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# Method of Calculating Operation Models of Underground Gas Storage

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***Abstract:***

***Purpose:*** *The work is devoted to the numerical implementation of the filtration model of reservoirs and the algorithmic model of compressor stations operated at underground gas storage facilities.*
***Design/Methodology/Approach:*** *For this, fast-converging methods and algorithms of minimum complexity are proposed for calculating the hydraulic parameters of the gas filtration process in heterogeneous reservoirs with concentrated sources and modes of operation of multi-shop compressor stations with various types of gas pumping units. The proposed methods and algorithms became the basis for the development of mathematical methods and software, which is operated by the dispatching service of underground gas storages. The time parameters of the proposed methods and algorithms made it possible to formulate the optimization problems of dispatch control of processes at underground gas storage facilities and to solve them effectively. The developed software are separate modules of the integrated complex that ensured: optimal planning, analysis of UGS operating modes and calculation of technical productivity; use it for optimal daily balancing of gas in the GTS.*
***Findings:*** *Among the advantages of this research (compared to similar ones known at this time), two should be highlighted, representation of the filtering area by different models and a combinatorial optimization method with adjustable complexity was developed.*
***Practical Implications:*** *Special attention is paid to the problems of model adaptation based on the results of numerical experiments. The main difficulty in carrying out adaptation lies in the significant uncertainty of the parameters of the studied facilities and, accordingly, their models, as well as input data and parameters of empirical expressions. The performance of the developed mathematical methods and software was confirmed by the results of numerical experiments and work in the mode of industrial operation for six years.*
***Originality/Value:*** *The article presents methods and tools for the effective dispatch contro of*

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*underground gas storage facilities.*

***Keywords:*** *Underground gas storage, optimization methods, mathematical methods and software, adaptation, planning of work modes, process management.*

***JEL codes:*** *L71, L95, C6, C88, C93.*

***Paper type:*** *Research article.*

***Abbreviations:*** *Underground gas storage (UGS), hydrodynamic model (HDM), gas pumping unit (GPU), compressor station (CS), piping and instrumentation diagram (P&ID), booster compressor station (BCS), gas gathering station (GGS), centrifugal compressor (CC), variable flow parts (VFP), gas transmission system (GTS).*

## 1. Introduction

Underground gas storage (UGS) is a complex controlled system. The main feature of the complexity of such a research object is not only a large number of interconnected elements and subsystems, but also the complexity of the functions performed by this system. In particular, the complexity of the system function is related to:

- its multidimensionality, which is due to the presence of a large number of connections between subsystems;
- interaction of the system with the environment;
- functioning of the system under the influence of weakly predictable and random factors;
- the presence of a set of criteria (often competing with each other), which should be taken into account when assessing the quality of functioning of both the entire system and its subsystems.

Moreover, such a system has an extensive hierarchical structure and an information network with intensive information flows. Management of such a system is a complex process caused by the following factors:

- the diversity of the physical nature of the subsystems, which is related to their different physical essence;
- lack of possibility to obtain reliable information about the properties of the system in general (during the study of its individual elements);
- the large size and complexity of the system model, which requires (when studying it) the use of modern mathematical methods of decomposition, macro modeling, simulation modeling, etc.

Thus, UGS, as a complex hierarchical system, represents a set of interconnected and interacting elements and subsystems of different physical nature (heterogeneous structure), which make up an indivisible whole that ensures the performance of a complex function defined by the system.

Modeling the operation of the UGS, both as a separate object and in combination with the gas transmission system (GTS), requires the following steps:

I. Conducting theoretical (fundamental) research
II. Formulation of specific problems – taking into account the goals of the research in mathematical terms of the description of the system (processes) inherent in it (them)
III. Formalization of problems – construction of mathematical models of the system and processes (gas dynamic, filtration, etc.)
IV. Implementation of models – development of convergent methods, algorithms of minimum complexity and their software implementation

Modeling complexes are an effective tool for optimal management of the operation process of a complex system (in particular, UGS). Their development is based on the results of fundamental research in many fields of science, including in the field of underground hydrodynamics.

This article is devoted to solving specific problems that arise in the process of developing multifunctional complexes for modeling underground gas storages.

## 2. Analysis of Literary Data and Formulation of the Problem

This work is a continuation of works (Prytula *et al.,* 2017a; Prytula *et al.,* 2017b; Iwaszczuk *et al.,* 2022a; Prytula *et al.,* 2022), which are devoted to: development of models of gas flows in separate facilities of UGS (Prytula *et al.,* 2017a), problems of construction of integrated mathematical models of gas flows in UGS facilities (Iwaszczuk *et al.,* 2022a), development of methods of managing operation of groups of technologically related UGSs in general, and in peak operation modes in particular (Prytula *et al.,* 2022), methods of calculating optimal modes of operation of UGSs (Prytula *et al.,* 2017b).

In open sources, there are no systematic studies on software tools for managing gas dynamic and filtration processes in underground gas storages. There is also a lack of detailed information on the functionality of the existing software on existing UGSs and its qualitative and quantitative indicators.

The range of works devoted to underground storage facilities is considerable. For example, (Syed, Lawryshyn, 2020) developed a quantitative model to test the operational reliability risk of an underground gas storage facility. Nilsen (2020) proposed the use of hydropower technology in Norwegian oil and gas storage facilities, created in rock caverns. (Gangxiong *et al.,* 2017) focused on studying the challenges faced by the Chinese UGS sector compared to other countries. Guosheng *et al.* (2015) emphasized that the increase in UGS construction efficiency is influenced, among others, by issues such as "geologic evaluation, gas reservoir engineering, drilling and completion engineering, UGS injection and gas recovery engineering, surface auxiliary technologies and UGS integrity evaluation". Rqiq *et al.* (2020) assessed the impact of investments in cross-border gas pipelines on the energy security of EU countries. Tajduś *et al.* (2021) proposed a method that will help predict surface deformations in large fields of underground gas storage facilities, created in salt caverns.

Zhang *et al.* (2022) proved that risk management in the UGS industry is of key importance for the safety and integrity of the underground gas storage infrastructure, and thus for the energy reliability of countries and regions. For this purpose, they proposed to use advanced monitoring and simulation of UGS operation as part of the Integrated Risk Management and Decision Support System (IRMDSS). Tongwen *et al.* (2021) proposed an integrated technology for constructing crude oil displacement tanks and underground gas storage.

The authors described the advantages of this technology as well as technical connotations, rules for selecting a location, and the process of optimizing the operating parameters of gas storage facilities. Sadeghi and Sedaee (2022) applied a mechanistic numerical simulation method to study the effects of molecular diffusion, operating conditions, and bed and rock properties on pillow gas replacement in conventional reservoirs.

However, works devoted to operational parameters of real software for UGS in open sources are missing. Close to this topic is the article (Jeannin *et al.,* 2022), in which numerical approaches to modelling the operation of gas storages in salt caverns are considered. The authors emphasize taking into account the heat exchange between the well, the cavern and the rock massif, as well as modelling the volume losses of the cavern. The model provides quick results, is simple and convenient to use. The use of this model in the context of monitoring gas storage operations is illustrated.

In connection with the dynamic changes in the natural, economic and geopolitical environment, gas storages are gaining more and more importance. First, the traditional gas supply system, which once met the winter peak demand, is now unable to meet the summer peak gas consumption. Secondly, the summer peak demand for natural gas is constantly increasing due to the production of electricity at gas-fired power plants.

In recent years, drought combined with heat has caused record electricity demand and shortages in parts of both the United States and Europe (Declaration of Emergency…, 2022). Thirdly, today energy resources, methods and potential of their accumulation in the world play the role of not only an important economic resource for the development of the world economy, but also a powerful political and military tool in realizing the geopolitical interests of individual countries.

The military aggression of the Russian federation against Ukraine provoked a large-scale energy crisis at the national and global levels. This led to the destruction of the current world economic order and the need to prioritize the development and safety of the logistics of transportation and storage of hydrocarbons, including natural gas.

So recently, the Baltic Pipe gas pipeline (with a capacity of 10 billion cubic meters per year) was opened in Gdansk, which supplies gas from Norway to Poland. Not only Poland will be able to import Norwegian gas through Denmark for the first time, but also neighbouring countries, in particular Slovakia and the Czech Republic (Baltic Pipe…, 2022).

Today, the filling of gas storages is one of the main factors of the country's energy security, especially on the eve of the autumn-winter period. Fourth, in the absence of Russian gas supplies, Europe is expected to import 40 million tonnes of liquefied natural gas (LNG) this winter and slightly more in the summer to replenish supplies. In the process of LNG regasification, a significant part of it will go directly to UGS.

However, a cold winter in North Asia could take 5.6mt from Europe, mainly for Japanese needs, while the following hot summer will see demand rise to 6.9mt over the next 12 months. All these factors led to a sharp increase in competition for gas supply sources in the world's gas hubs (True global…, 2022).

In the study of Farahani *et al.* (2015), an economic assessment of underground gas storage methods was carried out under conditions of low investment costs and low gas reserves in exhausted oil and gas reservoirs. Basically, these tanks are more economical than other types. It happens that gas storage in aquifers and salt caves (in terms of investment costs) can also be economical.

The work of Zemke *et al.* (2006) is devoted to the description of the functionality of CARE software, which is an effective assistant for optimal management of underground gas storage, configured taking into account the characteristics of each layer and customer requirements.

It was developed on the basis of many years of practical experience in the operation of storage facilities, analysis of formations and parameters of wells. CARE provides an optimal mode of operation, which increases the productivity of the storage and ensures a longer service life of each well.

In Lin *et al.* (2017), the optimal technology of the process of construction of underground gas storages in depleted gas reservoirs is considered. A multi-objective optimization model for underground gas storage in the winter peak load period is described in Tan *et al.* (2003). In Liu *et al.* (2013), the problem of modelling –

integration based on VB and HYSYS 22 of the pressure in the injection/withdrawal well with the pressure in the above-ground pipelines in UGS is considered. Optimization of the energy-saving operation of pumping underground gas storages based on NSGA became the main goal of the work of Liu *et al.* (2017).

In the article of Iwaszczuk *et al.* (2022b) a mathematical model for describing gas flows in underground gas storage facilities was developed. In the future, this model may be used to build an integrated model describing the functioning of such facilities.

In turn, the article of Prytula *et al.* (2023) is devoted to the problem of well research and modelling of gas flows in wells and their drilling zones. The accuracy of calculating the depression/repression of the drilling zones of wells significantly affects the accuracy of the calculation of operational parameters of underground gas storages.

## 3. Formulation of the Problem

Most of the works in open sources are devoted to: problems that arise at the stages of designing individual components of the UGS; economic aspects of operation; assessment of energy efficiency; and the prospects of hydrogen accumulation in its reservoir layers.

It is advisable to study these and other problems with the help of integrated tools of a single thermo-hydraulic complex, since in such cases it is possible to study the synergistic effects of such a combination. Such tools are built on the basis of mathematical models and software and make it possible to plan such modes of operation that ensure optimal operation of UGS facilities. The above justifies the expediency of conducting systematic research for the construction of multifunctional modelling systems for UGS.

## 4. The Purpose and Objectives of the Research

The subject of the research is gas dynamic and filtration processes in the reservoirs of underground gas storages. The purpose of the study is to build a model for the UGS dispatching control system as part of the GTS – in the operation modes of gas injection and withdrawal.

To achieve the goal, we set the following problems:

- implementation of a filtration model for the hydraulic calculation of pressure distribution in a heterogeneous porous medium – reservoir;
- development and implementation of an algorithm of minimum complexity for calculating the operating modes of multi-shop compressor stations with various types of gas pumping units (GPUs).

## 5. Materials and Methods of Implementing Models, their Adaptation and Research

To achieve the goal, we applied methods of rapid calculation of reservoir pressure distribution (in gas withdrawal and gas injection modes) and algorithms for calculating compressor station operating modes.

*Research hypothesis and accepted assumptions:*
The operation process of UGS is variable both in terms of gas volumes and the number of involved wells. This affects the change in the rate of filtration processes in the reservoir and, especially, in the wells' bottomhole zones. The existing anisotropy in permeability in the reservoirs and in the bottomhole zones of the wells, as well as their possible unpredicted contamination, generate the variability of filtration flows in terms of directions and intensity. This, in turn, affects the variability of the filtration resistance coefficients of the bottomhole zones. As a result, significant problems appear when predicting gas permeability in the reservoir and in the bottomhole zones of wells.

The vertical component of the size of reservoir layers in most UGSs is (on average) two orders of magnitude smaller than the horizontal dimensions. Therefore, it is advisable to use a two-dimensional model for modeling filtration processes in such reservoirs. Representation of the reservoir by combining the areas of the well bottomhole zones and the area beyond it allowed to establish the limits of action for different models of gas filtration:

- area of implementation of Darcy's law – numerical linear model of gas filtration;
- well bottomhole zones – a nonlinear analytical model of gas inflow to the well bottomhole.

Such a model of reservoir provided triangulation of the reservoir with a minimum number of elements and, accordingly, reduced (by an order of magnitude or more) the dimensionality of the matrix in the finite element method. As a result, we obtained a sufficient speed of calculating the distributed parameters of the reservoir for solving optimization dispatch problems.

Another assumption that significantly reduced the time in the process of adapting the filtration equation: the permeability of the reservoir decreases in the direction of the peripheral zones. In parallel with the process of developing methods and algorithms for implementing models of UGS facilities, we identified the parameters of their models – based on real measurement data. This allowed us to:

- to investigate the sensitivity of the models and the stability of the methods in the process of specifying the parameters of the models;

- build (on the basis of empirical data) thermal-hydraulic equivalents – models of ill-defined multifactorial processes.

*Regarding modeling of compressor stations (CS):*
Gas flows in CS facilities are discrete-continuous. That is why we proposed to use an algorithmic (simulation) model of the compressor station and combinatorial algorithms to form a complete set of modes of its operation.

*Input data for the study:*
We obtained additional input data as a result of numerical experiments using GIMS and GTS Calculation software (Prytula *et al.,* 2017b; Iwaszczuk *et al.,* 2022a), which are involved in the process of solving mode-technological problems of planning of operational and predictive modes of operation of UGS.

- results of studies of wells in gas injection and withdrawal modes for ten years or more (reports of geological and technological operation of underground gas storages);
- information bases of measured data (accounting and analytical system of the gas transmission enterprise).

Realized models of filtration and gas dynamic processes are given in Prytula *et al.* (2017a) Iwaszczuk *et al.* (2022a). They provided the solution of a set of direct and inverse problems for the calculation and analysis of UGS operating modes.

## 6. Methods and Algorithms for Implementation and Adaptation of Models: The Results of Solving the Problems

We started the process of construction of a system model by developing models of individual processes (those that have the same mathematical representation) and their adaptation to real measured operation model data (Prytula *et al.,* 2017a; Prytula *et al.,* 2017b; Iwaszczuk *et al.,* 2022a; Prytula *et al.,* 2022). After that, we “stitched” individual models into more complex systems, as well as developed methods and algorithms for their implementation.

However, the simple process of “stitching” models did not always lead to success. We were forced to include in the model processes described by equations with different mathematical representations, as well as to combine mathematical and algorithmic (simulation) models, which required the development of new approaches to their implementation.

It is worth emphasizing that an important stage in the development of system models (and modelling systems based on them) is the process of adapting models and methods to real measured data. There are both general (systemic) and specific problems of adaptation of individual models.

## 6.1 General Problems of Identification of Model Parameters and Methods of Their Implementation

Models of physical processes in UGS facilities (Prytula *et al.,* 2017a; Iwaszczuk *et al.,* 2022a) are non-linear and therefore sensitive to the accuracy of finding adaptive parameters. Most of the input measured data (required for finding the adaptive parameters of the filtering model) have little accuracy (no more than three significant digits), and part of the data is measured episodically (in the process of routine work).

In addition, the difficulty of adapting gas dynamic and filtration flow models in UGS facilities is also influenced by the fact that during the operation of UGS facilities, the parameters of their models change. This is due to different modes of their operation, when filtering gas flows change their intensity and direction of movement.

The effectiveness of identification methods is closely related to the methods of implementing models and problems of UGS dispatch control. This places certain requirements on gas flow models of UGS, methods of their implementation and the process of their adaptation. Such requirements can be:

- a minimum number of adaptive parameters, easy access to all adaptive parameters and convenient for analysing the presentation of adaptation results;
- sufficient speed of obtaining results when solving operation mode problems;
- the maximum level of automation for the process of updating models and information support;
- achieving such accuracy of identification of model parameters, which would ensure the solution of the set operational and forecasting operation mode problems for UGS dispatching management;
- multifunctional user interface.

In Figure 1, we presented a general diagram, which shows:

- the main facilities for which gas flow models and their names have been developed;
- a list of methods of implementation of relevant models;
- a list of measurement/calculation parameters and their location on the consolidated UGS scheme.

Measurement parameters are used to adapt individual models and groups of technologically related models.

Let's consider the gas withdrawal mode from the storage. The calculation algorithm for withdrawal a given volume of gas $Q_1$ will consist of the following steps:

1) we calculate $P_1$ (possible options are stationary and non-stationary gas pipeline-withdrawal modes of operation) – according to the given $Q_1$ on P&ID1;
2) we calculate the pressure $P_2$ (at the inlet/outlet of the gas pipeline-outlet of the compressor stations (CS)) – based on the known $Q_1$ and $P_1$;
3) we calculate the pressure $P_3$ at the gas gathering station (GGS) – based on the formation pressure distribution P(x,y) and the given $Q_1$;
4) we determine the type of UGS operation mode (self-flowing or compression mode) – according to $Q_1$ and the found pressures $P_1$ and $P_3$;
5) if the CS operation mode does not exist for the given volume of gas $Q_1$, then we reduce or increase the previously set volume (with a set step); after that, we repeat the previous steps of the algorithm until the system finds the operating mode of the CS with the given stability of the operation of the centrifugal superchargers, in particular, the flow rate of fuel gas $Q_f$;
6) after each change in the flow rate of withdrawal gas, we recalculate the reservoir pressure distribution P(x,y);
7) at each iterative procedure, we add $Q_f$ (fuel gas volume) to the given $Q_1$ to obtain the planned gas withdrawal.

Mathematical methods is up-to-date (that is, the implementation of this algorithm will be successful) if the calculated operational parameters of the CS (pressure $P_3$ and withdrawal ($Q_1$+$Q_2$) of gas at the gas gathering station (GGS)) and the reservoir pressure distribution P(x,y) coincide (with satisfactory accuracy) (in the area of wells) with corresponding measured data.

There are two main types of UGS operation modes: 1) self-flow; 2) gas compression. Among the possible calculated sustainable modes (in the compression mode), the following are distinguished: a) a mode with a weighted criterion (minimum consumption of fuel and energy resources); b) mode with a given degree of stability of the gas pumping unit (GPU). Among the UGS facilities, the parameters of the filtration model of its reservoir are the most uncertain. And therefore, basically, the development of the UGS model begins with the study of the geological structure of the reservoir, its structural map, cartographic maps of wells and the analysis of operational information, etc.

This and other information is used to develop a model of the software – hydraulic calculation of gas filtration parameters in the porous medium of the reservoir of UGS.

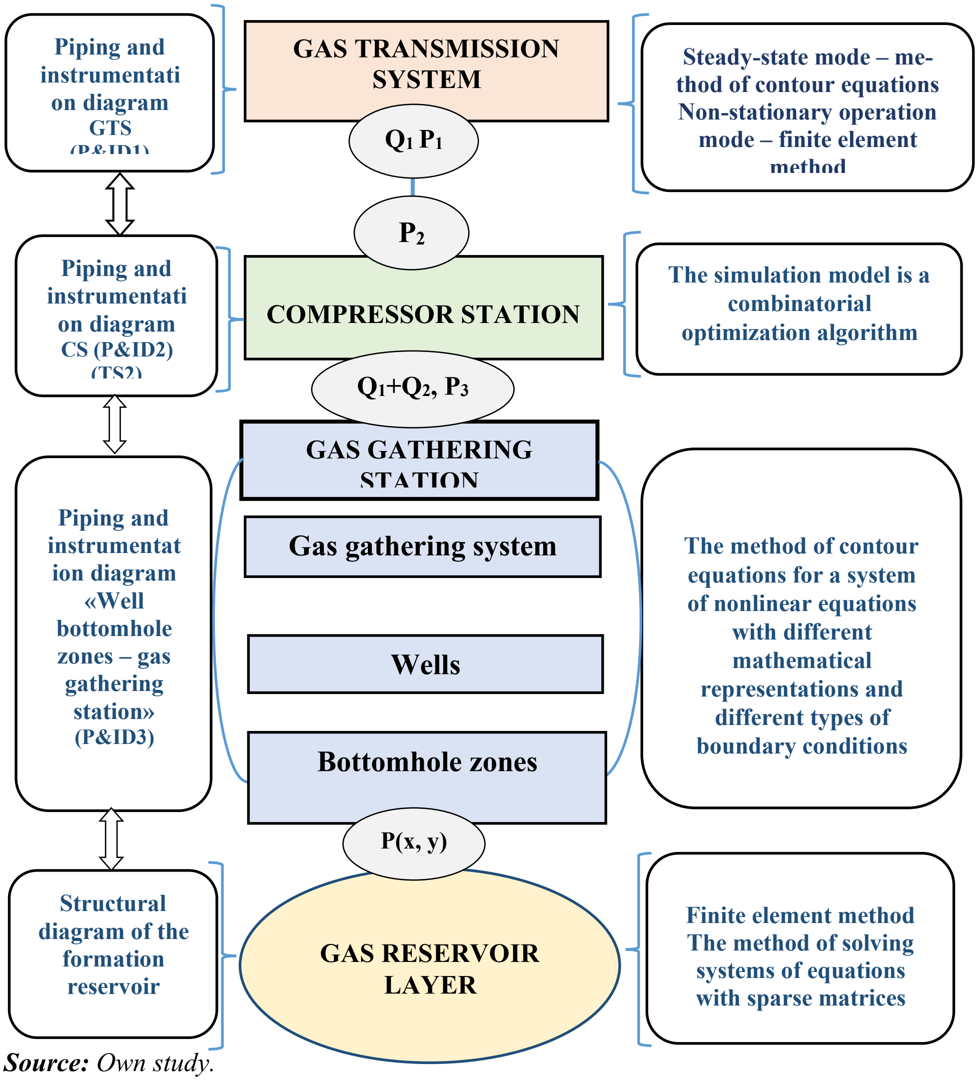
## 6.2 Hydraulic Calculation of Gas Filtration Parameters in a Heterogeneous Porous Medium

### *6.2.1 Numerical Implementation of the Reservoir Filtration Model*

The finite element method was used to calculate the pressure distribution in reservoirs with concentrated sources (Tolok and Krychevskyi, 2003; Zienkiewicz and Taylor, 2000a; Zienkiewicz and Taylor, 2000b; Smith and Griffits, 2004). For this, two-dimensional triangulation of the reservoir surface was carried out (Figure 2). Triangular elements increase in area in the direction of the outer gas saturation contour of the reservoir. This is explained by the fact that often peripheral reservoirs have a lower permeability and, accordingly, a lower speed of filtration flows.

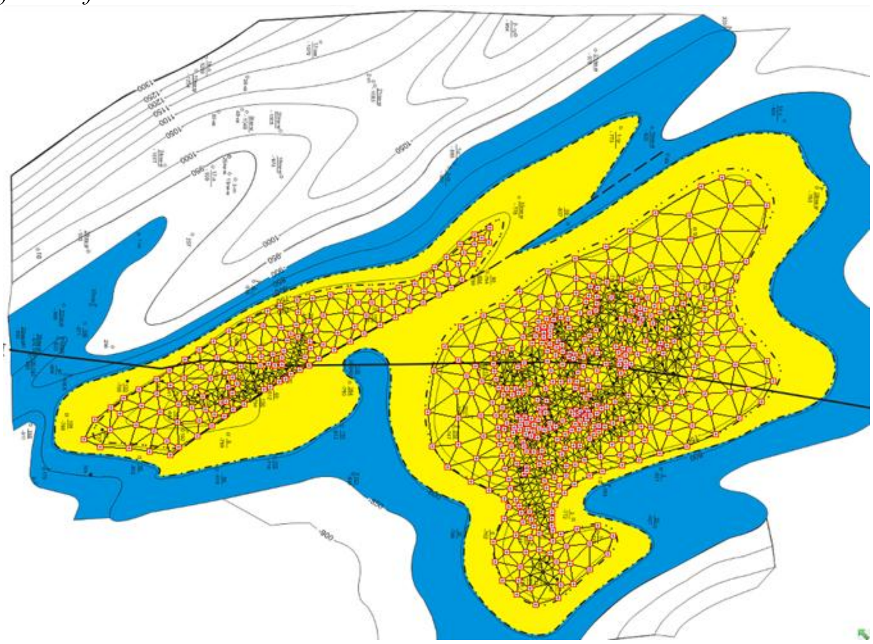
Each triangular element in the reservoir has the following parameters: vertex coordinates, average porosity, permeability, power of the vertical component and gas saturation (if necessary). Instead, the coordinates of all wells coincide with one of the coordinates of the vertex of the triangular elements.

***Figure 1.*** *General structural diagram of the underground gas storage and methods of implementing its models.*




***Source:*** *Own study.*

***Figure 2.*** *Triangulation of the reservoir surface in Bilche-Volytsko-Uherske UGS for the finite element method*



***Source:*** *Iwaszczuk et al., 2024.*

The finite element method reduces the solution of the boundary value non-stationary filtering problem with lumped sources to the solution (at each iteration step) of system of linear equations with sparse matrices. Before implementing the algorithm for solving systems of linear equations, we identify and remember the coordinates of the placement of non-zero elements in the matrix of the system, which are unchanged.

The process of solving the system of equations is as fast as possible, after which the operation is performed only on the nonzero elements of the matrix. Such an approach can also be created for the hydraulic calculation of gas networks, with an unchanged topology.

The result of solving the system of equations is the gas pressure at all vertices of the triangular elements. The coordinates of individual vertices of the triangular elements coincide with the coordinates of the wells. Therefore, we consider the gas pressures found in these peaks to be reservoir pressures around the wells (pressure on the "feed" contours of the wells).

It is used to calculate the bottomhole pressures of working wells, which, in turn, is used to find their flow rates (Prytula *et al.,* 2917b). In the next iterative step, the calculated flow rates of the wells make it possible to calculate the new distribution of pressures in the reservoir and, in particular, on the "feed" contour of the wells.

### *6.2.2 Identification of Parameters of the Reservoir Filtration Model*

Each layer is characterized by geometric, filtration and geophysical parameters, etc. The main parameters of the two-dimensional reservoir model that must be set are: $\Omega(x, y)$ – coordinates of the surface of the filtration area; $\Gamma(x, y)$ – coordinates of the contour of the surface of the filtering area; $h(x, y)$ – gas-saturated layer thickness coefficients; $k(x, y, p)$ – permeability coefficients; $m(x, y)$ – porosity coefficients. It is not always possible to find each parameter with sufficient accuracy, because in the gas filtration equation, all the mentioned parameters are interconnected, and their number significantly exceeds the number of equations to find them.

Clarifying some adaptive parameters may require changing others. Previously, in order to start the process of adapting the filtration model (Prytula *et al.,* 2017a), we conditionally divide the reservoir area into:

- bottomhole zones,
- peripheral poorly permeable zones;
- the working area of wells.

We adapt the filtering equation in several stages. At the first stage, we specify the geometric dimensions of the reservoir, set the coefficients of porosity, permeability and gas saturation for each triangular element, etc. This stage is considered completed if (with sufficient accuracy) the calculation of the volumes of accumulated gas in the reservoir is close to the actual established over many years of operation of the gas storage reservoir in the modes of gas injection and withdrawal.

The volume of gas that is in reservoirs is best estimated at the end of the neutral period (after the end of gas withdrawal). Problems of assessing the degree of imbalance may arise due to the lack of pressure measurements on a significant part of the reservoir. In the case of an excessive imbalance, it is necessary to establish the factors affecting its value and take it into account in the process of forming the balance. Such factors can be:

- movement of gas (trapped in the pores) outside the pores, in case of the necessary difference between internal and external pressures;
- gas from poorly permeable areas appears in the working zone with a significant delay (six or more months), etc.

At the second stage, we establish the average permeability of reservoirs in the area of well placement, according to well survey data. Permeability can be estimated in the process of analysing the coefficients with the linear component of the quadratic dependence of the flow rate of the wells on the squares of the difference in reservoir and bottomhole pressures (Iwaszczuk *et al.,* 2022a). It should be expected (as it often happens) that the permeability will decrease in the direction of approach to the outer contour of the impermeability of the reservoir.

During the numerical experiments, we refine the permeability of the reservoir triangle elements until the measured and calculated data differ by an acceptable amount. At the same time, the system of visual interpretation of calculation results and measured data significantly accelerates the adaptation process.

The problem of identifying the parameters of models with distributed parameters (within the required accuracy) has a non-unique solution due to insufficient certainty of the distributed filtering and accumulating parameters of the reservoir. And that is why there is not a single variant of the set of reservoir identification parameters.

Separate sets of identification parameters (for a certain period of time) provide sufficient convergence of measured and calculated reservoir pressures in control wells. It happened that with significant changes in the operating modes of the UGS, there was a need to re-specify the parameters of the reservoir.

After that, we managed to achieve the required accuracy of UGS modelling for the entire previous period of its operation. So the process of studying the distributed parameters of reservoirs during its operation is practically constant.

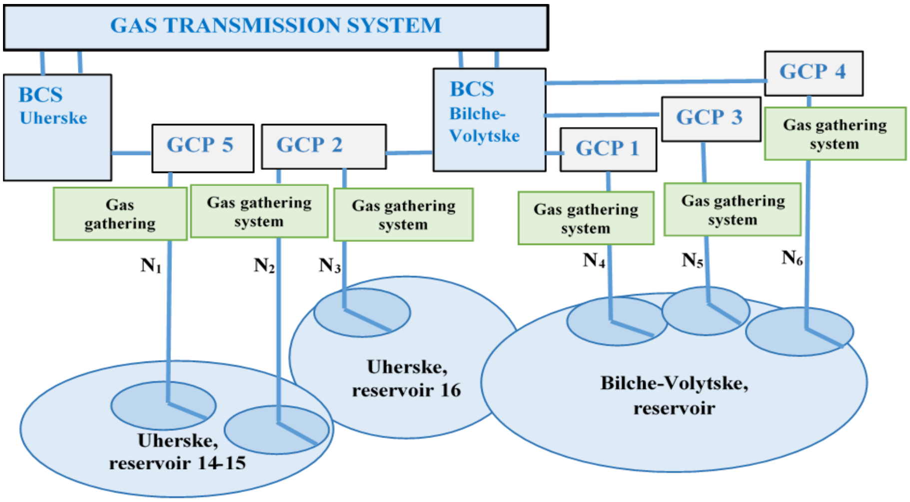
***6.2.3 Numerical Experiments***

We conducted numerical experiments using the software module "Gas filtration in heterogeneous reservoirs" from the GIMS complex (Prytula et al., 2017b). This module enables:

- calculate the distribution of gas pressure in the entire area of filtration under the condition of impermeability of the boundary;
- to clarify the coefficients of porosity, permeability, gas saturation in the heterogeneous reservoir of the storage;
- to clarify the geometrical and geological-physical parameters of reservoir layers;
- calculate the volumes of accumulated gas based on the pressure distribution;
- to specify hydrodynamic filtration parameters during the operation of the UGS;
- to analyse the gas balance and factors affecting the magnitude of its imbalance.

After adapting the filtration model (according to the measured flow rate, with a frequency of one hour, for the last several seasons of gas injection/withdrawal at Bilche-Volytske-Uherske UGS, which is technologically connected to the Uherske gas storage) (Figure 3), we calculated the reservoir pressure in the working zone of the wells – during the operation of three gas gathering systems (1, 3, 4), during three seasons of gas injection/withdrawal.

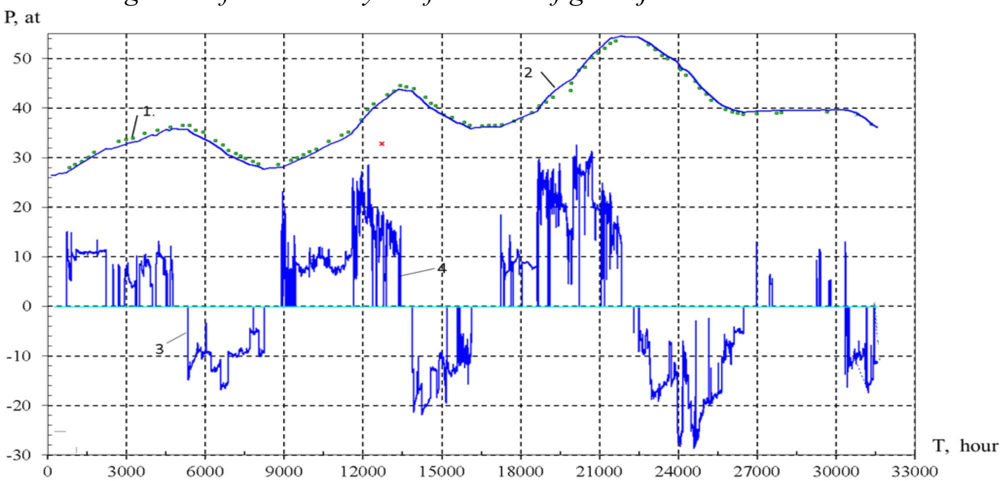
***Figure 3.*** *Simplified diagram of two technologically connected Bilche-Volytske and Uherske reservoirs*




***Source:*** *Gas Storage Development Plan…, 2021.*

General characteristics of the two storage facilities (shown in Fig. 3): total gas capacity of 37,300 million nm3; active gas capacity of 18,950 million nm$^3$; number of wells N1+N2+N3+N4+N5+N6=429; the total capacity of the HPP is 344.0 MWh (Gas Storage Development Plan…, 2021). The results of the adaptation of reservoir systems in the Bilche-Volytske-Uherske UGS are shown in Figure 4.

***Figure 4.*** *Calculated average reservoir pressure in the Bilche-Volytske reservoir in the working area of the wells by the flow rate of gas injection and withdrawal*




***Source:*** *Own study.*

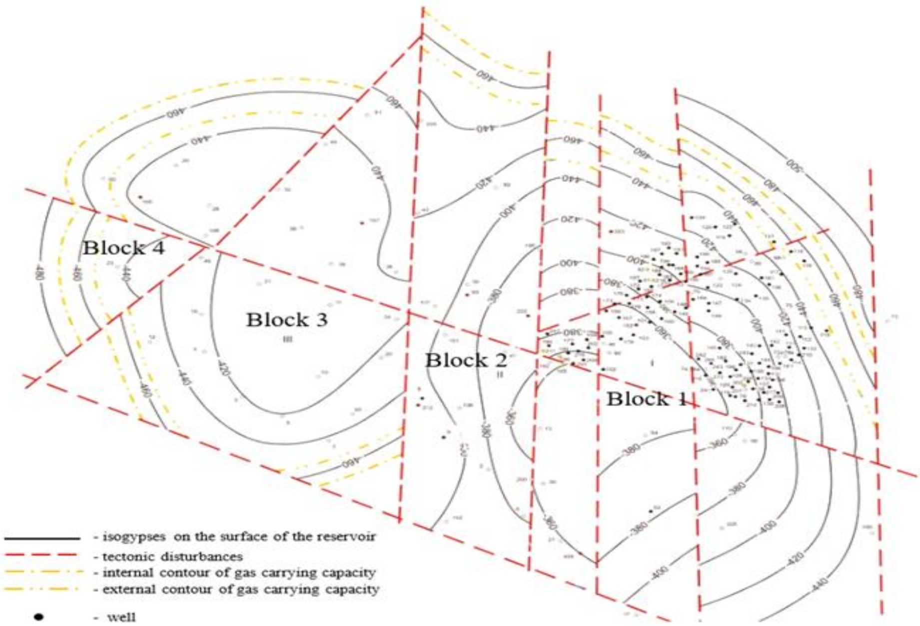
In Figure 4 is marked: 1 – average measured gas pressure in the working area of the wells, 2 – average calculated gas pressure in the working area of the wells, 3 – volume of gas injection per day, 4 – volume of gas withdrawal per day. The coincidence of measured and calculated during three seasons of gas injection and withdrawal is quite accurate.

The criterion for successful determination of reservoir permeability is the sufficient accuracy of the convergence of the calculated and measured average reservoir pressure in working wells during 3-10 seasons of gas injection and withdrawal. However, there are no approaches that would ensure the development of universal methods for identifying the parameters of filtering models, let alone the algorithmization of this process.

For more complex reservoirs with geological fractures and poorly permeable porous layers, the permeability of the areas must be set to ensure the convergence of measured and calculated pressures in all observation wells during all years of UGS operation (if data are available).

To create a reservoir filtration model for the Dashavske UGS (Prytula *et al.,* 2017b), we used a structural map of the reservoir with geological faults that formed four blocks with different parameters $k_i, m_i, h_i (i = 1,2,3,4)$ (Figure 5).

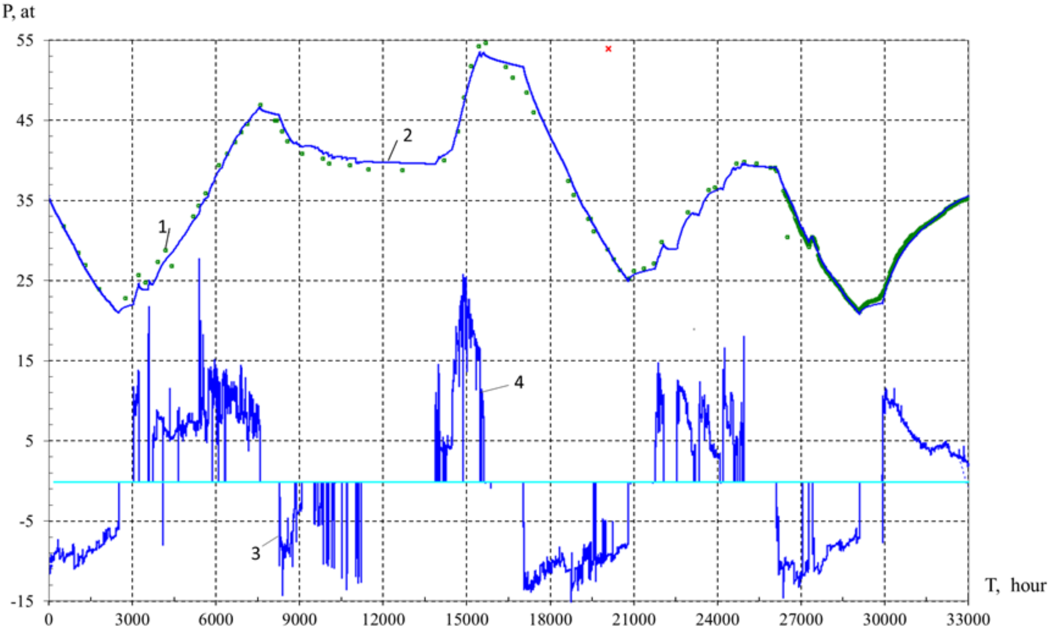
***Figure 5.*** *Structural map of the Dashavske UGS with the division into activity blocks*




***Source:*** *Prytula et al., 2017b.*

In each of the blocks (in observation wells) for many years, we have measured reservoir pressure. Now it is necessary to find such $k_i, m_i, h_i$ for each layer and interlayer permeability, so that in the process of modelling the gas filtration process (according to the measured volumes of gas injection and withdrawal, during several seasons) to ensure the convergence of the measured and calculated pressures in the working zone and in the gas pressure measurement wells, with the predetermined accuracy (Figure 6).

***Figure 6.*** *Calculated average reservoir pressure of the Dashavske UGS in the working area of the wells*




***Source:*** *Own study.*

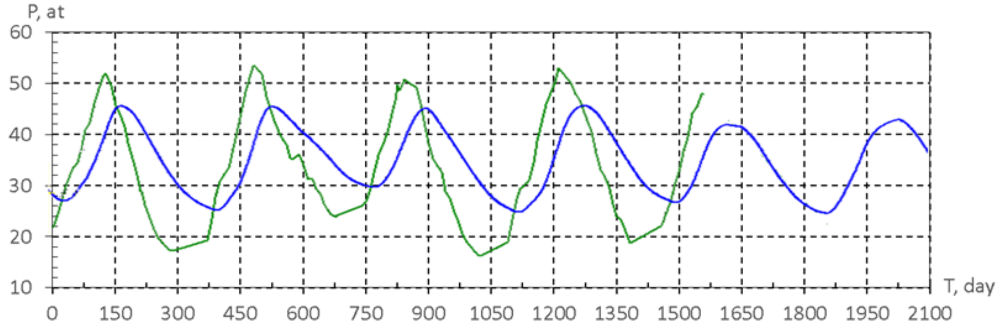
In Figure 6 is marked: 1 – average measured gas pressure in the working area of the wells, 2 – average calculated gas pressure in the working area of the wells, 3 – volume of gas injection per day, 4 – volume of gas withdrawal per day.

We checked the validity of the choice of parameters $k_i, m_i, h_i (i = 1,2,3,4)$ during numerical experiments. To do this, we calculated the pressures in the observation wells, which are located in the corresponding block. The obtained results are shown in figures 7-9 in different colours: green – average reservoir pressure in the working zone of the wells; blue – reservoir pressure in the observation well.

We checked the coincidence of the results by comparing them with the data in the geological and technological exploitation reports of the corresponding UGS. As you can see, the phase shift of the pressures (in particular, the maximum) measured in the observation wells and in the working zone of the wells is approximated by: 45

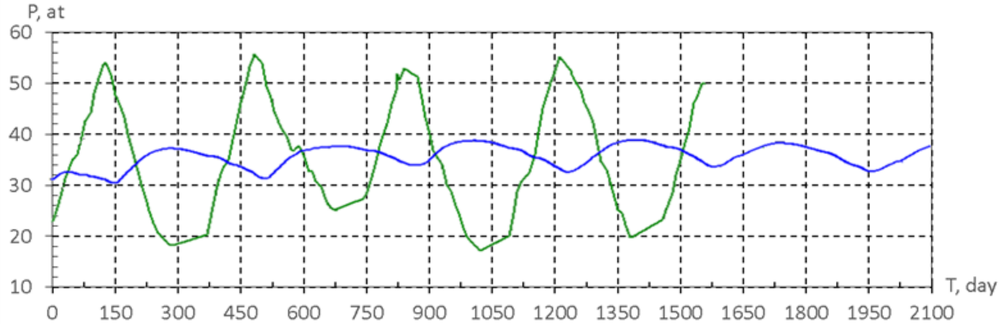
days (Figure 7), 190 days (Figure 8), 360 days (Figure 9). Such a phase shift characterizes the low speed of filtration processes and the different directionality of gas filtration flows over time in different parts of the reservoir.

***Figure 7.*** *Results of the pressure change calculation in block 1 during six seasons of gas withdrawal and injection*



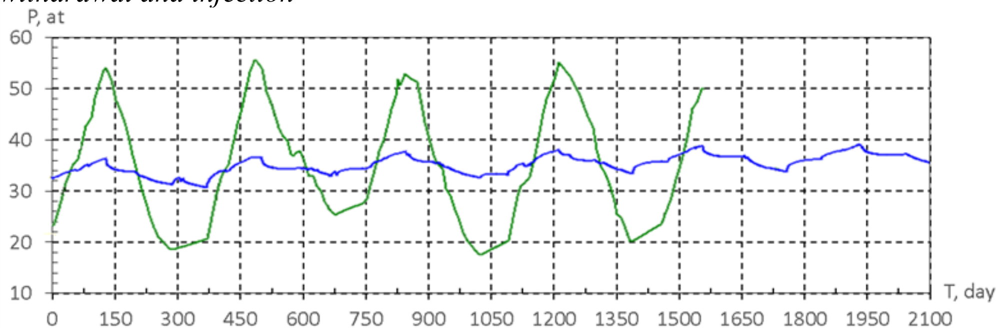

***Source:*** *Own study.*

***Figure 8.*** *Results of the pressure change calculation in block 2 during six seasons of gas withdrawal and injection*




***Source:*** *Own study.*

***Figure 9.*** *Change in average pressure in block 3 during six seasons of gas withdrawal and injection*




***Source:*** *Own study.*

The presented modelling results (Figures 7-9) showed that the range of reservoir pressure changes in the observation wells is smaller than the range of changes in the working zone of the wells. It should be noted that as a result of the adaptation of the filtration model of dynamics, the change in pressure in the indicated wells is close to the measured one.

## 6.3. Calculation of Operating Modes of Compressor Stations

### *6.3.1 Algorithm for Calculating the Operation Mode of the CS*

Compressor stations (CS) at UGS can be equipped with gas pumping units (GPU) of two types: 1) GPU with centrifugal compressors on gas turbine (or electric) drives; 2) GPU piston type on gas engine drives. Compressor stations with GPU of the first type provide several stages (two or three) of gas compression.

To calculate the operation modes of the CS, we used two approaches. The first approach is based on a detailed piping and instrumentation diagram of the CS. For this purpose, we used the software for calculating gas transmission systems operating modes on detailed piping and instrumentation diagram (P&ID) (without simplifications) (Prytula *et al.,* 2017a). To calculate hydraulic losses in such a vehicle, it is necessary:

- set the hydraulic equivalents of the quadratic type,
- take into account the influence of many local resistances, between which (perhaps) there is also a hydraulic interaction.

The advantages of this approach are the fact that working with a detailed P&ID allows you to automate the process of forming a piping and instrumentation diagram for the implementation of the calculated modes of operation of the CS. The second, somewhat simpler approach, which we implemented, provided a quick solution to dispatching problems. For each CS, we established hydraulic equivalents – between the degrees of gas compression and on the input and output pipelines of the CS.

To calculate the operation modes of the CS, you must have the following data:

- graphical presentation of the piping and instrumentation diagram;
- set of all possible schemes of operation of UGS and its facilities;
- type and characteristics of GPU – operating parameters of drives and centrifugal superchargers;
- flow rate, pressure, temperature and density of gas at the entrance of the CS;
- gas pressure at the CS outlet;
- type and characteristics of air cooling devices;
- reduced values $(z_{pr}, R_{pr}, T_{pr})$;
- value of calculated values $\varepsilon$, $\eta_{pol}$,$N_i$;
- gas component composition.

The main modules of the developed software:

***Module 1.*** Calculation of the properties of natural gas based on the given component composition of the gas, pressure $P$ and temperature $T$ of the gas. Using the module, you can calculate:

- gas constant $R$;
- compressibility coefficient $z(P,T,\rho)$;
- gas density $\rho(P,T)$;
- gas volume $q(P,T)$.

***Module 2.*** Modelling of the GPU operating mode. With the help of the module you can:

- calculate the reduced rotation frequency of the supercharger rotor $\left[\frac{n}{n_n}\right]_{pr}$;
- calculate the specified volumetric productivity $[q]_{pr}$;
- check the centrifugal compressor (CC) for the minimum and maximum volume;
- calculate the reduced relative internal power $\left[\frac{N_i}{\rho_n}\right]_{pr} = \frac{N_i}{\rho_n}\left(\frac{n_n}{n}\right)^3$;
- calculate the degree of compression $\varepsilon = \varphi_1\left([q]_{pr}, \left[\frac{n}{n_n}\right]_{pr}\right)$;
- check the working conditions without pumping;
- calculate the power of the centrifugal compressor $N_i$;
- calculate the power on the drive coupling $N$;
- calculate the available capacity of the gas turbine power plant $N_p$;
- check gas turbine power limitations (working power $N$ should not exceed available $N_p$);
- calculate the gas temperature at the outlet of the centrifugal compressor $T_n$;
- calculate the volume of fuel gas.

However, in the practical application of the module, there are a number of technological limitations for CC of GPU, in particular regarding:

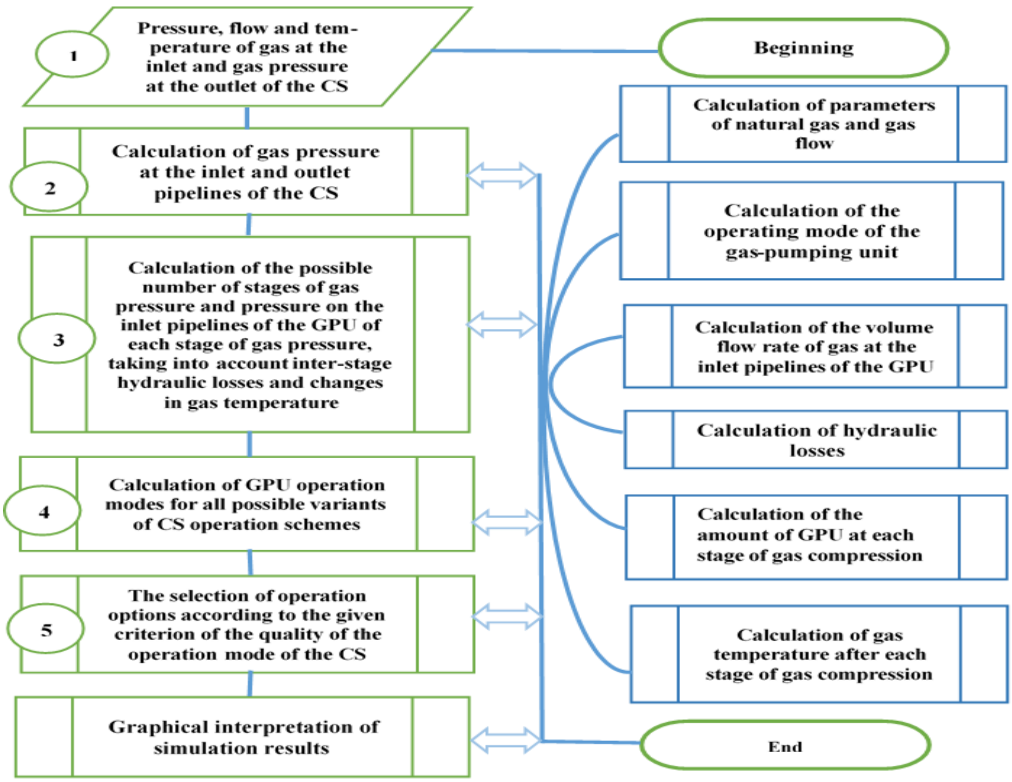
- the position of the working points on the characteristics of the CC to ensure pumpless operation of the GPU;
- minimum and maximum volumetric productivity of CC;
- frequency of rotation of the shaft ($n_{\min} \le n \le n_{\max}$);
- the maximum capacity of the drive of GPU;
- the maximum outlet pressure of the CC, which is determined by the strength of the pipelines at the outlet of the CC;
- the maximum temperature at the outlet of the CC, which is determined by the insulating coating of the pipelines;
- the minimum pressure value at the outlet of each CC;

- conditions related to the given level of stability of the GPU operation (distance from the surge zone);
- conditions of consistency of the CC connection scheme to the input and output circuits and main gas pipelines.

***Module 3.*** Calculation of the operation mode of the CS. The module allows:
- calculate the number of gas compression stages, the gas temperature after each stage, the temperature at the entrance of each gas compression stage and the amount of GPU at each stage;
- calculate the operating modes of each GPU – super charger revolutions, volumes of fuel gas, coefficient of distance from the surge zone;
- to form a scheme of work of the CS;
- to interpret the results of calculation of operating modes of the CS.

In Figure 10 presents the main modules of the software complex for calculating the operation modes of the CS and the expected results of their operation.

***Figure 10.*** *The main software modules of the algorithm for calculating the operating modes of multi-shop BCS with different types of gas pumping units*




***Source:*** *Own study.*

In addition, we implemented a selection of options for CS modes according to:

1) the distribution of gas compression coefficients between stages of CS;
2) by types of GPU at each step of gas compression;
3) different amount of GPU at each stage of gas compression;
4) different mode parameters of the GPU.

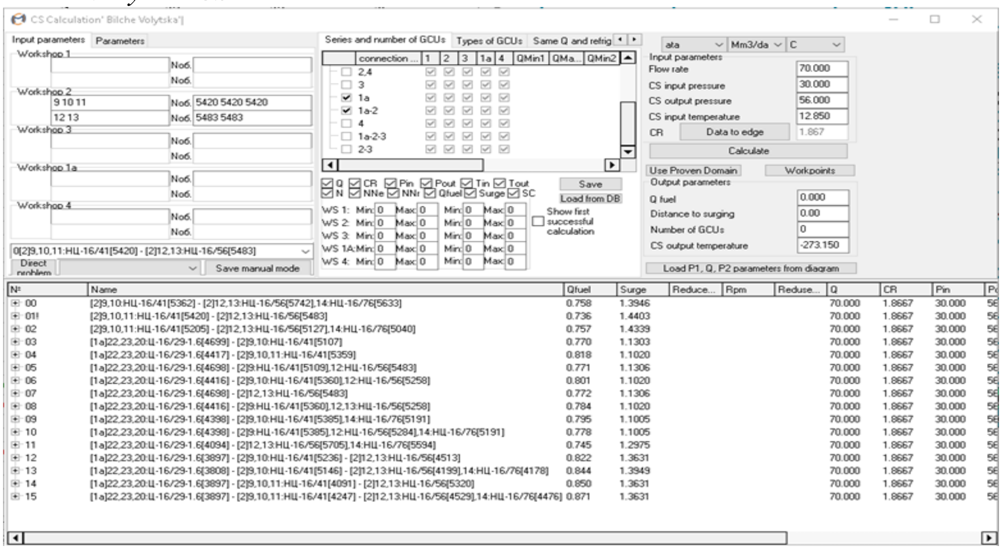
Then, according to the calculation, a complete set of all possible operating modes of the CS can be formed, among which modes can be distinguished according to the following criteria: optimality, according to fuel gas; according to the stability of the GPU operation; according to a weighted criterion. The developed modelling complex, among other modes, offers modes with different numbers of GPU at gas compression ratios. Calculation modes based on the fuel gas criterion (with different numbers of GPU at gas compression ratios) provide significant gas savings, which has been convincingly verified in practice.

### *6.3.2 Numerical Experiments*

#### (1) An Example of Calculating the Operation Modes of the CS

Let's give a real example (Figure 11). Based on the specified volumes of gas compression – 70 million m3 per day, gas pressures at its inlet – 30.00 at and at the outlet – 56 at, it is necessary to calculate all possible operating modes of the CS. The simulation results are presented in the Figure 11 and Table 1.

***Figure 11.*** *Interface of the software module "Calculation of operating modes of compressor stations". The results of the calculation of the operation mode of the Bilche-Volytske CS*



***Source:*** *Own study.*

***Table 1.*** *Calculation results of the operation mode of the CS*

| Mode number | Mode scheme | Consumption of fuel gas [Mm$^3$/day] | Overconsumption of fuel gas [Mm$^3$/day] | Super charger revolutions by stages Rpm 1 stage – Rpm 2 stage (Variable flow parts 1st stage – Variable flow parts 2nd stage) [revolutions/minute] |
|---|---|---|---|---|
| 00 | 2x2 | 0.758 | 0.022 | 5362 – 5742 (41 – 56,76) |
| 01 | 2x2 | 0.736 | 0.00 | 5420 – 5486 (41 – 56) |
| 02 | 3x3 | 0.757 | 0.021 | 5205 – 5127 (41 – 56,76) |
| 03 | 3x2 | 0.770 | 0.034 | 4699 – 5107 (29 – 41) |
| 04 | 3x3 | 0.818 | 0.082 | 4417 – 5359 (29 – 41) |
| 12 | 3x2x2 | 0.822 | 0.086 | 3897 – 5236 – 4513 (29 – 41 – 56) |
| 14 | 3x3x2 | 0.850 | 0.114 | 3897 – 4091 – 5320 |
| 15 | 3x2x3 | 0.871 | 0.135 | 3897 – 4247 – 4529 (29 – 41 – 56,76) |

***Source:*** *Own study.*

According to the results of the calculation of the operating modes, it is possible to formulate the requirements for the optimal mode, according to the consumption of fuel gas, for the operation of the CS. The operating mode is optimal if all the listed requirements are met at the same time:

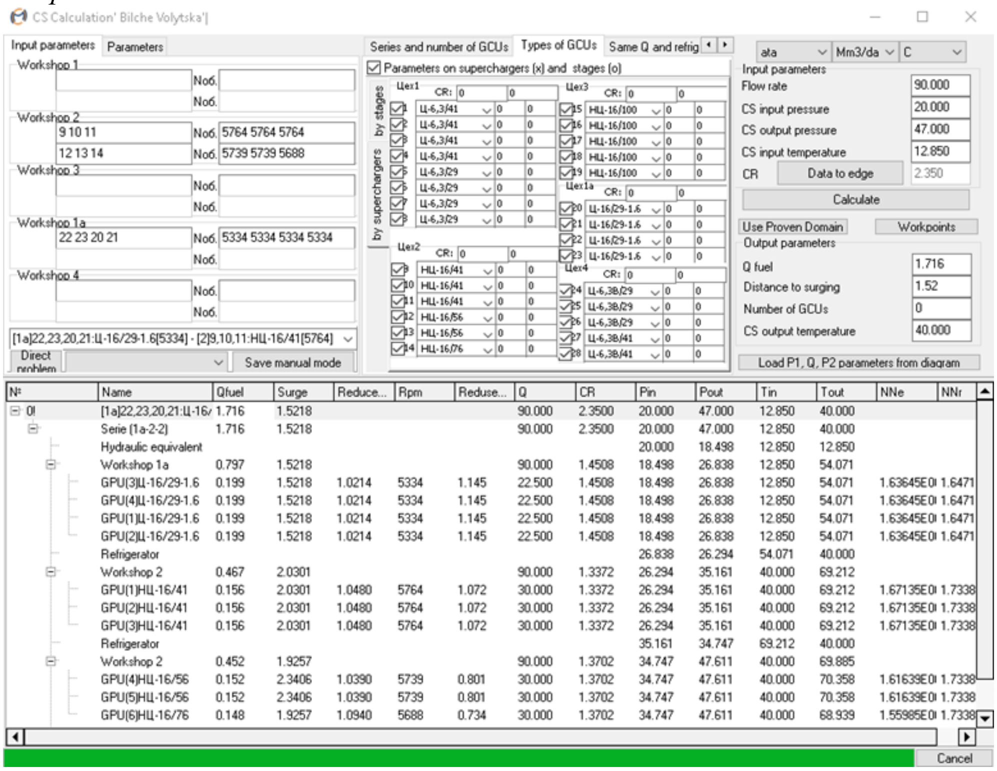
- minimum number of GPU (comparison of the mode 01 with modes 02, 03, 04, 12, 13, 15);
- minimum number of gas compression stages (comparison of modes 00, 01 with modes 02, 03, 04, 12, 14, 15);
- load by power is greatest at the first stages of gas compression (comparison of the mode 01 with the mode 00 and the mode 01 with the mode 02);
- selection of variable flow parts (VFP) according to output pressures (comparison of the mode 00 with the mode 01).

According to the results given in Table 1, it is possible to assess the potential for optimizing the operation of the CS. At today's fuel gas price of around 1,000 euros per 1,000 m$^3$, the optimization potential is in the range of (22,000 – 135,000) euros per day.

In the 12 shows the results of calculating the operating mode for significant daily volumes of gas withdrawal from the storage (90 Mm$^3$/day). Under the given conditions for the gas pressures at its inlet and outlet, the software module offers a single operation mode of the CS in three gas compression stages with a detailed calculation of the mode parameters of all GPUs (lower part of Figure 12).

The operating mode requires 1.716 Mm$^3$/day of fuel gas consumption during the day at 52% distance from the surge zone of the centrifugal superchargers (1.52). The minimum recommended distance from the surge zone of centrifugal superchargers should be at least 10%, otherwise the GPU will fall into the destructive surge zone.

***Figure 12.*** *Software module interface "Calculation of operating modes of compressor stations"*




***Source:*** *Own study.*

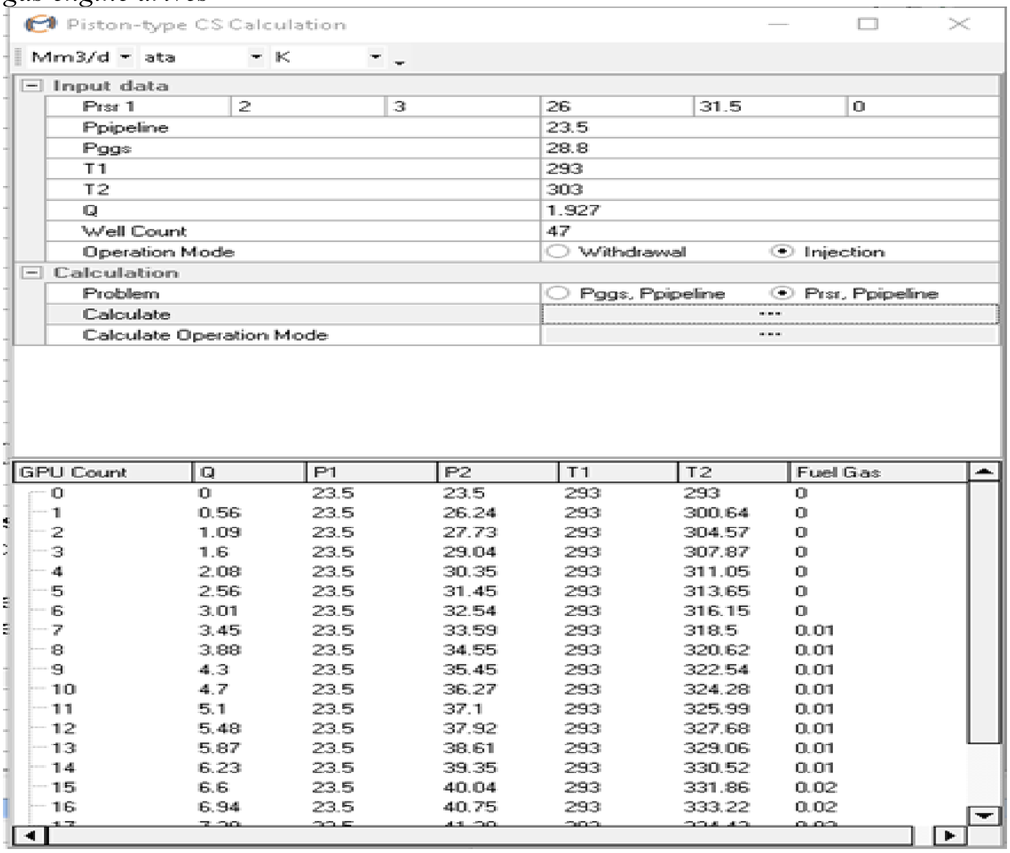
For CS with GPU with gas turbine drives and centrifugal superchargers, we have implemented the following functionality:

- calculation of operating modes of the GPU, shop, multi-shop BCS with different types of GPU;
- calculation of fuel and energy costs for the given mode of operation of the GPU, BCS;
- calculation of the optimal modes of operation of multi-shop BCS according to the energy criterion (implemented options according to: distribution of the compression ratio between the stages, change in the revolutions of the centrifugal superchargers, the number of GPU on the stages, etc.);
- calculation of operating points of centrifugal superchargers and drives based on operational measured data;
- displaying archival data of the operating modes of the selected GPU, BCS with the possibility of finding the area of their real modes;
- identification of the hydraulic parameters of the state of the GPU and multi-shop BCS;
- calculation of the parameters of the working area of the BCS modes.

### (2) An Example of Calculating the Operating Mode of a Piston-Type BCS

The mode of operation of such a CS is based on a different number of involved GPUs. The input data for calculating the operating mode are the pressure in the gas pipeline and the reservoir pressure in the working zone of the wells. In Figure 13 shows the results of the calculation of all possible variants of operation of the BCS with 18 GPU of the piston type in the gas withdrawal mode. In this example, the pressure in the outlet gas pipeline for different volumes of gas withdrawal was not calculated. In the example, the pressure in the outlet gas pipeline is assumed to be constant and equal to 50 at.

***Figure 13.*** *The results of calculating the operation modes of the piston-type CS with gas engine drives*




| GPU Count | Q | P1 | P2 | T1 | T2 | Fuel Gas |
|---|---|---|---|---|---|---|
| 0 | 0 | 23.5 | 23.5 | 293 | 293 | 0 |
| 1 | 0.56 | 23.5 | 26.24 | 293 | 300.64 | 0 |
| 2 | 1.09 | 23.5 | 27.73 | 293 | 304.57 | 0 |
| 3 | 1.6 | 23.5 | 29.04 | 293 | 307.87 | 0 |
| 4 | 2.08 | 23.5 | 30.35 | 293 | 311.05 | 0 |
| 5 | 2.56 | 23.5 | 31.45 | 293 | 313.65 | 0 |
| 6 | 3.01 | 23.5 | 32.54 | 293 | 316.15 | 0 |
| 7 | 3.45 | 23.5 | 33.59 | 293 | 318.5 | 0.01 |
| 8 | 3.88 | 23.5 | 34.55 | 293 | 320.62 | 0.01 |
| 9 | 4.3 | 23.5 | 35.45 | 293 | 322.54 | 0.01 |
| 10 | 4.7 | 23.5 | 36.27 | 293 | 324.28 | 0.01 |
| 11 | 5.1 | 23.5 | 37.1 | 293 | 325.99 | 0.01 |
| 12 | 5.48 | 23.5 | 37.92 | 293 | 327.68 | 0.01 |
| 13 | 5.87 | 23.5 | 38.61 | 293 | 329.06 | 0.01 |
| 14 | 6.23 | 23.5 | 39.35 | 293 | 330.52 | 0.01 |
| 15 | 6.6 | 23.5 | 40.04 | 293 | 331.86 | 0.02 |
| 16 | 6.94 | 23.5 | 40.75 | 293 | 333.22 | 0.02 |

***Source:*** *Own study.*

The calculation results show (Fig. 13) that with an increase in the number of GPU, the total flow rate of the wells increases disproportionately to its number. This is due to the fact that an increase in gas withdrawal volumes (*Q*) leads to a decrease in the wellhead pressure ($P_1$) and, accordingly, to an increase in the gas compression ratio.

The mode of operation of the UGS, for the given volumes of gas withdrawal, depends on the pressure distribution in the reservoir and the pressure in the gas pipeline-outlet. The pressure distribution in the reservoir can be characterized by the following parameters:

- average reservoir pressure, which depends on the volumes of accumulated gas;
- average pressure in the area of working wells, which depends on the dynamics of changes over time in gas withdrawal volumes;
- breakthrough pressure in wells, which depends on the dynamics of changes in their flow rates.

As for the pressure in the gas pipeline, it depends on the mode of operation of the gas transmission system. In the gas withdrawal mode, the consumption of fuel gas at the gas station can be minimized by reducing the pressure in the gas pipeline, which leads to an increase in the energy consumption of the gas transmission system. Therefore, dispatch services of different operators – GTS and UGS, in such cases, must find a compromise solution.

In 2022, gas storages in Ukraine are not fully filled. And therefore, if necessary, in order to maintain their necessary peak characteristics, there will be a need (to the extent possible) to reduce the pressures in the system of main gas pipelines, which are adjacent to the UGS branch gas pipelines.

There is another real possibility – to increase the peak rate of UGS at certain time intervals. For this, it is necessary to “correctly” plan the processes: filling of UGS reservoirs during the period of gas injection; and their operation in periods of time with off-peak load.

This will require the distribution (during UGS operation) of gas withdrawal volumes between the storages in such a way that for the forecasted time intervals, the residual volumes of active gas in the storage layers would ensure their total maximum peak capacity. The problem of UGS operation according to peaking criteria was considered by us in the work (Prytula *et al.,* 2022).

## 7. Discussion

The results obtained in the work are oriented, first of all, to their use by dispatching services to solve problems that are necessary for planning and monitoring the process of operation of the UGS. The main requirements for such systems are: speed of obtaining results; guaranteed accuracy and reliability of work in the entire area of changing input parameters. To ensure such parameters of the system operation, we presented the area of gas filtration of the reservoir as a combination of the bottomhole zones of the wells and the area beyond them. The highlighted areas differ in filtration models – gas flow to wells in their bottomhole zones has a nonlinear analytical model, while in the other area Darcy's law of gas filtration is fulfilled and therefore the gas filtration model is represented by a linear numerical model.

In our case, all underground gas storages work in gas mode, and water flow to the wells (mainly) appeared at the end of the gas withdrawal season. The dimensions of the surface of reservoirs of all UGS are significantly larger than the vertical component. This made it possible to use a two-dimensional filtration model of the reservoir. The use of a two-dimensional filtration model and the representation of the filtration area by various mathematical models allowed us to minimize the number of elements in the process of triangulation of the gas filtration area outside the bottomhole zones.

This, in turn, made it possible to apply the numerical method of finite elements with matrices of minimum dimension and take into account their sparsity (only non-zero elements are taken into account in the calculation). In this way, we achieved the maximum speed of the method, which is necessary not only for optimization problems, but also for fast adaptation of the filtering model.

In order to calculate the operation modes of UGS, we implemented algorithmic (simulation) models of compressor stations with different types of gas turbine drives and centrifugal superchargers. We implemented two variants of piping and instrumentation diagrams (P&ID) for compressor stations (CS) – simplified and detailed.

Since the implementation of the model of the detailed P&ID requires a significant time for its adaptation, we used the CS with a simplified P&ID in the operative dispatch planning of the operating modes of the UGS. For this, we have established hydraulic equivalents: from the entrance of the CS to the GPU, between the workshops of the CS and from the GPU to the exit of the CS.

This ensured a quick calculation of all possible modes of operation of the UGS. To calculate these modes, we developed a combinatorial optimization algorithm of minimal complexity. It made it possible to calculate individual modes, among which modes can be distinguished according to one or another quality criterion. The proposed algorithm has the advantage over classical algorithms that it does not require special properties of gas flows of gas in CS facilities.

Among the advantages of this research (compared to similar ones known at this time), two should be highlighted:

- representation of the filtering area by different models;
- a combinatorial optimization method with adjustable complexity was developed.

This ensured not only the quick obtaining of multivariate results of UGS simulation, but also the possibility of choosing high-quality operating modes according to the energy criterion, according to stability and other criteria of optimality. The obtained solutions close the problematic part defined in section 4.

The application of the conducted research requires constant analysis of adaptive parameters – the coefficients of nonlinear gas filtration in the bottomhole zones of the wells and the distributed permeability of the formation system beyond them. The change in the permeability of the reservoir especially affects the amount of depression/repression of the wells' bottomhole zones.

This often happens when the quality of gas changes at the stage of its injection – due to humidity and an increase in the proportion of heavy hydrocarbons in the gas composition. In such cases, it is necessary to carry out re-adaptation. In other cases (when the composition of the gas does not change significantly), the filtration model may be adequate for ten years or more.

It is necessary to constantly monitor the adequacy of the GPU model – drive efficiency for fuel gas and polytropic efficiency for a centrifugal supercharger. Such control requires high-quality measured data – according to the accuracy and synchronicity of their measurement. It is advisable to use the measured data in the stable mode of operation of the UGS.

## 8. Conclusions and Prospects for Further Research

The developed methods and algorithms for the implementation of the filtering equation, as well as software (in terms of functional, qualitative and quantitative parameters of work) are primarily aimed at their use in dispatching services and geological services as a decision support system. This is what set the requirements for the simultaneous achievement of the necessary speed of calculating the pressure distribution in the reservoir and the accuracy of the system.

We achieved this thanks to: the use of a justified two-dimensional filtering model; the selection of subduction zones in the reservoir with its non-linear model of gas inflow to the wells; using the method of solving systems with sparse matrices, etc.

This approach also ensured the ease of adaptation of the filtering model (triangulation with a minimum number of elements was necessary). The estimated time of the process of filtering a formation with concentrated sources (more than 300 wells), the surface area of which is more than 120 km2, for 5 seasons of gas injection and extraction was no more than one minute. A software module with such parameters, when simulating the operation of the UGS, made it possible to include it in the software for solving problems of optimal dispatching control in the UGS.

The developed combinatorial method (with adjustable complexity) made it possible to calculate operating modes with specified accuracy for multi-shop compressor stations with various types of gas pumping units.

To ensure the accuracy of the calculation of the operating modes of each gas pumping unit of the CS, a module for its adaptation based on real data. The developed methods of calculation of CS made it possible to solve optimization problems according to the consolidated criterion – the minimum amount of fuel gas per unit volume of gas withdrawal/injection.

Regarding the prospects for further research, it should be ensured:

- the maximum possible automation of the process of updating information and software of UGS;
- automation of the support system for all stages of decision-making for optimal dispatch control in UGS.

In the continuation of this publication, we will provide methods and algorithms for solving problems of dispatching control of underground gas storage facilities. It will be devoted to the development of systems of effective dispatching control of the operation process of the UGS. For this, we will formulate the necessary direct and inverse problems for planning the operating modes of the UGS, according to various optimality criteria. To solve them, we developed fast-converging methods and algorithms of minimal complexity, in particular, combinatorial optimization methods.

This allowed us to achieve the necessary level of operational decision-making by dispatch services, thanks to the application of the method of automating the solution of optimization problems for the formation of optimal operative and predictive modes of operation in UGS. Special attention will be paid in the work to the development of a method for solving the problem of flow analysis in a network-type system with various boundary conditions.

Such an analysis problem connects the filtration processes in reservoirs with concentrated sources and the discrete-continuous processes occurring in many workshop compressor stations. The proposed approach will make it possible to combine different (according to mathematical representation) models of processes of different physical nature (which take place in UGS) into a single thermohydraulic complex.

In the article, we will give examples of solving problems of analysis and dispatching of work modes. In addition, we will show the results of the analysis of qualitative and quantitative characteristics developed and tested in real operating conditions of both individual modules and the software as a whole.

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*The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper*

***Data availability statement:***

*Most of the data used is freely available. The rest of the data will be made available upon request.*