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Developing a gas-dynamic model of an underground gas storage facility

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ABSTRACT

Purpose: The aim of the study is to create a gas-dynamic model of the Dashava underground gas storage (UGS) facility. It studies reservoir properties and well operation parameters during underground gas storage facility (UGSF) operation in the seasons of withdrawal and production.

Design/methodology/approach: The research methodology comprehensively examines the findings from geophysical, seismic, and gas-dynamic investigations. It also encompasses data on well design, operational indicators, and the primary parameters associated with the underground storage facility's operational performance during its operational lifespan. Additionally, geological and gas-dynamic models are created. The geological model will be refined by adapting its filtration and capacitance characteristics to align with the actual gas-dynamic parameters of cyclic operation. Additionally, a gas-dynamic model will be developed and adapted to align with the calculated reservoir pressures in the wells and the actual reservoir pressure in the actively drained zone.

Findings: The reservoir and operational parameters of the gas storage wells were analysed, and gas-dynamic calculations were performed using the Petrel software package. The Petrel software package was used to build a 3D geological model of the Dashava structure for the gas-bearing horizons ND-8 (XIV) and ND-9 (XV), and the physical properties of gas reservoir rocks were substantiated. A gas-dynamic model was developed and adapted by comparing the main indicators of the gas storage facility between the calculated and actual values of the Dashava UGSF. Based on the results obtained, it was found out that the discrepancy between the average calculated and actual pressure values is minimal. The developed gas-dynamic model provides forecasting of the main indicators of the gas storage facility with a reliability of more than 90%, which indicates the feasibility of using the model for approximate calculations of the predictive mode of operation of the Dashava UGSF.

Research limitations/implications: The results of the research and calculations have shown that it is advisable to consider various criteria, including the geological and gas-dynamic model of UGS facilities, to draw up operating modes for wells in gas storage facilities.

Practical implications: The studies performed by means of gas-dynamic modelling of UGS facilities allow for a more thorough approach to the study of the reservoir system of gas storage facilities and promptly perform forecasting of the main indicators of its operation during gas withdrawal and production.

Originality/value: The application of the developed gas-dynamic model of the UGS facility will provide an opportunity to quickly analyse the main indicators of its work to solve problematic issues in a timely manner.

Keywords: Well, Modes, Operation, Gas storage performance, Gas-dynamic modelling

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ANALYSIS AND MODELLING

1. Introduction

Currently, Ukraine is making great efforts to ensure energy independence by reducing its dependence on oil and natural gas imports. To solve this complex problem, reducing natural gas consumption significantly is advisable, as is using more alternative energy sources (solar, wind) and increasing domestic production. In this regard, private and state-owned companies are developing and implementing ambitious programs that will stabilise production and increase it. Today, JSC "Ukrgasvydobuvannya" provides the largest gas production, although most fields are at the final stage of development.

During the operation of wells at depleted gas and gas condensate fields of JSC "Ukrgasvydobuvannya", problems arise that cause production decline. Therefore, they need to be resolved in a timely manner. It requires a comprehensive approach, first analysing the problems in detail and then proposing existing technologies and methods for their implementation or developing new ones. Fields are developing various measures to prevent fluid accumulation in well flowlines and hydrate formation. To remove liquid contaminants from the internal cavity of pipelines of gas collection systems, it is advisable periodically to clean them by creating a high-speed gas flow [1,2], using a surfactant solution [3,4], and using foam of various multiplicity [5,6]. Timely measures should be taken to prevent hydrate deposition in the well, the pipeline, and the gas gathering point [7,8]. In order to ensure stable hydrocarbon production from depleted fields, it is necessary to apply the latest technologies, implement booster compressor stations, etc [9-11].

To objectively assess the efficiency of gas and gas condensate wells, as well as underground gas storage facilities, it is necessary to use numerical modelling to prevent possible complications in a timely manner [12]. It will also improve the accuracy of well operation modes and the reliability of forecasting the main indicators of UGS facilities.

Creating digital three-dimensional models is integral to managing the development of oil and gas fields and underground gas storage facilities. After all, it is the permanent geological and technological model designed to solve the main tasks of field development to fully recover hydrocarbon reserves and achieve the required gas storage capacity and maximum economic benefit.

2. Literature review

Scientific and technological progress, which used to be relatively slow, has nowadays accelerated significantly. The modern scientific and technical development of software and computing tools allows it to operate with large amounts of information, providing the possibility of its systematisation, static processing and establishing the main consistent patterns between them [13].

The revolution shows that it encompasses not only the technosphere but also science. From the mid-50s of the 20th century, technology began to develop under the decisive influence of scientific knowledge. Science is becoming a constant source of new ideas that point to ways of developing material production.

A rapid transition from one qualitative state to another also occurred in the oil and gas industry, namely in the direction of designing the development of oil and gas fields. In addition to the classical methods of production forecasting, such as material balance, production decline curves, or displacement characteristics, three-dimensional numerical geological and technological models have become widespread over the past 15-20 years [14].

The main advantage of permanent geological and technological models is the ability to take into account the “real” geological structure of the field and, accordingly, the heterogeneity of the filtration and capacitive properties of rocks both in area and thickness, combined with complex processes of phase transformations, rheology of reservoir fluids and impact agents, and various equations of well inflow, taking into account their complex geometry [14,15].

The “realism” of the geological structure directly depends on the quality and quantity of input information, namely 2D seismic profiles, 3D seismic cubes, and the results of logging curve interpretation.

Oil and gas fields in Ukraine were discovered in the 70s and 80s of the last century. The available geological and industrial information is characterized by low quality and high uncertainty. This pattern is explained by the lack of modern research in accordance with the world practice and methodology of research and design of hydrocarbon deposit development [13].

In leading foreign companies, there is usually too much initial information to build a permanent geological and technological model of a field obtained over several years of development, giving them much freedom of action. In this case, the obtained geological and industrial information requires detailed analysis to ensure the model is accurately adapted to the data. The following problem arises in this regard: it may take several months or even years to create a three-dimensional model.

Solving the problem of building a permanent geological and technological model of an oil and gas field in conditions of limited information has led to the development of new methods and methodological approaches to determine the parameters necessary for building a model using available geological and industrial information.

In [16], the authors studied deterministic and stochastic approaches to modelling the properties of reservoir rocks in one of the fields of the Dnipro-Donetsk Basin. The results of the work clearly indicate the advantage of the stochastic method of facies modelling in the case of complex multi-layer, highly heterogeneous fields.

Combining a volumetric ranking method with a filtration method limited by P10 reserves estimated by the material balance by P/z allows us to effectively select a representative model implementation for further use in reproducing the development history. It allows to obtain high quality even in the presence of significant uncertainties.

In [17], the authors developed a methodology that, under conditions of limited geological and production data, ensures the integration of petrophysical, geological, and hydrodynamic models as integral components of a permanent geological and technological model of a field by establishing physical links between parameters describing the entire system.

Papers [18,19] describe the methodology for reproducing the PR equation of state under conditions of limited input information, namely, the presence of the component hydrocarbon composition of reservoir gas only up to C_{5+}, the peculiarities of conducting initial thermodynamic studies using a differential condensation experiment and the absence of such an experiment in the list of standard experiments in commercially available PVT simulators.

Adapting complex models of permanent geological and technological models of a field requires large expenditures of material and human resources. Therefore, a three-dimensional model is expensive for controlling field development [20,21].

Quite often, operating companies believe that it is better not to spend a lot of time and money on model refinement if there has already been a decline in hydrocarbon production at the field but to direct the efforts of their development engineers to a new field, which is much more interesting from all points of view, ignoring the fact that it is possible to increase free cash flow by artificially maintaining production at a depleted field.

Practical experience shows that the use of digital three-dimensional models allows for optimising the system of oil and gas field development and, accordingly, improving technical and economic indicators by justifying the feasibility of laying design production wells by determining their optimal location, justifying the feasibility and priority of wells for production stimulation and repair and insulation works, improving the system of control and regulation of reserves production and reducing the rate of turnover.

For example, works [22-24] show optimised technologies for developing natural gas fields under water pressure and operating highly watered wells based on homogeneous and heterogeneous synthetic digital three-dimensional models. Based on the results of their research, the authors substantiated the duration of the injection period of nitrogen [22] and carbon dioxide [23], the number (density) of injection wells in the gas-bearing area [24], and the technological modes of operation of both production and injection wells.

The developed technologies were tested for the conditions of the B-16 horizon of the Gadjatsky oil and gas condensate field located in the Dnipro-Donetsk depression (Ukraine). The modelling results indicate the high technological efficiency of the developed technologies, which allows the achievement of significantly higher final hydrocarbon recovery factors compared to depletion development.

Numerical modelling of the northeastern Hitchcock field development, located in Texas, allowed us to improve the existing technology for the completion of productive deposits of the field while ensuring significantly higher final hydrocarbon recovery factors. The calculation of various options for field development made it possible to substantiate the optimal rates of hydrocarbon production and choose a rational field development system [25].

Also, using a digital three-dimensional model of one of the fields located near the Sierra de Chiapas mountain range in Mexico, the efficiency of implementing secondary technologies for enhanced condensate recovery using both hydrocarbon and non-hydrocarbon gases was studied. Dry gas, carbon dioxide, nitrogen, and flue gases were used as injection agents. The results show that the most efficient option is the carbon dioxide injection. The least efficient option, according to the modelling results for the conditions of a particular field, was the option of nitrogen injection [26].

Numerous studies have been devoted to numerical modelling [27-30]. Modelling of field development will help establish exactly what needs to be done to stabilise gas production in the last years of the final stage of development. The strategy for further work may include drilling new wells to bring micro- and macro-constrained gas into development, improving how wells are operated, and optimising operating conditions.

By calculating different scenarios of field development using a permanent geological and technological model of the field, it is possible to compare the effectiveness of each possible measure and assess the economic efficiency of these works. However, in gas industry practice, some difficulties often arise when adapting three-dimensional models because too much statistical information is used, and the research takes too much time and leads to production losses.

In addition, it is advisable to develop a geologic and gas-dynamic model to improve the accuracy of well operation modes and the reliability of forecasting the main UGS facilities indicators.

3. Methods and materials

A prerequisite for creating a geological and gas-dynamic model of an underground gas storage facility is a comprehensive analysis of the results of geophysical, seismic, and gas-dynamic studies, information on the design of wells, data on the performance of gas deposits, etc. After the geological model is created, its filtration and capacitance characteristics are adapted to the actual gas-dynamic parameters of cyclic operation. It is necessary to improve the accuracy of well operation modes and the reliability of gas storage performance forecasting based on modelled data. The adapted model improves the quality of monitoring of gas-dynamic processes in the reservoir system of a gas storage facility and provides reliable forecasting of the distribution of thermobaric characteristics.

Using the Petrel 2016 software package developed by Schlumberger, a 3D model of the Dashava structure was built for the main gas-bearing horizons ND-8 and ND-9, as well as the physical properties of gas reservoir rocks, such as porosity and permeability.

The modelling was based on the results of 3D seismic surveys performed by Vicoil LTD.

At the first stage of geological structural modelling, the Petrel 2016 software package was loaded with the coordinates of the Dashava UGSF wells, their stratigraphic and lithological breakdowns, and some data on their design, such as perforation intervals and standard logs. These data were used to build correlation profiles for the Dashava UGSF wells (Fig. 1).

The next step is to create a 3D grid within the specified polygon. The 3D model of the Dashava UGSF was created using a 3D grid cell size of 25 m by 25 m. The total number of cells is 2417256. Based on the modelling results, structural maps of the roof of horizons ND-8 and ND-9 with lines of geological sections, geological sections, and 3D sections of Dashava UGSF in the northern direction were drawn up (Fig. 2).

In order to model the petrophysical properties of the reservoir formation, the Petrel 2016 software package was loaded with data on the porosity and permeability of the UGS productive horizons obtained from well logs interpreted by Ukrgeoecology LLC specialists and geological and technical reports of the Dashava UGSF. This made it possible to build three-dimensional models of porosity and permeability of the Dashava UGSF and extract from them maps of porosity of productive horizons and histograms of the percentage distribution of the porosity coefficient in the reservoirs of horizons XIV (ND-8) and XV (ND-9), maps of permeability of productive horizons in the lateral and vertical directions and histograms of the percentage distribution of permeability values in the lateral and vertical directions in the reservoirs of horizons ND-8 and ND-9 of the Dashava UGSF.

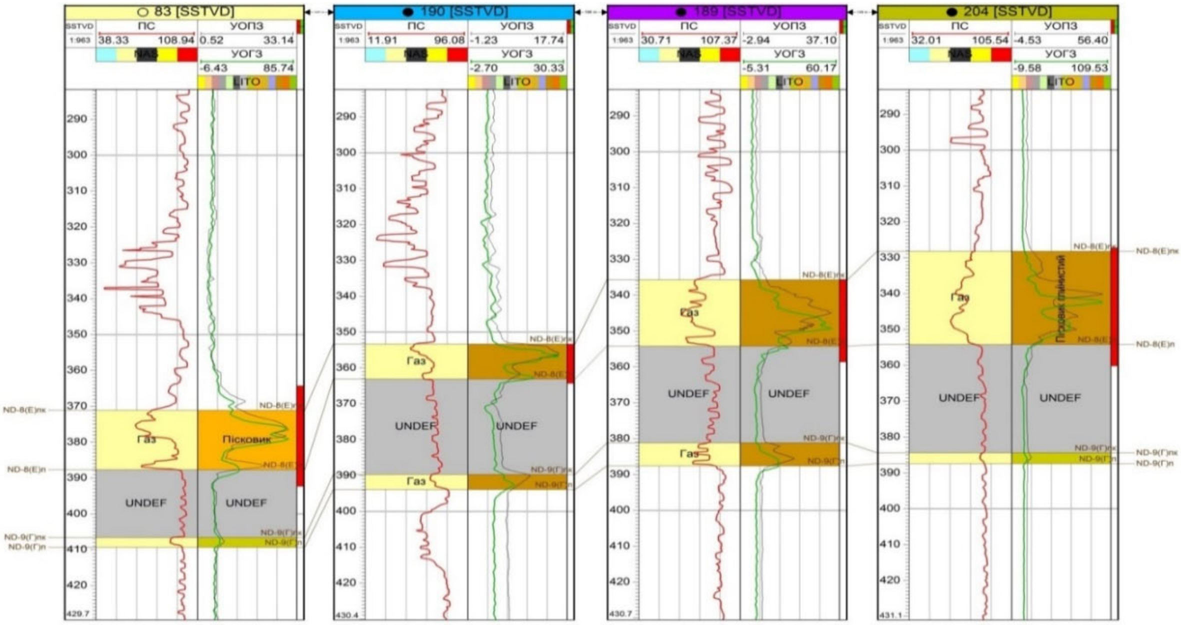

Fig. 1. Correlation of geological and geophysical profile for wells 83, 190, 189, 204 at Dashava UGSF

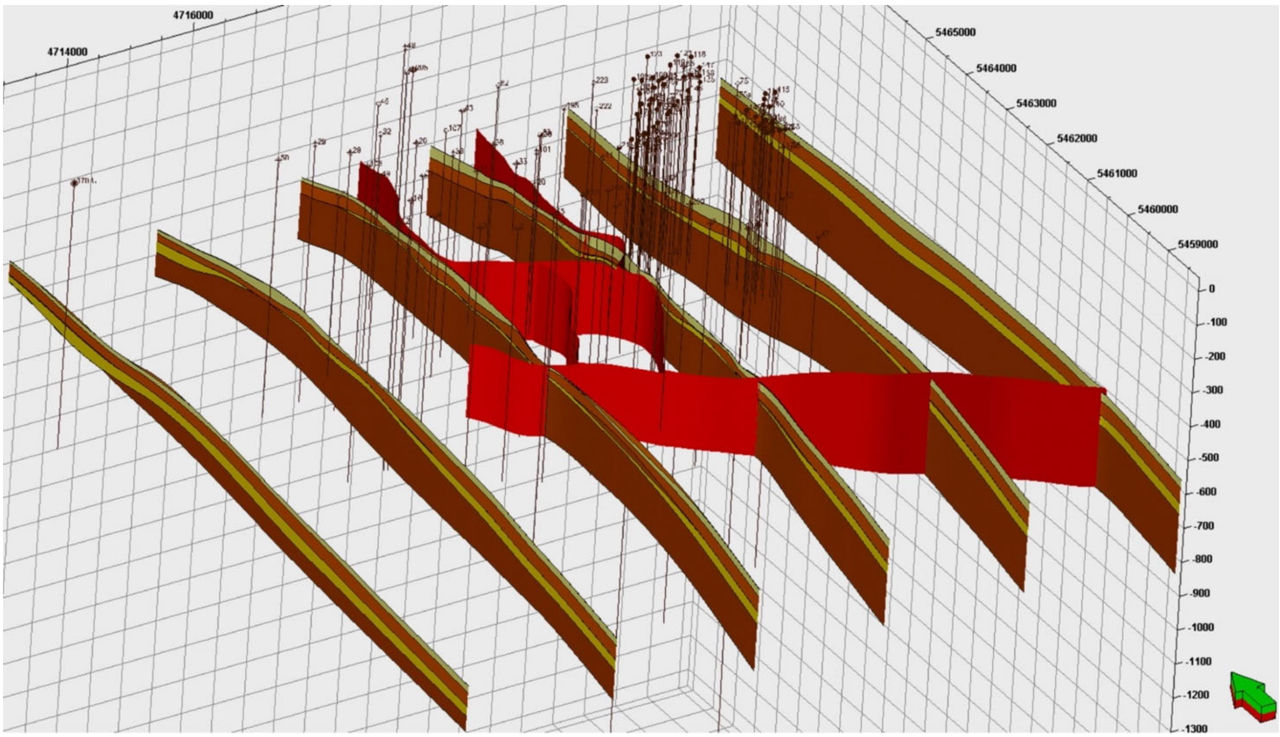

Fig. 2. 3D diagram of the Dashava UGSF in the northern direction

The histograms found that the values of the porosity coefficient of the modelled reservoir formation of the ND-8 horizon are in the range of 0.12%-0.2%, and the reservoir formation of the ND-9 horizon - 0.08%-0.18%. Based on the constructed histograms, it was found out that the permeability values in the lateral direction of most of the modelled reservoir of the ND-8 horizon are in the range of 900 mD-1500 mD, and the reservoir of the ND-9 horizon - 600 mD-1400 mD.

According to the results of the histograms, it was found out that the permeability values in the vertical direction of the modelled reservoir of the ND-8 horizon are in the range of 22.5 mD-32.5 mD, and the reservoir of the ND-9 horizon 12.5 mD-30 mD.

Stages of creation and characteristics of the gas-dynamic model

The three-dimensional gas-dynamic model of the UGS facility is based on the geological model. It is used to perform hydrodynamic calculations that take into account the geological structure of the facilities, changes in reservoir properties, reservoir fluid properties during operation, as well as the design and condition of the bottomhole zone.

The building of a gas-dynamic model consists of the following main stages:

- collection, generation, and analysis of initial data;
- justification of the hydrodynamic grid dimension and layer selection schemes;
- characteristics of reservoir fluid properties (pressure, volume, temperature);
- modelling of wells, conditions, and nature of their operation;
- adaptation of the gas-dynamic model to historical production data.

To build the gas-dynamic model, the following data were used:

- structure of the object being modelled (system and orientation of coordinate axes, number of cells along the coordinate axes, their size or geometry depending on the grid type, coordinates of structural faults);
- distribution of filtration and capacitance parameters (porosity and permeability);
- allocation of reservoir layers;
- initial saturation of reservoirs and initial reservoir pressure;
- perforation intervals, well inclinometry;
- well construction parameters;
- rates of gas injection and production by wells;
- bottomhole and reservoir pressures with the indication of measurement dates;
- technical condition of the wells;
- activities carried out at the wells;
- well logging results;
- physical and chemical dependencies of gas characteristics on pressure (compressibility factor, viscosity, density);
- physical and chemical properties of formation water;
- elastic and capacitive properties of the pore space.

All the initial data required for model building were converted into appropriate formats and loaded into the project.

A graphical representation of the initial data required to perform and evaluate the results of gas-dynamic calculations is shown in Figures 3 and 4.

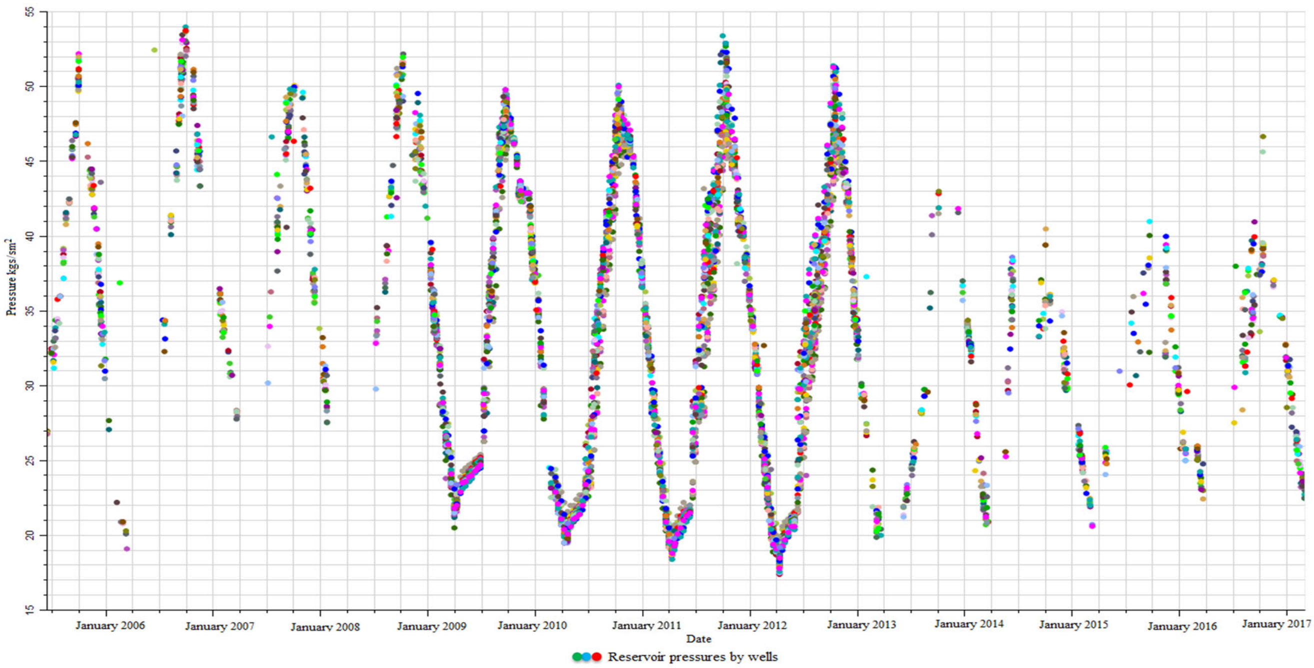

Fig. 3. Dynamics of reservoir pressure in the wells of Dashava UGSF

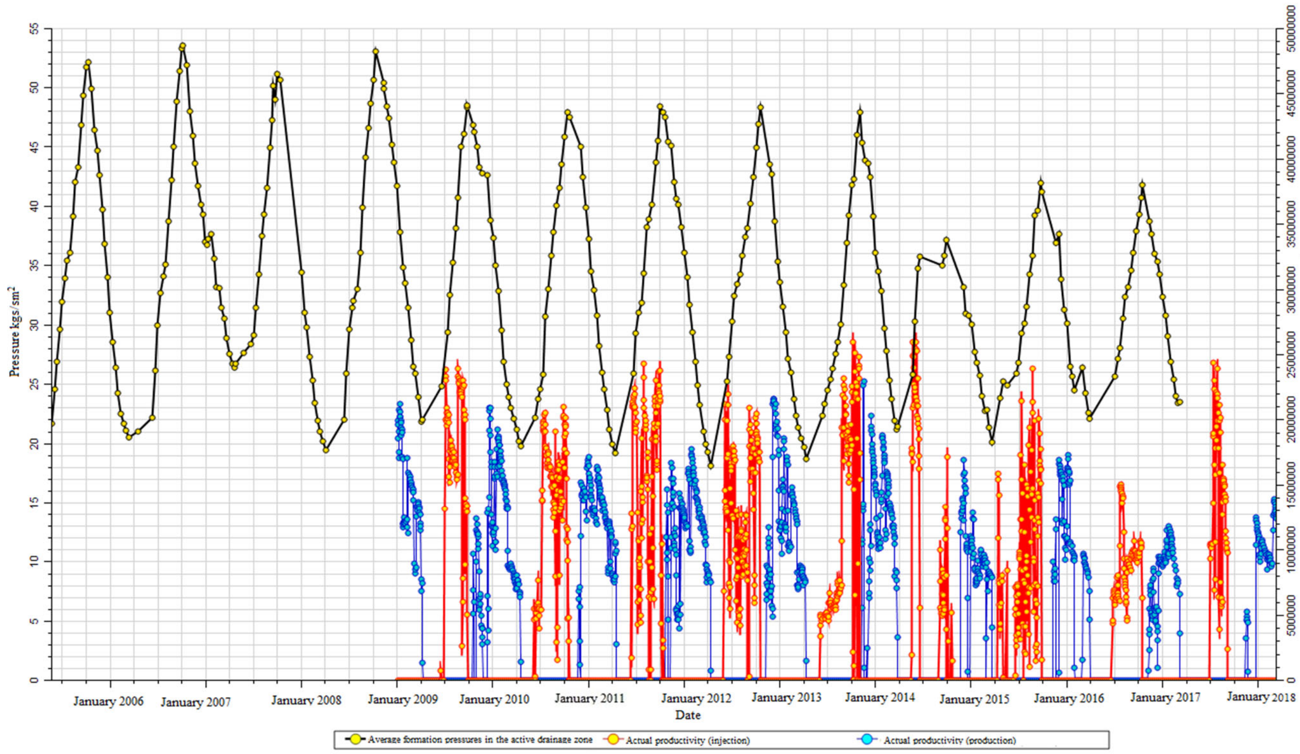

Fig. 4. Dynamics of the main indicators of cyclic operation of Dashava UGSF

The analysis of the dynamics of reservoir pressure values of the production wells shown in Figure 3 demonstrates a significant discrepancy in pressure values in different formation zones. The pressure difference between individual wells is 7 kgf/cm^2-10 kgf/cm^2. The largest pressure difference is observed during maximum UGS facility productivity periods and decreases during the neutral period.

The period from 2009 to 2018 (Fig. 4) adopted for modelling the Dashava UGSF operation is characterised by the maximum capacity during injection – 26 million m^3/d (October 2013), during production – 23 million m^3/d (November 2013). The average capacity of the gas storage facility during injection over the entire analysed period was 3.7 million m^3/d and during production – 4.2 million m^3/d. Reservoir pressures ranged from 17.4 kgf/cm² to 53.9 kgf/cm^2.

Historical injection data for gas-dynamic calculations were verified by comparing checksums with the reported data.

Based on the available data, well designs were built, indicating the types of columns and their technical characteristics (length, diameter, wall thickness, steel grade, etc.), perforation intervals, and depth of the cement plug head. For example, Figure 5 shows the design of well 136 of the Dashava UGSF.

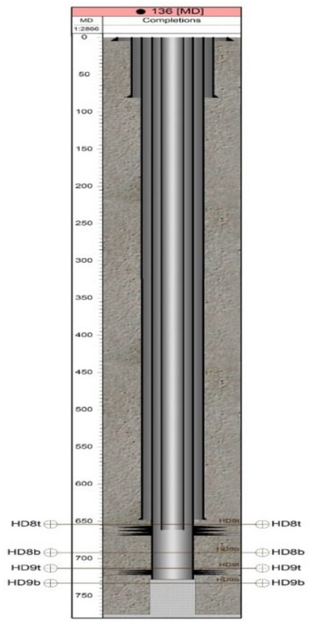

Fig. 5. Design of well 136 at Dashava UGSF

The initial data on changes in fluid properties depending on thermobaric conditions were prepared using the PVT software package. It implements methods for calculating vapour-liquid equilibrium based on equations of state and adjusting the results obtained with the data from industrial and laboratory studies. In each cell of the model, the composition of the reservoir fluid, volume coefficient, and viscosity were determined depending on the reservoir pressure.

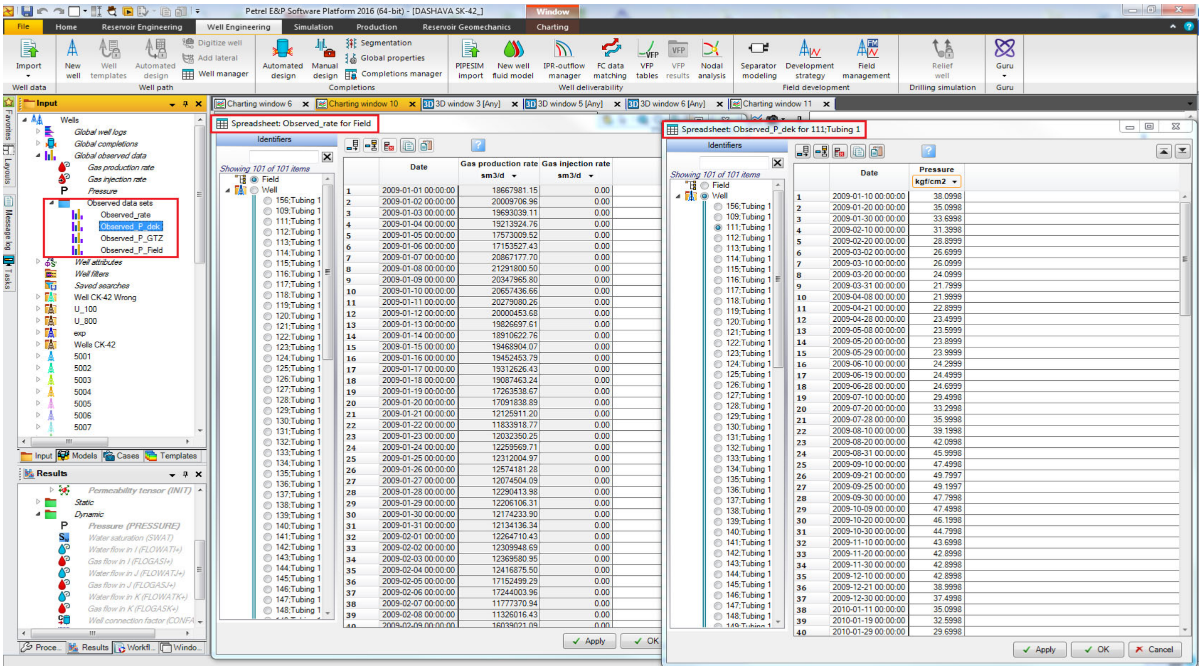

Fig. 6. Interface for displaying the initial data on reservoir pressure and gas injection and production rates entered into the information array of the Petrel software package

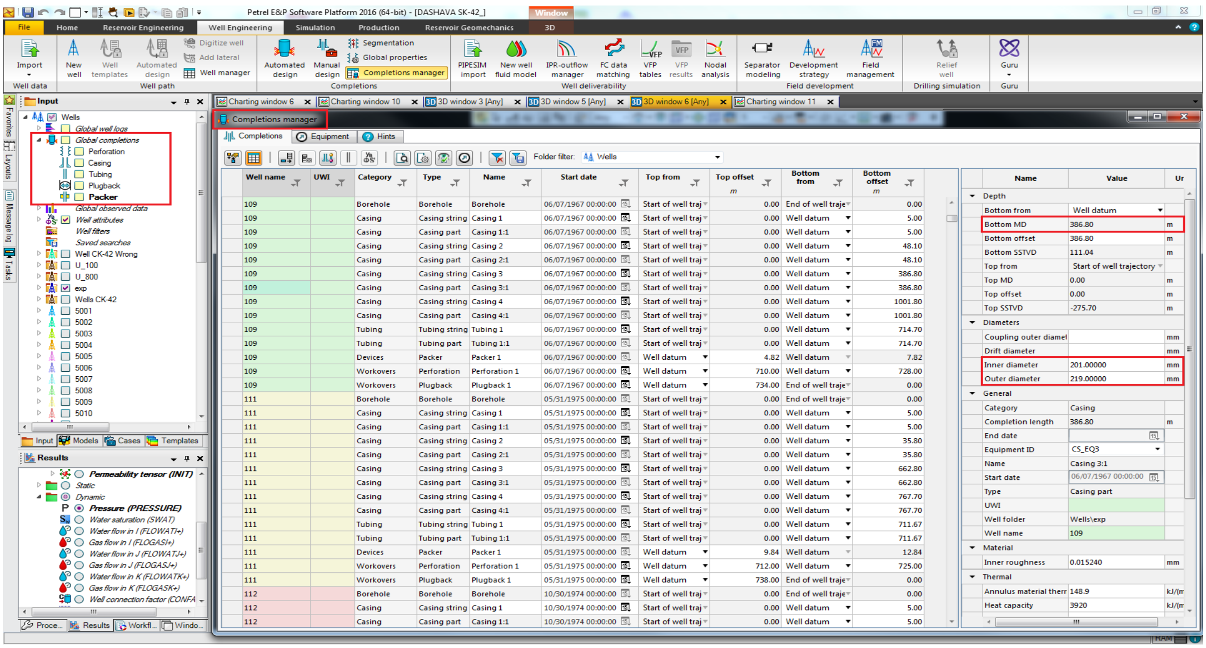

Fig. 7. Interface for displaying initial data on well designs entered into the information array of the Petrel software package

As initial reservoir conditions for gas-dynamic modelling, the reservoir pressure and gas-water contact were set at the initial date of the specified calculation period.

As a result of the formation of the initial parameters for the calculation, databases on the values of reservoir pressure, injection, and production rates (Fig. 6) and well designs (Fig. 7) were created.

The unified information space created in the Petrel software package made it easy to update and control the quality of the facility information and maintain the homogeneity of the information arrays used to build the three-dimensional gas-dynamic model.

4. Results and discussion

To create the gas-dynamic model, the Eclipse hydrodynamic modelling package developed by Schlumberger was used, which implemented numerical methods for solving the equations of underground gas hydrodynamics on a cellular model.

The main task of adapting the model was to achieve maximum compliance of the calculated gas injection and production rates with the actual ones without significant differences in reservoir pressure. The gas-dynamic model was adjusted by iteration, i.e. by repeating the calculation with changes in certain parameters, which made it possible to increase the accuracy of the gas-dynamic model gradually. A typical diagram of the sequence of construction and adaptation of the gas-dynamic model is shown in Figure 8.

Actual data on gas injection and production rates are used for gas-dynamic modelling, and the calculation results are used to determine the pressure in each cell of the gas-dynamic model. Gas-dynamic calculations are performed, considering the restrictions applied to the well operation mode. Therefore, it is necessary to monitor the results of calculations and, if necessary, adjust the initial data to achieve consistency between actual and modelled gas injection/production rates.

Comparing the calculated and actual gas injection/production rates shown in Figure 9, it can be concluded that the calculated daily productivity practically corresponds to the actual one during the entire calculation period. There is a slight deviation of the calculated value of the total gas volume in the UGSF from the actual value over the past two years is due to synthetic values of well productivity and the lack of constant accounting for injected/recovered gas for individual wells.

To assess the correspondence between the modelled and actual values of reservoir pressures in wells 116, 145, 158, and 202, we compared the measurement results and the calculated values of reservoir pressure (Fig. 10).

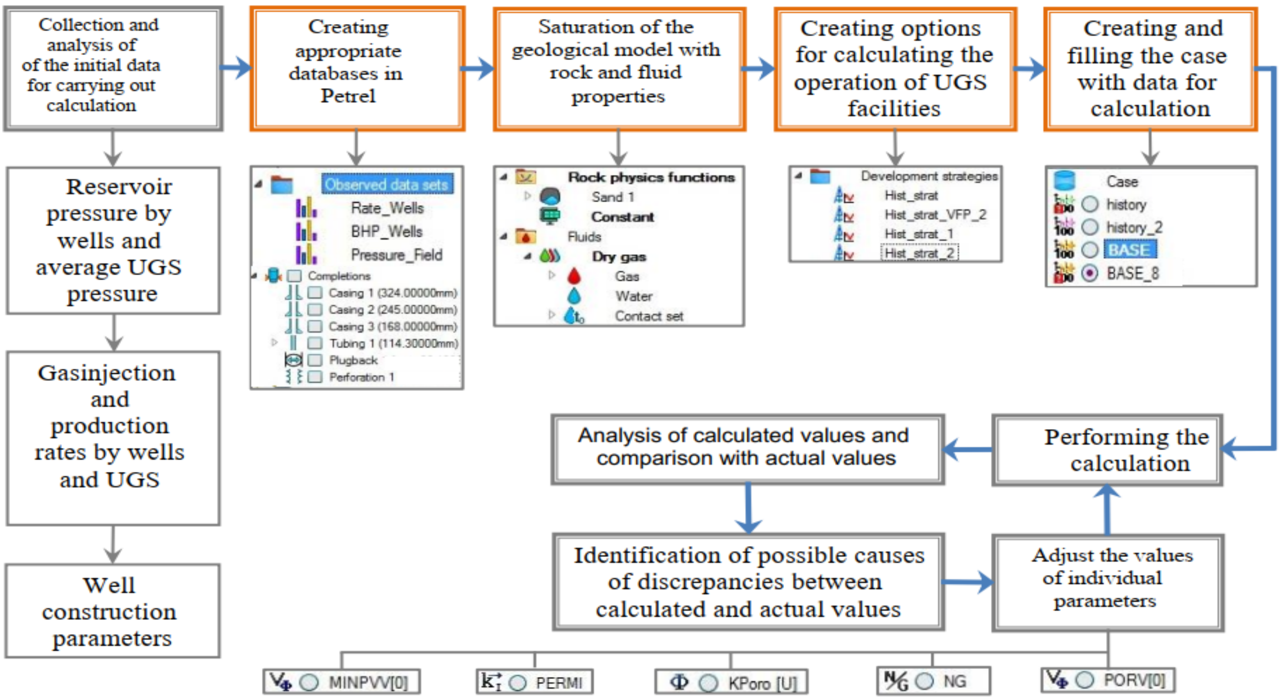

Fig. 8. Algorithm for building and adapting the gas-dynamic model

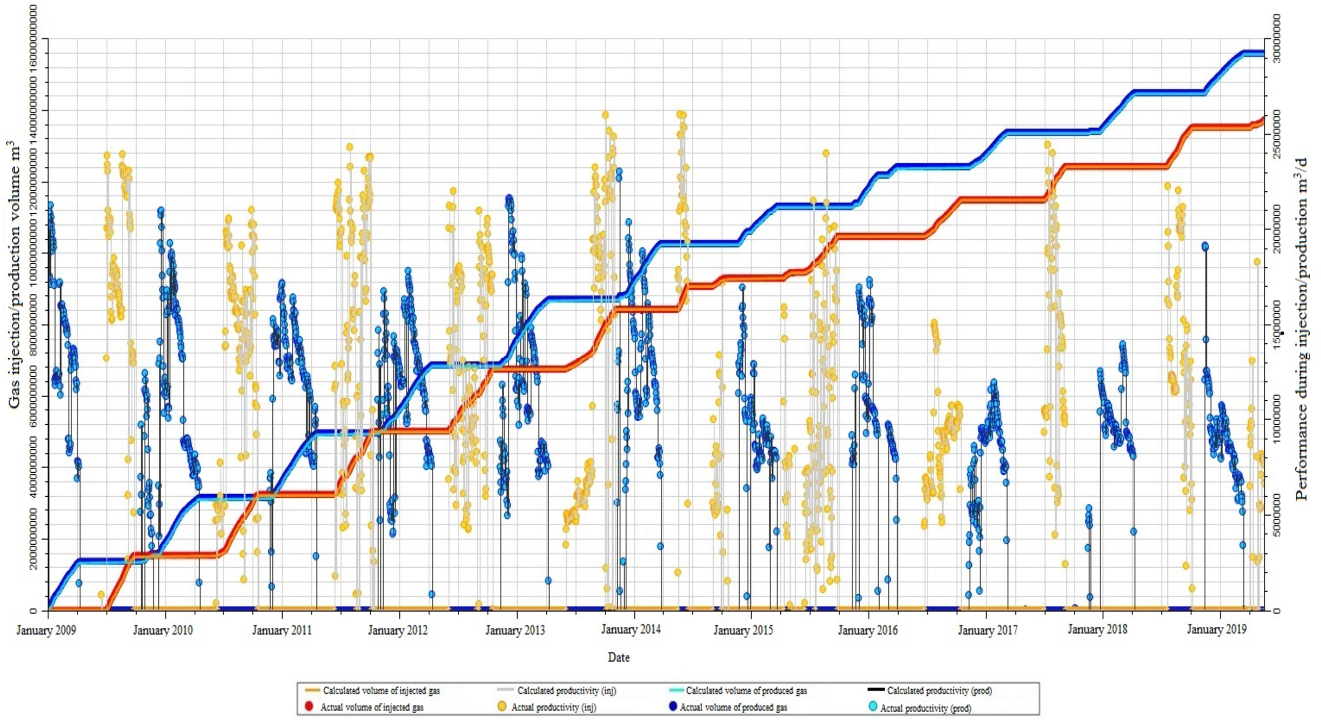

Fig. 9. Comparison of the calculated gas injection and production rates with the actual ones

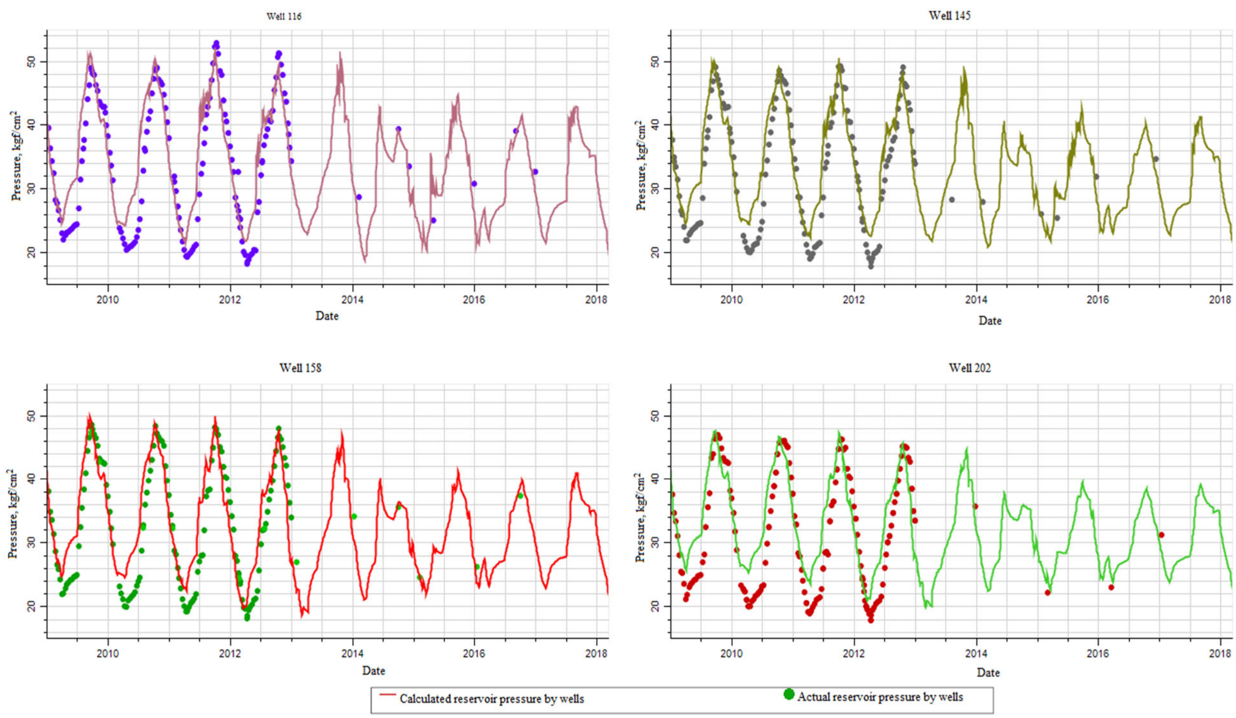

Fig. 10. Comparison of calculated reservoir pressure values in wells 116, 145, 158, and 202 with actual reservoir pressure values

In Figure 10, the values of calculated and actual reservoir pressure measurements indicate a satisfactory accuracy of modelling gas-dynamic processes in the gas storage reservoirs. The accuracy of modelling differs for individual wells, so in the future, it is planned to refine the gas-dynamic model and adapt the filtration characteristics of the bottomhole formation zone of individual wells.

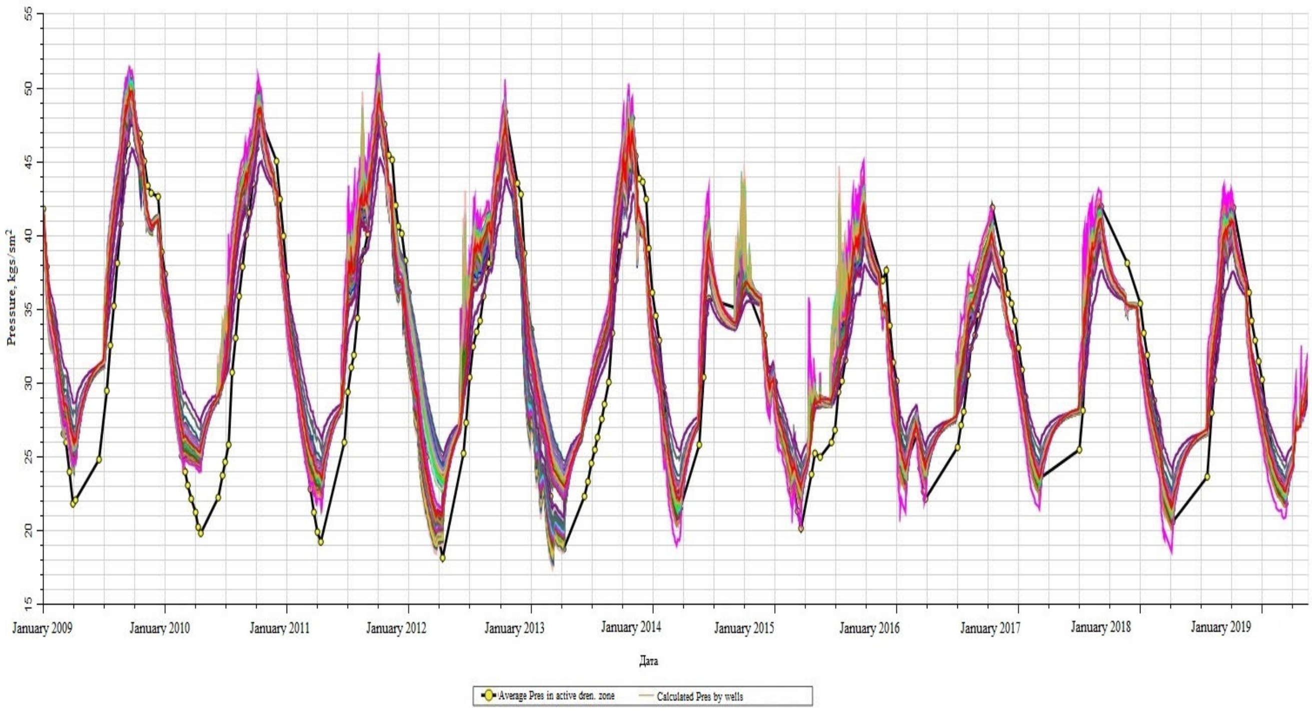

Fig. 11. Comparison of calculated reservoir pressure values in wells with actual reservoir pressure values of Dashava UGSF

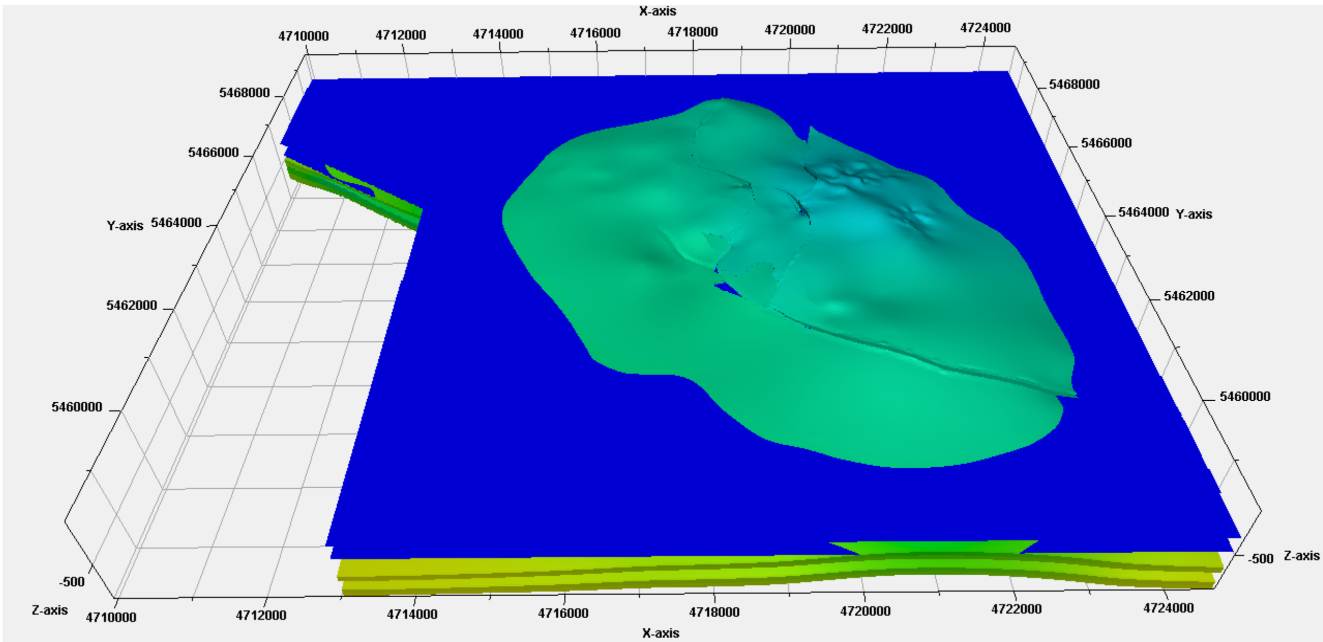

Fig. 12. 3D model of reservoir pressure distribution at Dashava UGSF

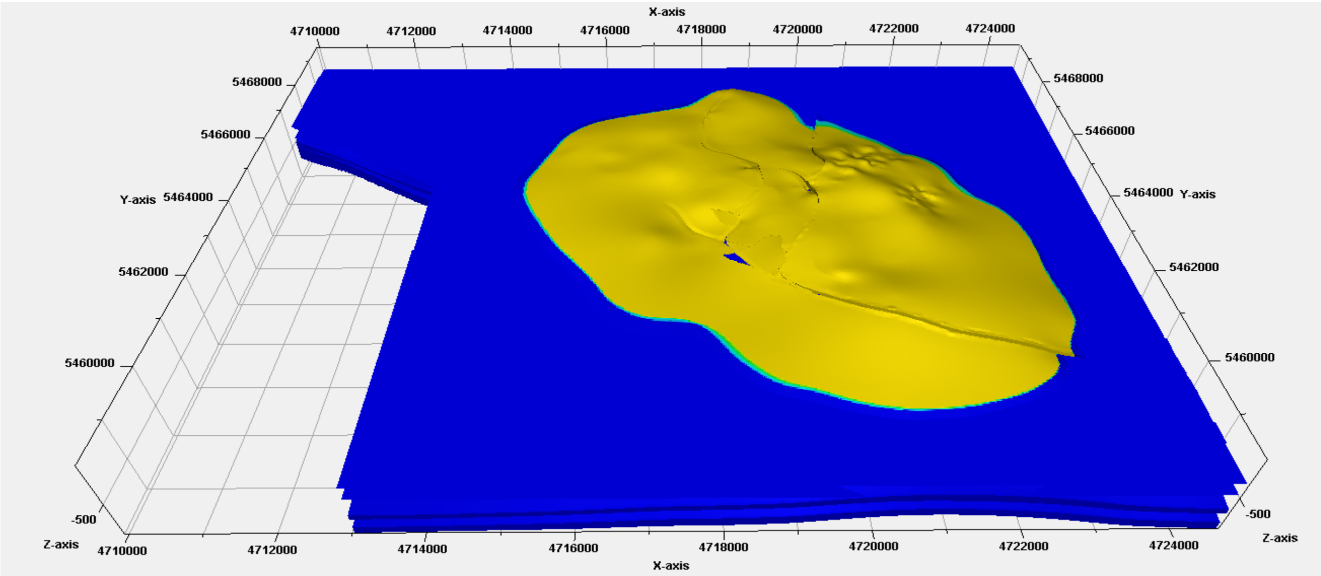

Fig. 13. 3D model of gas saturation distribution at Dashava UGSF

Figure 11 shows the values calculated for each of the production and injection wells and the actual average value of the reservoir pressure of the Dashava UGSF. Thus, having analysed these pressure parameters, we can say that the dynamics of the calculated reservoir pressure are close to the actual pressure values. The discrepancy between calculated and actual pressure values is in the range of 1 kgf/cm^2-7 kgf/cm^2 and averages 3 kgf/cm^2.

The calculations also resulted in building pressure and saturation distribution cubes that can be used to visualise and evaluate the dynamics of pressure and saturation distribution within the reservoir formation in time and space (Figs. 12 and 13). Such analysis makes it possible to identify reservoir zones with different drainage intensities and adjust the operating modes of individual wells to concentrate reservoir energy in the actively drained reservoir zone.

After completing all the stages of construction, a three-dimensional model was obtained that reproduces the reservoir conditions of the modelled reservoirs and the results of their operation.

5. Conclusions

In this study, gas-dynamic calculations were performed based on the Dashava UGSF geological model to compare the gas storage wells' actual and calculated characteristics. The actual data (filtration and productive characteristics of wells) were collected and loaded into the modelling complex to perform gas-dynamic calculations.

Using the Petrel 2016 software package developed by Schlumberger, a 3D geological model of the Dashava structure was built for the gas-bearing horizons ND-8 (XIV) and ND-9 (XV) and the physical properties of gas reservoir rocks. The 3D model of the Dashava UGSF was created using a 3D grid cell size of 25 m × 25 m within a given polygon. In order to model the petrophysical properties of the reservoir formation, the Petrel 2016 software package was loaded with data on the porosity and permeability of the UGS productive horizons in the bottomhole zones obtained from geophysical surveys of wells and geological and technical reports of the Dashava UGSF. It enables the building three-dimensional models of the porosity and permeability of the Dashava UGSF by interpolation, taking into account the zoning and nature of reservoir rock layering.

A gas-dynamic model was developed and adapted to reduce the discrepancy between the calculated values of reservoir pressures in wells and the actual values of reservoir pressure in the actively drained zone of the Dashava UGSF. The discrepancy between the average calculated and actual pressure values ranges from 1 kgf/cm^2 to 4 kgf/cm^2 and averages 2 kgf/cm^2. It indicates satisfactory accuracy in modelling gas-dynamic processes in gas storage formations.

Some discrepancy between the calculated values of reservoir pressures of wells and the actual average value of reservoir pressure in the actively drained zone of Dashava UGSF at the beginning of the modelled period is explained by the lack of reliable data on development indicators during the period of gas reservoir exploitation before their use as a gas storage facility. The factor makes it impossible to accurately study the dynamics of changes in gas reserves within a reservoir, including stagnant zones. Accordingly, the possibilities for adapting the pressure distribution within the reservoir are significantly limited.

In general, the achieved accuracy of the developed model provides forecasting of the main indicators of the gas storage facility with a reliability of more than 90%, which indicates the possibility of using the model for approximate calculations of the forecasted operation mode of the Dashava UGSF.

Authors contribution

All authors contributed equally to the article. All authors have read and agreed to the published version of the manuscript.

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