on the solution of the Buckley–Leverett problem. In this case, the streamlines represent the trajectories where the fluid particles move from the injection well to the production ones. The method essence lies in calculating the saturations and flow rates of oil and water on the streamlines considering the pressure field [26–28]. This method is used in flooding modeling problems [29, 30]. The main advantage is the clear visualization of the fluid flow and the ability to model on a field-wide scale which is discussed in detail in this paper [31].

The simplest type of facilitated formation model is the material balance one. It is the simplest dynamic model form of an oil or gas field obeying the mass conservation law according to which the extracted volume is equal to the sum of the change in the original and added volumes over the entire history of exploitation. In other words, this is the balance of formation volumes which is expressed in the equality of the volume of fluid production and the sum of the volumes of expansion of the components and the external influx of water [32]. The material balance model can be used to solve problems of hydrocarbon reserves assessment, calculation of water inflow from the aquifer area, determination of useful injection coefficients, impact assessment of technological development indicators (production and injection) on the formation pressure dynamics [33–35]. The method application involves an assumption associated with the requirements absence for the boundaries and spatial position of the modeled objects and processes – the formation is considered coherently as an isolated pore volume. However, this method allows one to analyze the object by dividing it into separate blocks and perform calculations taking into account fluid flows between them as discussed in papers [36, 37]. The fact that the considered types of formation models are simplified, compared to three-dimensional geological and hydrodynamic ones, on the one hand, imposes restrictions on their detail, and on the other hand, facilitated models have the advantage connected with relative ease of setup and reduced calculation time, while considering the most important factors affecting the calculated indicators [8]. For the high-quality using such formation models, it is necessary to take into account the boundary conditions and the mutual well influence or individual well groups within the formation (object), therefore, in the practice of formation modeling using the material balance method, the division of the formation (object) into zones is widely used which allows improving the quality of the forecasting the development indicators dynamics.

Qualitative reservoir differentiation into individual zones should be understood as ensuring minimal flows between blocks [38], since their direct assessment is difficult and carries significant uncertainty.

To identify areas within a relatively large formation (807 wells), this paper proposes a method based on the analysing accumulated compensation for flooding centers, while many options for combining flooding centers into single zones are carried out on an unstructured grid (Voronoi polygons) using the Monte Carlo method.

Characteristics of the production facility

The proposed method of reservoir differentiation into zones is considered by the example of the production facility in one of the fields in Western Siberia developed by 807 wells. The productive formation is represented by sandstones with siltstones and clays interlayers. The facility includes three oil deposits of the layer-arch type with areas of lithological replacement combined in plan.

To assess the reservoir properties the following characteristics of the facility were analyzed based on the results of geophysical well logging interpretation (RGWLI): K_p - porosity coefficient, fractions of units; K_{per} - permeability coefficient, 10-3 μm²; $H_{ef.os}$ - oil-saturated thickness, m. Based on these parameters, the main statistical characteristics were determined (Table 1).

The porosity coefficient varies from 0.171 to 0.233 fractions of units; the average value is 0.193 fractions of units. The permeability range is from $2.07 \cdot 10^{-3}$ to $159.3 \cdot 10^{-3}$ μm², with an average value of $20.06 \cdot 10^{-3}$ μm². Most of the K_{per} values (90 %) are in the range from $2.07 \cdot 10^{-3}$ to $40 \cdot 10^{-3}$ μm². The oil-saturated thickness varies from 0.4 to 13.8 m, the average value is 5.1 m.

The facility is being developed using an inverted nine-spot system in combination with focal flooding. Since the start of operation (1985) and up to the present, 807 wells have been involved in oil production including 638 production and 169 injection wells. At the date of the analysis the facility is being operated by 189 production and 55 injection wells, the average production water-cut is 69 %.

The object is quite large, therefore the processes of creating, adapting, updating and calculating development indicators on a full-fledged geological and hydrodynamic model take considerable time and resources. In this regard, there is a need to use a simplified formation model based on the material balance method which will correctly reflect the processes of hydrocarbon production.

Formation differentiation into zones

At the first stage, the formation area was divided into well ones around each well using an unstructured grid - polygons or Voronoi cells [39–41]. A Voronoi cell is a geometric place of subspace points which is the closest one to the considered point [42–44]. For each well (production or injection) the cell boundaries in this area are determined by the coordinates of the well's formation intersections for the considered formation. Then, the Voronoi cells were combined into flooding centers based on the closest distance between the production and injection wells. In this work 109 flooding centers were identified within the formation (Fig. 1).

For each flooding center the accumulated compensation was calculated. Then, using the geometric principle, the Monte Carlo method formed 27,000 different zones variants

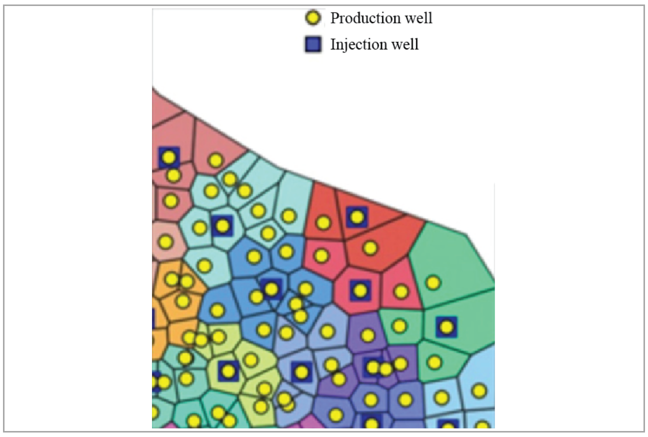

Fig. 1. A section of the deposit with highlighted flooding areas

Fig. 2. Correlation field of different zone configurations

Table 1

Main statistical characteristics of the development object according to RGWLI data

Parameter	Average amount	Median	Minimum value	Maximum value	Standart deviation
K_p, fr. unit.	0,193	0,192	0,171	0,233	0,008
K_{per}, 10^{-3} μm ²	20,06	14,18	2,07	159,3	17,297
$H_{ef.os}$, m	5,1	5,0	0,4	13,8	2,314

(configurations) from 109 flooding centers. The Monte Carlo method is a simulation modeling method based on the using a stochastic (probabilistic) process to obtain a set of realizing the modeled process or phenomenon. The method is widely used in assessing the uncertainties of the results obtained under conditions of uncertainty in the input parameters usually specified by distributions (distribution density functions) [45, 46].

For the successful application of the Monte Carlo method it is necessary to specify constraints on the input parameters during modeling [12]. The constraints use on the input parameters eliminates the receipt of implausible results and ensures the rational use of computing power which allows a logical and justified result.

The proposed approach for differentiating a formation into zones is implemented in such a way that there were identified from 3 to 7 zones within the formation and in each zone there were at least 4 flooding sites in order to avoid identifying very small areas.

The zones were identified by setting the initial flooding centers randomly using the Monte Carlo method, then the entire zone was formed from the remaining centers using the nearest neighbor method. The use of random zone centers

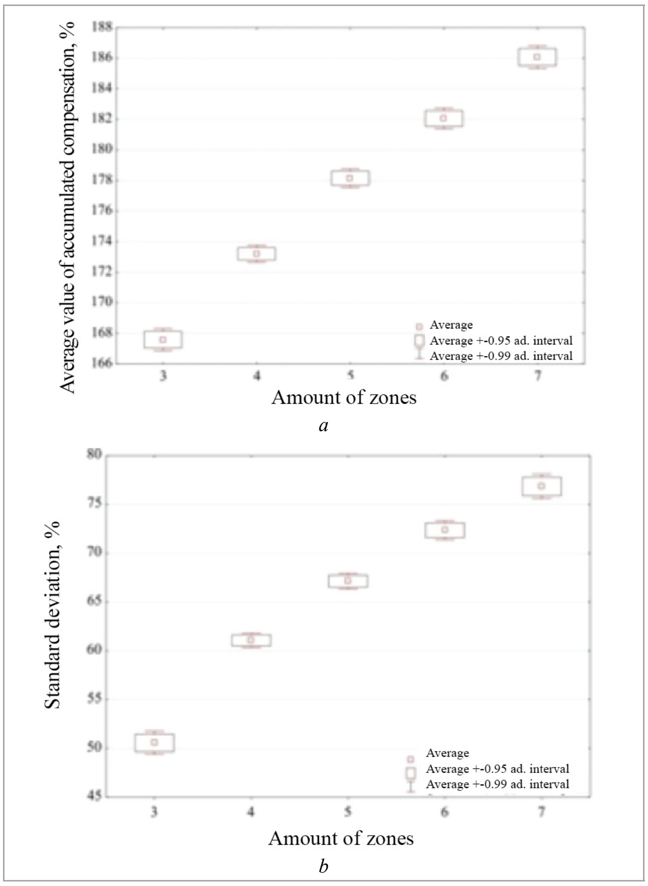

Fig. 3. Average values of the options final quality characteristics for dividing an object into zones depending on the number of zones: *a* – average value of accumulated compensation *Av Comp zones*; *b* – standard deviation *SD Comp zones*

Table 2

Main statistical characteristics of the options quality for dividing an object into zones depending on the number of zones

Number of zones	Average value of the accumulated compensation, %	Median on accumulated compensation, %	Standard deviation of the accumulated compensation, %	Median on standard deviation, %
3	167,6	167,7	50,6	46,8
4	173,2	172,5	61,1	59,6
5	178,2	177,2	67,1	65,1
6	182,1	180,6	72,3	69,0
7	186,1	184,2	76,8	71,6

ensures a variety of modeled configurations and zone sizes by the deposit area.

For each of the obtained zones, the accumulated compensation was calculated at the end of the considered period. The final characteristics describing the option quality for dividing the object into zones are: the average value (*Av Comp Zones*) and the standard deviation (*SD Comp Zones*) of the accumulated compensation zonally.

The value of the average accumulated compensation by zones *Av Comp Zones*, tending to 100 %, indicates the equality of injection and production volumes in the identified zones, however, in practice this indicator exceeds 100 %, therefore its minimum values in the range from [100; + ∞) indicate the lowest value of the excess injection volume over production. The value of the standard deviating the accumulated compensation zonally *SD Comp zones*, tending to 0 %, indicates the equality of all accumulated compensations in all allocated zones.

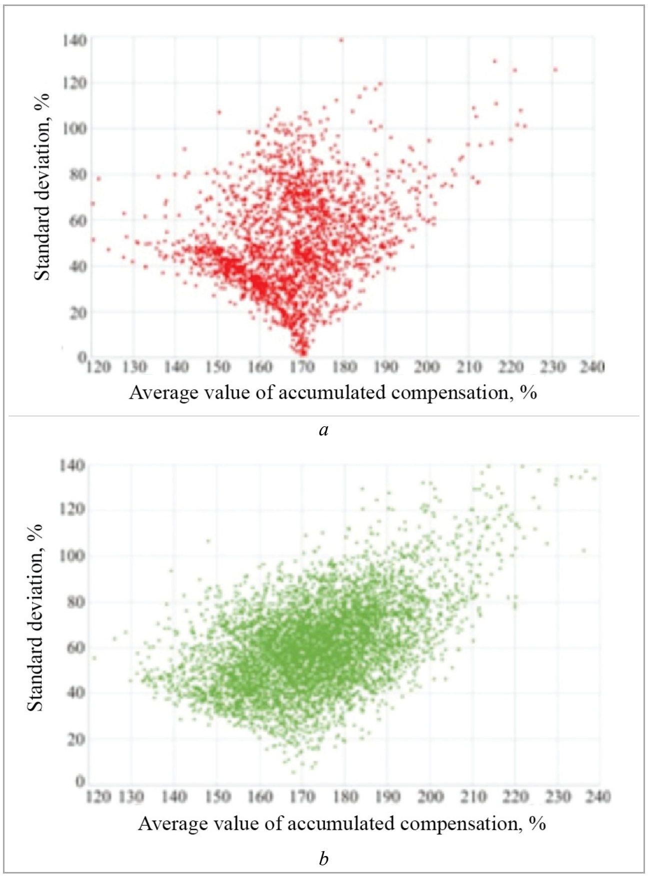

Fig. 4. Correlation fields of different options while dividing an object into zones: *a* – three zones; *b* – four zones

Thus, the simultaneous fulfilling the two considered conditions in the minimum of *Av Comp zones* and *SD Comp zones* allows us to obtain zones with a minimized volume of flows between them which ensures optimal boundary conditions for methods based on the material balance.

Fig. 2 shows the dependence where the ordinate axis shows the values of the standard deviating the accumulated compensation *SD Comp zones*, and the abscissa axis shows the average value of the accumulated compensation *Av Comp zones* for all considered options. The graph shows the number of zones allocated within the deposit in different colors.

Among the 27,000 different simulated options the number of zones within the deposit randomly changed from 3 to 7; the value of *SD Comp zones* for all options varies from 1.2 to 139.2 %; the value of the *Av Comp Zones* varies from 118.6 to 239.4 %. From the data in Fig. 2 it is evident that the variants with division into three zones (marked in red) have the lowest value of *SD Comp Zones* and accumulated compensation close to 170 %. At the same time, the value of accumulated compensation for the deposit generally without its differentiation into zones is 170.4 %.

After that the differences in the final values of the quality characteristics connected with the variants of dividing the object into zones were analyzed depending on the number of allocated zones.

Fig. 3 shows a comparison of the average values of the considered final characteristics about the zones quality depending on the number of allocated zones; Table 2 shows their statistical characteristics.

With an increase in the number of allocated zones, it is observed an increase in the average accumulated compensation *Av_Comp_Zone* from 167.6 to 186.1 % and an increase in the standard deviation *SD Comp Zones* from 50.6 to 76.8 % (see Fig. 3, Table 2). Thus, the options with the allocation of three or four zones to the deposits have a lower dispersion in compensation and are more optimal compared to a larger number

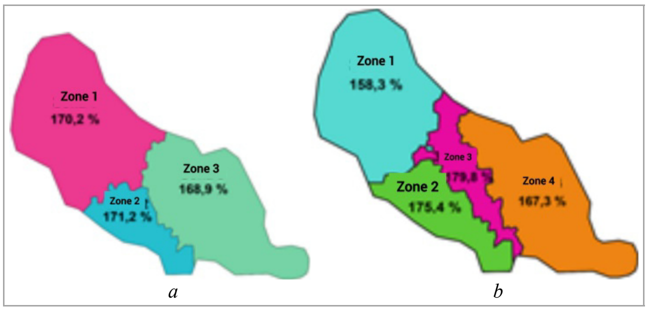

Fig. 5. Dividing the object with indication of the accumulated compensation values (a generalized outline of the deposit is presented): *a* – into three zones; *b* – into four zones

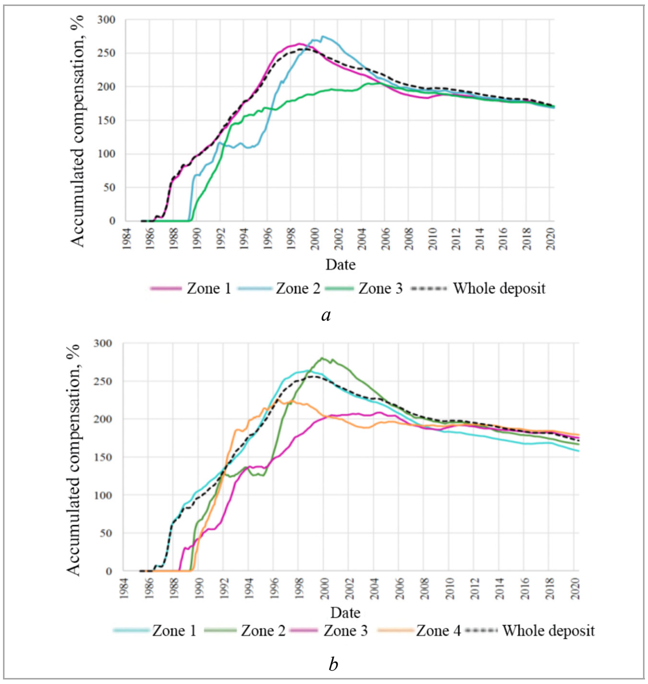

Fig. 6. Change in accumulated compensation: *a* – in three zones; *b* – in four zones

Table 3

Characteristics while dividing an object into three zones

Parameter	Value		
Number of zone	1	2	3
Amount of production wells	277	96	259
Amount of injection wells	64	32	65
Amount of flood starting point	48	20	41
Accumulated compensation zonelly, %	170,2	171,2	168,9
Average value of the accumulated compensation zonally, *Av Comp Zones*, %	170,1		
standard deviation of the accumulated compensation, *SD Comp Zones* , %	1,2		

Table 4

Characteristics while dividing an object into four zones

Parameter	Value			
Name of zone (on well)	1	2	3	4
Amount of production wells	205	110	116	201
Amount of injection wells	51	34	26	50
Amount of flood starting point	36	22	17	34
Accumulated compensation zonelly, %	158,3	175,4	179,8	167,3
Average value of the accumulated compensation zonally, *Av Comp Zones*, %	170,2			
standard deviation of the accumulated compensation, *SD Comp Zones* , %	9,5			

of allocated zones. The correlation field of various options with the division of the deposit into three and four zones is shown in Fig. 4.

It is evident from the data in Fig. 4 that the correlation field for three zones is in a region closer to the point with the "ideal characteristics of division into zones" with coordinates (100, 0) compared to the correlation field for four zones. At the same time, both fields overlap significantly. A visual analysis of 50 zone locations configurations within the object with the lowest values of *Av Comp Zones* and *SD Comp Zones* allowed us to select one best option for identifying three and four zones where the zones are large enough and at the same time there is no identification of relatively small local areas on the edge object parts.

Fig. *5, a* shows the best option for differentiating the object into three zones with the values of accumulated indicated compensation. The configurations of the zone boundaries are defined according to the contours of the flooding centers identified by the Voronoi polygons.

The resulting zones are characterized by the values of accumulated compensation of 170.2, 171.2 and 168.9 %, the average value is 170.1 %. Table 3 shows the number of wells and the characteristics describing the quality of dividing the object into three zones.

Fig. *6, a* shows the dynamics of accumulated compensation for three zones and for a single deposit without differentiation. The identified zones are characterized by similar dynamics of change in the indicator under consideration, periods of growth and decline are distinguished, due to the stage-by-stage development of the deposit sections. The growth stage (duration 10-15 years) corresponds to the formation of a development system through production drilling and, as a result, the achievement of maximum production levels; stages of decline are reduction of liquid withdrawals due to the abandonment of highly watered wells and injection limitation in these areas.

The best option for dividing the deposit into four zones is shown in Fig. *5, b*, its main characteristics are given in Table 4.

The resulting zones are characterized by values of accumulated compensation from 158.3 to 179.8 %, the average value of the parameter is 170.2 %. Fig. *6, b* shows a graph of changes in accumulated compensation for four zones as well as for a single deposit without dividing it. It is worth noting that the dynamics of the indicator corresponds to the data presented in Fig. *6, a,* and is also established by the stage-by-stage development of the deposit zones under consideration.

For both considered variants of dividing the deposit (into three and four zones), the accumulated compensation for the selected zones corresponds to the value for the deposit entirely without its differentiation (170.4 %), the standard deviation takes the values of 1.2 and 9.5 %. At the same time, the dynamics of the accumulated compensation demonstrates a greater values discrepancy between the zones for the variant with division into four zones which allows us to accept the variant with three zones (see Fig. 5, *a*) as the optimal deposit division.

Conclusion

1. A method for differentiating the formation into separate sections based on the principle of combining flooding centers into single zones with Voronoi polygons has been developed.

During the work, 109 flooding centers were identified and 27,000 different options for combining them into zones were calculated; the number of considered zones in a formation was modeled from 3 to 7. An analysis of the final considered characteristics describing the quality of the option for dividing an object into zones showed that dividing the reservoir into three or four zones is optimal, various configurations are also possible. The average values of the characteristics connected with the quality of dividing an object zonally into three and four zones based on accumulated compensation are 167.6 and 173.2 %, and the average standard deviation is 50.6 and 61.1 %, respectively.

2. The performed analysis of 50 zone arrangement configurations within the object allowed to select the optimal options for combining flooding centers for three and four zones where the standard deviation takes values of 1.2 and 9.5 %, the accumulated compensation is 170.1 and 170.2 %, respectively (the whole deposit is 170.4 %). The highest priority is the option of differentiating the deposit area into three zones (see Fig. 5, *a*) due to smaller discrepancies in the compensation values in the selected zones.

3. The application of the proposed method allows to differentiate the deposit area into separate zones based on the accumulated compensation and to determine the configuration of these zones in space. The selected zones can be used to improve the quality of formation models based on the material balance method while solving a variety of problems including: calculating the main development indicators, assessing the injection efficiency, designing and monitoring the field exploitation.

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