UDC 621.64.029
DOI: 10.15587/2312-8372.2018.128574

Prytula N.,
Prytula M.,
Boyko R.

DEVELOPMENT OF SOFTWARE FOR ANALYSIS AND OPTIMIZATION OF OPERATING MODES OF UNDERGROUND GAS STORES

Об'єктом дослідження є підземні сховища газу (ПСГ) та їх технологічні об'єкти, які задіяні в процеси нагнітання, зберігання та відбирання газу. Однією із найважливіших виявлених проблем є забезпечення надійної та економної експлуатації ПСГ у складі газотранспортної системи (ГТС) України. Один із шляхів рішення проблеми – розробити ефективне програмне забезпечення (ПЗ) як інструменти прийняття рішень, які, в ході проведених досліджень, виявилися відсутніми у диспетчерських служб із управління ГТС.

Проведений аналіз існуючих ПЗ на ринку програмних продуктів показав їх невідповідність необхідним вимогам за функціональністю, набором та швидкістю розв'язування задач. В основному розроблене ПЗ було орієнтоване на експлуатацію вугледобувних підприємств і не могло бути адаптованим для експлуатації ПСГ, в яких процеси, особливо фільтраційні в пластах-колекторах, проходять на порядок швидше.

Розроблення нового багатофункціонального програмного продукту було орієнтовано на забезпечення процесів моделювання газодинамічних та фільтраційних процесів в об'єктах ПСГ, ідентифікації їх технічного та технологічного стану та планування експлуатаційних параметрів об'єктів ПСГ.

Розроблений програмний продукт забезпечив уточнення геофізичних параметрів пластів-колекторів більшості ПСГ України. Отримані оцінки величини ефекту від реконструкції ПСГ у випадках фізико-хімічних обробок вибою свердловин, заміни компресорних станцій газоперекачуючих агрегатів на імпортні з кращим ККД, при переході зі шлейфово-колекторної системи збору газу на повністю шлейфову. Розроблене ПЗ використовується і для високоточного моделювання режимів роботи в екстремальних умовах експлуатації ПСГ.

Системний ефект від експлуатації розробленого програмного забезпечення досягається за рахунок проведення досліджень для формування передпроектних рішень. А також числових експериментів на предмет вивчення та оцінки потенціалу оптимізації, та оптимального планування перспективних рішень і оперативної експлуатації.

Ключові слова: *програмне забезпечення, підземне сховище газу, фільтрація газу, оперативне планування, компресорна станція.*

1. Introduction

The developed system model, mathematical software and on their basis allow to deliver and effectively solve a set of operating mode problems that arise in the process of operation of underground gas storages (UGS) as part of the gas transportation system (GTS) [1].

An evolutionary model [2] is taken for the software development life-cycle model, which offers a sequential implementation of the software system design blocks. The requirements for the blocks are set partial and are refined in the process of their validation on real data. In the process of implementing the following intermediate blocks of the system structure, the previous blocks, if necessary, are corrected. In parallel with the software development, the domain is researched to study the customer's needs and to analyze the possibility of using this model for the implementation of the system. The software development model used does not require the formation of a complete set of requirements. Therefore, the system is created by iterative way of its evolutionary development with obtaining working systems – prototypes. Over time, requirements have changed under the influence of developments conducted for the GTS. So, effective operating software modules – calculation of distribution gas networks with altitude marks at the tops and calculation of multi-station compressor stations [3], provided a quick calculation of the UGS operation modes. This allows to deliver and solve the main optimization tasks of efficient operation of separate groups technologically connected as part of UGS GTS facilities.

It should be recalled that in January 2009, in the conditions of the complete cessation of transit and import gas flows of the Ukrainian GTS, the dispatch services of Ukrtransgaz provided, in conditions of non-project GTS operation, an increase in the required volume of gas from gas storage facilities. Non-project mode of GTS operation was implemented by means of the software complex [3]. By that time, Ukrainian UGS facilities had provided gas to both consumers of Ukraine and its neighbors. Due to the effective operation of underground storage facilities during the gas injection and recovery seasons, gas problems were also successfully solved and in 2018, these cases required the rapid implementation of the operation of the GTS and UGS facilities under extreme conditions. Currently, effective software tools – modeling, optimal scheduling and control of gas-dynamic and filtration processes in the

ISSN 2226-3780

GTS and UGS have become an important component of the energy security system in Ukraine.

New requirements for problem statements, developing mathematical and software were dictated by the above events, as well as changes in the conditions in the gas markets of Ukraine and Europe (technological and economic) operation of both the GTS and UGS.

2. The object of research and its technological audit

The object of research is both separate underground storage facilities in Ukraine and underground storage facilities within the gas transportation system.

A certain sequence of operations has been developed to produce a hydrodynamic UGS model, which is analogous to the oil and gas field simulation sequence and includes the sequential construction of three interrelated models: petrophysical, geological and filtration (hydrodynamic) [4]. The results of each of the simulation stages are used in the next step as input data. To build each of the models requires the use of specialized techniques and software.

A fundamental feature of this approach is the significant influence of the geological model on the results of hydrodynamic modeling. The use of the geological model is mainly useful in solving the problems of estimating the volume of a trap, analyzing the integrity of an object, and the like. Because of the similarity of tasks of modeling UGS facilities in depleted fields and in aquifers with the task of modeling oil and gas fields, the same program products are traditionally used for modeling UGS, and for modeling oil and gas fields.

At the same time, the long-term practice of modeling UGS has made it possible to identify a number of specific aspects that differentiate the modeling of UGS from the modeling of oil and gas fields, and require corrections in the applied methods and software products. Exploitation of many UGS facilities and analysis of processes in the reservoir significantly increase the role of filtration modeling as a tool for studying and controlling the reliability of the geological structure of the facility.

At the same time, the cyclic operation of UGS facilities potentially allows solving the task of modeling such system with fundamentally different approaches, the possibility of using them in the case of reservoir modeling is absent. In the long term, this makes it possible to increase the overall likelihood of modeling, abandoning the traditional model for oil and gas deposits, a consistent scheme for constructing the petrophysical, geological and hydrodynamic models, which forces them to perform iterative refinement. On the other hand, using a slightly different approach requires the development of a new methodological and software base, since the necessary functionality can't be implemented on the basis of existing software products.

During the analysis of methodological, metrological, software and the existing system of decision-making (strategic and operational scheduling) it is shown that:

– part of the adopted decisions are justified by the information obtained during the long-term operation of the UGS. The analysis of the UGS operation modes for many years has shown that there are not at least two seasons with the same modes of storage operation;
– process parameters outside of existing working areas are obtained by extrapolation method without taking into account their essential nonlinear character;
– for the purpose of conducting a correct system analysis of the behavior, depending on the time of individual operating mode parameters and predicting the behavior of processes with the necessary accuracy at large intervals of time, it would be expedient to measuree parameters by metrological means in the mode of continuous monitoring of indicators;
– many necessary operating mode data for calculating the parameters of operational control of processes are not measured;
– to ensure a high level of automation and telemechanization of underground storage facilities (intellectualization of the UGS operation processes), considerable resources are needed;
– often there is a need to conduct an analysis of the UGS behavior outside the design modes of its operation (contingencies and that appear in the analysis of options for the reconstruction of UGS facilities).

A significant part of these problems can be solved by mathematical methods, requires implementation of the developed mathematical software [7].

3. The aim and objectives of research

The aim of research is carrying out the implementation of the developed mathematical software [5] to solve the operating mode and technological problems that arise in the process of scheduling and operation of the UGS.

To achieve this aim it is necessary to carry out the following work:

1. To develop a set of typical scenarios for the use of software by the services of PJSC «Ukrtransgaz».

2. To form requirements for the functionality of the software, dictated by the existing dispatch control system and ensure their effective implementation.

4. Research of existing solutions of the problem

The main tool for scientifically based decision making on rational options for the operation of gas storage facilities and the full use of all the available technological capabilities for influencing the operating mode described above is the developed modeling and optimizing software package. The software tools, which are a complex software package, must provide a functional service to ensure the effective resolution of the maximum set of tasks that arise during the UGS operation. The quality of software development depends, first of all, on the quality of the the development of mathematical algorithms.

Software for modeling have a significant impact on:

– development of high-quality operational technological solutions and finding parameters for optimal process control under real conditions of UGS operation;
– assessment of the factors influencing the operational parameters of certain facilities at the decision stage for decommissioning of certain facilitiess;
– assessment of the quality of repair and preventive maintenance and decision-making on the replacement of equipment and the like.

The analysis of existing software products will be carried out from the point of view of their effective use for the scheduling and operation of underground gas storage facilities.

Currently, the main software products for creating hydrodynamic models most often are Eclipse (Schlumberger), Tempest (Roxar), VIP (Landmark), TimeZYX (group of companies «Trust»). HydroGeo, t-Navigator (RF Dinamics) is used for hydrodynamic and geochemical modeling in oil and gas hydrogeology [8].

The main are three software products: Petrel, Eclipse, Techlog. Petrel software allows creating volumetric models of the geological structure of gas, gas condensate and oil and gas fields. Having a static model built in the Petrel software package, the next stage of the Eclipse program simulates the development of oil and gas deposits. The Techlog software package is designed to process well logging results.

Now in Ukraine it implements the software of Schlumberger, which will allow creating detailed 3D-models of deposits. With the help of this software package, it is possible to detail and refine the geological structure of existing deposits, to clarify the boundaries of deposits and hydrocarbon reserves, and, possibly, to discover previously undiscovered productive layers.

The main software systems, even at the development stage, are oriented, mainly, to geological and hydrodynamic modeling of hydrocarbon production processes. The effectiveness of using these and other software products is demonstrated in the process of their implementation at specific facilities [7, 8]. The main drawbacks are the integration of many software products to solve one problem leads to a significant complication of the modeling process and the emergence of problems with the coordination of different types of interrelated physical processes. This leads to instability of the modeling process, requires significant time resources and affects the adequacy of the modeling process to real processes and the accuracy of the results.

The solution of the problem is the integration of software modules that relate to one of the facilities in the technological chain of the reservoir-main gas pipeline, but the integration of models of certain facilities into a single thermohydraulic model, as was done in [5]. In the works mentioned above, problems arose with the reconciliation of the processes that take place at the boundary of the seams and the concentrated sources (wells). Using Eclipse (Schlumberger) to model the filtration processes in reservoirs of UGS reservoirs is complex and often impractical. For UGS, as practice has shown, two-dimensional filtration models are sufficient in accuracy. These models, in addition to accuracy, provide a few orders of magnitude higher speed of the modeling process, allows to set and solve a fairly complete set of optimization tasks. Existing foreign software, in addition to the mentioned problems with their use, still requires appropriate information and technical support.

Most of the foreign works that are involved in solving the considered problems are mainly devoted to improving the technology of gas storage, control, optimization and innovation, which improve the efficiency of the gas storage process [9–13]. Interesting was the work on the use of inert gas as a buffer gas for underground storage, which addressed practical and economic issues [14]. To solve such problems [15], the functionality of the software package for modeling the UGS operation was expanded. This allowed the construction of software tools for developing the technology of substitution of natural gas (buffer gas) inert and to provide a forecast of the behavior of inert gases in the cyclic operation of such UGS.

Thus, the results of the analysis make it possible to conclude that software packages that would fully satisfy the dispatching services in terms of functionality, classes of solved mode problems, ease of operation and implementation, information support requirements and speed of response to dispatcher actions are still not available.

The present work is devoted to the development of software complexes that provide the solution of a complete set of dispatch tasks with quality and speed.

5. Methods of research

Approbation of software is done on:
– multi-year operational data (10–20 years);
– the maximum possible intervals for changing the initial, marginal and adaptive parameters;
– different types of gas storages that differ in the sets of technological equipment, essentially different structural traps in the bowels of the earth for the conservation of gas deposits, different rates of operation of facilities and UGS facilities in general.

6. Research results

The software consists of several program modules, each of which is oriented to the analysis of separately selected objects, or connected groups from the same objects (Fig. 1). Developed software modules that allow to analyze groups of technologies connected with different types of objects. For such integrated objects, the corresponding mathematical support was processed, which ensured the possibility of a stable iterative linkage of the gas dynamic parameters at the junctions of different types of objects with different mathematical representations of their models.

Basic software requirements are set and implemented – functional, operational (range of values), operational, as well as requirements for interfaces and security of use.

The developed software takes into account the thermohydraulic interaction of all objects influencing the parameters of gas flows. Software facilities provide automation of the process of forming an integrated model for various modifications of equipment, changes in the state of technological facilities, modernization and reconstruction of individual facilities and UGS in general. The information block is connected to the databases of the measured data and their processing enables the modeling software to be constantly in an updated state. Fast, rapid execution of multiple calculations ensures the search for optimal operating mode parameters at significant intervals of time and, if necessary, allows a comparative analysis of possible options for the reconstruction of UGS. The possibility of a comparative analysis of the efficiency of the use of various technological equipment in the course of modernization and reconstruction of UGS facilities is envisaged.

The software can work in several variants. Among the main ones, one should single out the mode of operation, in which all the parameters of objects and input data are available to the user. In this variant, software tools are available for the user, which allow you to edit the piping and change the parameters of the process equipment of the UGS. For the operational scheduling system, only the predicted input data – the pressure in the main gas pipelines (MG) and the volumes of gas withdrawal or injection are allowed.

Software calculation modules are implemented in the Borland Delphi software development environment. The client part of the modules is developed in the Ionic environ-

 ISSN 2226-3780

ment by means of TypeScript, which are backwards compatible with JavaScript. In fact, after compiling programs on TypeScript, they can be executed in any modern browser or used in conjunction with the server platform Node.js. Node.js is an open source platform for performing high-performance network applications written in JavaScript. To work with databases and data models, the PHP system is used. Due to the standard of open communication interface with MySQL databases, PostgreSQL, mSQL, Oracle, dbm, Hyperware, Informix, InterBase, Sybase, the PHP system prevents writing multiline functions intended for the user. This problem is typical for C or Pascal.

The software is focused on the solution of such sets of routine tasks: operational scheduling, strategic scheduling, finding control parameters for the process of gas withdrawal and injection, modernization and reconstruction of underground gas storages, energy audit, contingency analysis, etc. (Fig. 1).

It is possible to present the P&ID of compressor stations (CS) with different levels of detail (the maximum detail of the P&ID of the CS is shown in Fig. 2).

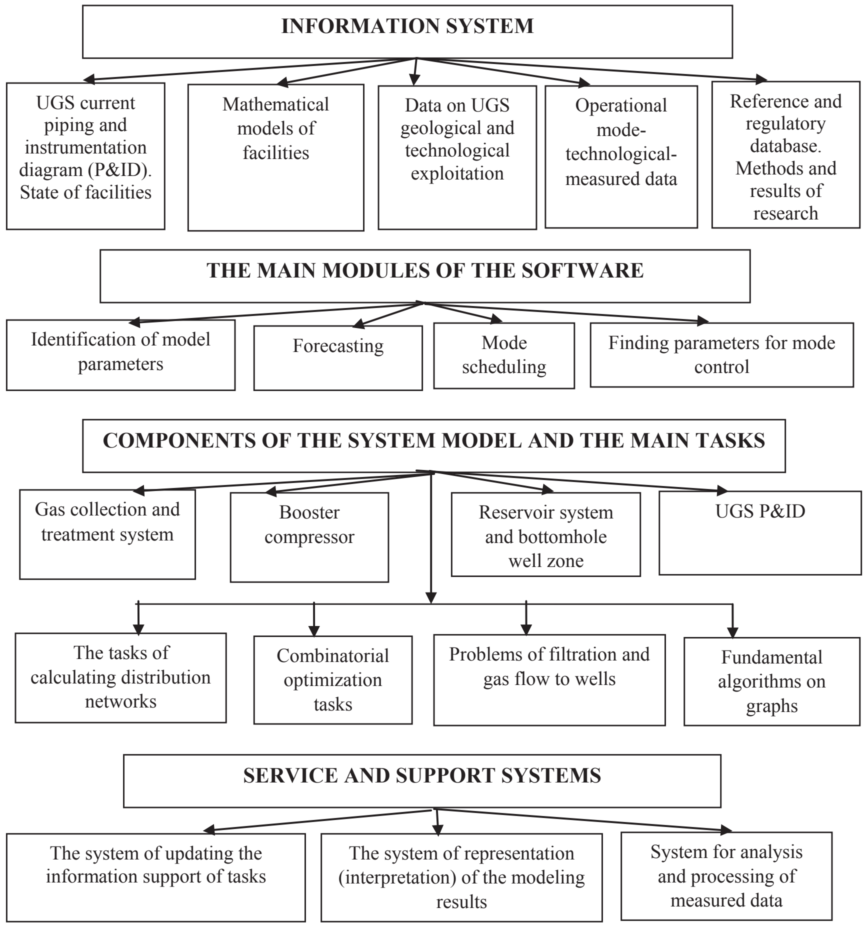


Fig. 1. Structure of the software, models and main tasks

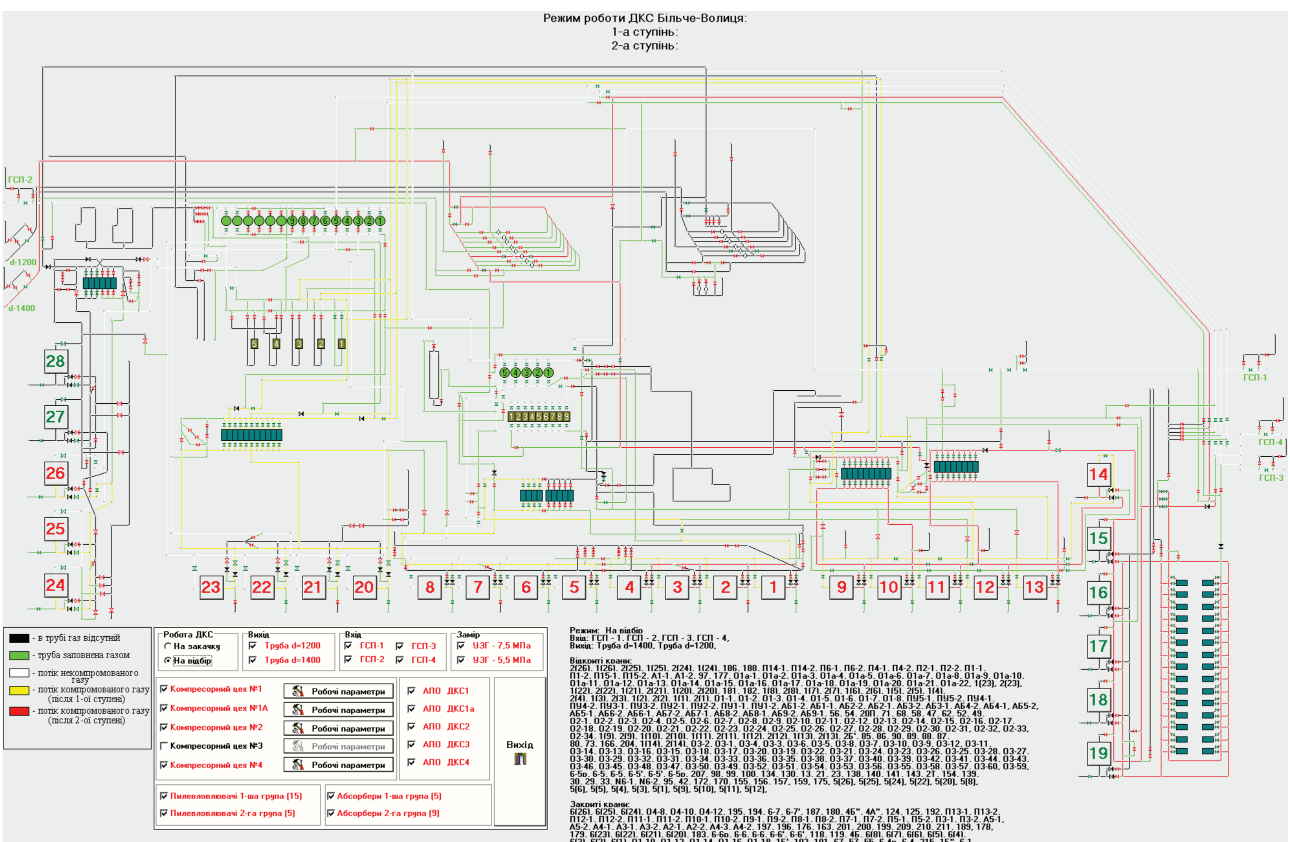


Fig. 2. P&ID of the Bilche-Volitsa booster compressor station with partial representation of simulation results

The detail of the P&ID, basically, somewhat affects the speed and accuracy of the result. The optimum operation of the compressor station is ensured by minimum energy costs for the mode at a given stability level of its operation (a given distance from the pump zone of operating points of all gas compressor units is provided.

By hovering the cursor on the object, it is possible to see the results of calculating the gas flow parameters (pressure, temperature, flow) and the degree of its compression (interpreted by color). The system also forms the P&ID topology, that is, it establishes the state of all the stop valves and other process equipment. The results of the software for extreme operating conditions of the Bilche-Volytsko-Uherske UGS are given in Tables 1, 2. Two gas reservoirs are technologically united in this UGS.

Table 1

Calculation of the maximum gas withdrawals at a pressure in the main gas pipelines 40 atm.

No.	Mean pressure in the working region of the formation	The pressure at the entrance of the first CS unit	Pressure at the entrance to the MG	Daily volume of withdrawal (million m^3)
1	5.50	35.00	40.00	95.27
2	5.20	35.00	40.00	83.99
3	4.90	35.00	40.00	71.96

Table 2

The results of calculating the operating modes with the data presented in Table 1

No.	Consumption of fuel gas (million m^3/day)	Operating mode of booster compressor station
1	0.31	[1]1:C-6.3/41[6060], [2]9,10,12:NC-16/56[3922], [4]27:C-6.3V/41[7162]
2	0.26	[1]1:C-6.3/41[5824], [2]9:NC-16/56[3849], 11:NC-16/41[3910], [4]27:C-6.3V/41[7418]
3	0.22	[1]3:C-6.3/56[6094], [2]9:NC-16/56[3795], 11:NC-16/41[3670], [4]27:C-6.3V/41[6099]

Tape structure mode [2]9,10:NC-16/56[4692], 11:NC-16/41[4872] – [2]12,13:NC-16/56[4562], 14:NC-16/76[4564], [4]24,25:C-6.3V/29[6086] – [4]27.28:C-6.3V/41[6511] is such – [No. workshop]No. CS1, No. CS2[revolutions] – [No. workshop]No. CSA1, No. CS2[revolutions], [No. workshop]No. CS1, No. CS2[revolutions] – [No. workshop]No. CS1, No. CS2[revolutions].

Another thing to be aware of is that «–» is separate the compression ratio of the gas, «,» – gas pumping unit (GPU) runs in parallel.

The operation of the software complex requires systematic updating of the parameters of the developed models, and, if necessary, their specification. For the identification, the physical relationships between the parameters are mainly used.

Complex «UGS operating mode» allows to carry out adaptation of models of facilities on large time intervals. For this purpose, the ability to visualize the calculated and measured data is realized, which makes it possible to quickly assess the effect of a change in a parameter on the change in reservoir pressure or reservoir parameters (geometric, filtration, geophysical).

Fig. 3 shows the results of refinement of reservoir parameters. The two upper curves show the proximity of the calculated and measured pressures in the working well area. The lower curves correspond to the daily sampling volumes (the curve under the coordinate axis) and the discharge (the curve above the coordinate axis) of the gas. In the process of identification, the correctness of the measured data is also examined, manifested in the form of a significant discrepancy between the measured and calculated data.

The optimal operation of UGS is considered from the point of view of the optimal operation of the GTS. An important component of effective UGS operation is also the optimal organization of interaction between technologically coupled UGS facilities and the main gas pipelines of the gas transportation system in particular.

There are several factors to influence the optimality of UGS operation. These factors can be divided into two groups – external and internal. The internal factors of influence include the operation of a booster compressor station (BCS), gas cooling systems, wells and a gas reservoir. The criterion for assessing the performance of UGS is the combined energy costs per unit of selected gas. This value is directly related to the value of the gas pressure in the working area of the deposit, the number of production wells and the pressure in the main gas pipeline. Both optimal operation and UGS operation in the peak operating mode are performed subject to technological limitations on the operation of facilities and maximum utilization of the capacity of technological facilities.

Given the reservoir pressures and pressures in the MG, the maximum volumes of injection and withdrawal of gas (peak characteristic – the maximum volumes of gas withdrawal per unit of time) depend on the throughput of its process facilities. At each stage of UGS operation, the bottleneck in capacity can vary. The peak characteristic of UGS (for gas withdrawal) is constructed unambiguously over the entire gas-removal time interval under certain conditions. Among the basic requirements – the presence in the UGS of the maximum volume of active gas and fixed pressure in MG. Additional conditions are the participation of all production injection wells in the gas extraction process, the maximum loading of the BCS and the minimum gas withdrawal time. Peak (instantaneous) is established at known pressures in the main gas pipeline and medium pressure in the working zone of the formation (Fig. 4). As can be seen in Fig. 4, the peak characteristic has discontinuities and jumps.

For carrying out numerical experiments on software «UGS-mode», the following are implemented: task tasks (the initial data can be taken from the dispatching journal, and the predicted ones can be specified or calculated in the process of balancing the GTS):

- for pressure and flow in the MG, the operating mode of the BCS is calculated;
- for the pressure on the GCP, the total well production is calculated;
- on the total flow rate to the GCP, the pressure at the input of the BCS is calculated;
- the maximum volumes of the selected gas are calculated for the pressure in the MG.

The need for upgrading UGS equipment, changing operating conditions, necessitates an assessment of the efficiency of UGS reconstruction – selection of new equipment and evaluation of its operational characteristics in real conditions. The equipment at the UGS is very valuable and, accordingly, is commensurate and the price of the error.

ISSN 2226-3780

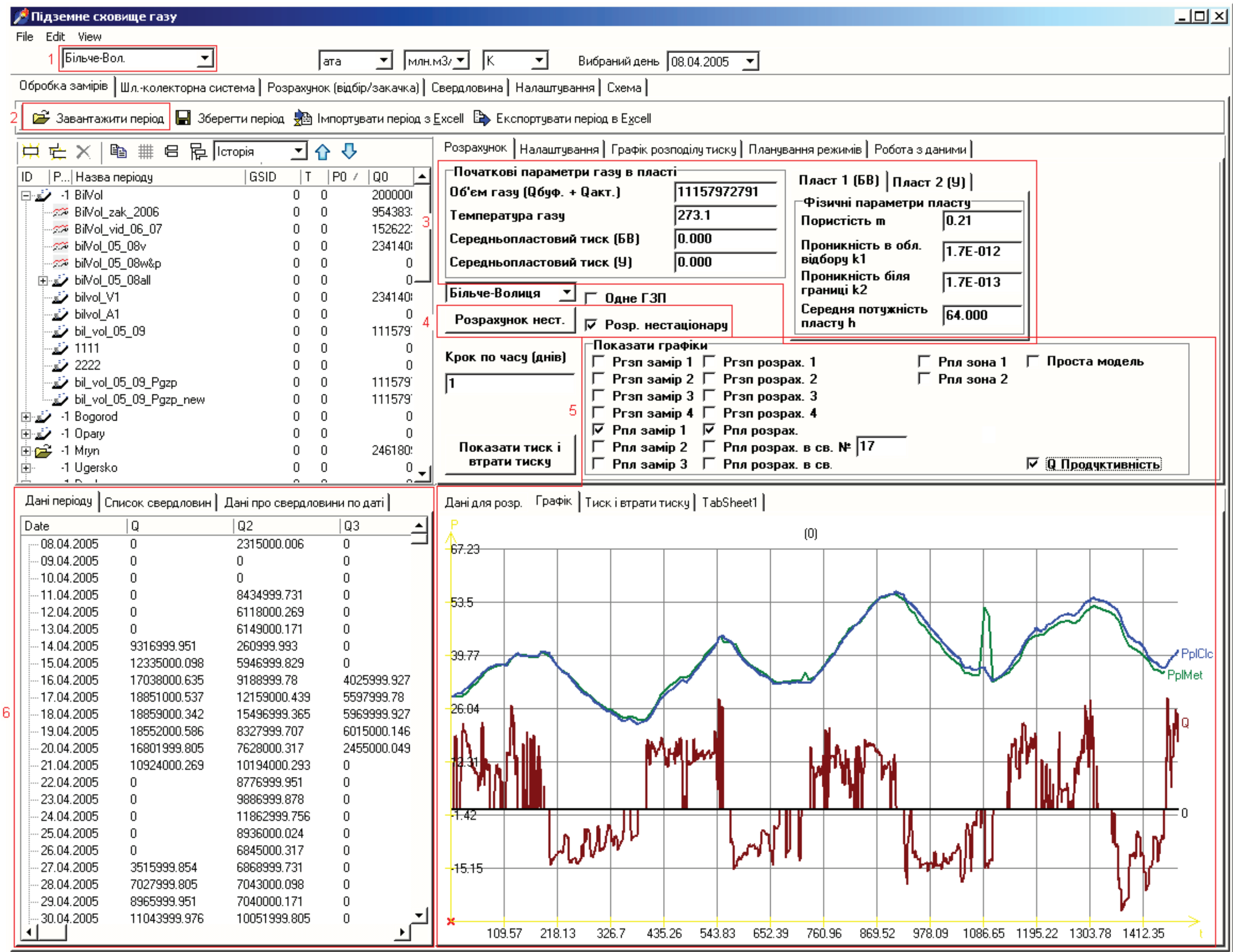


Fig. 3. Measured and calculated average reservoir pressures in the working area (blue and green curves) by daily sampling and discharge volumes (brown curve)

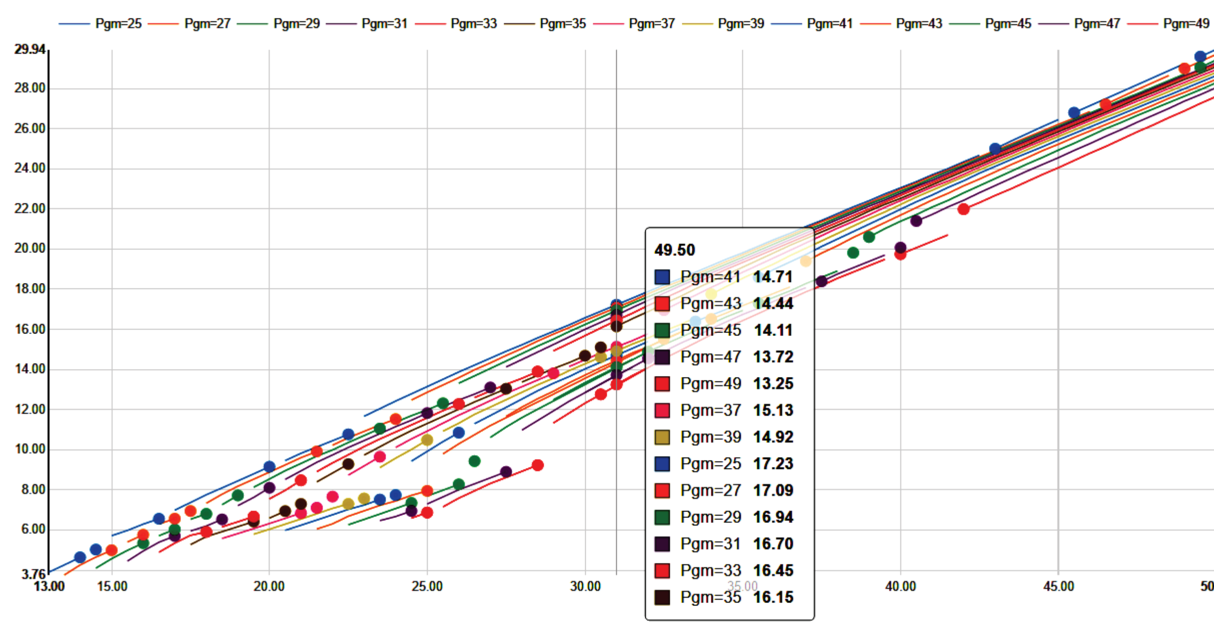


Fig. 4. Maximum gas extraction volumes (million m^3/day), depending on the reservoir (10^{-1} MPa) – vertical axis, and pressure on the main gas pipeline – horizontal axis

As an example, let's assess the impact of changes in buffer gas volumes on fuel gas economy. Let's consider the selection season, which averages 151 days. Let's replenish the buffer gas in such way as to ensure an increase in the minimum pressure in the formation by 0.2 MPa, and a maximum pressure of 0.1 MPa. This allowed to save volumes of fuel gas in the amount of 220.88 thousand USD for the year at a cost of 317.65 USD per 1,000 m^3.

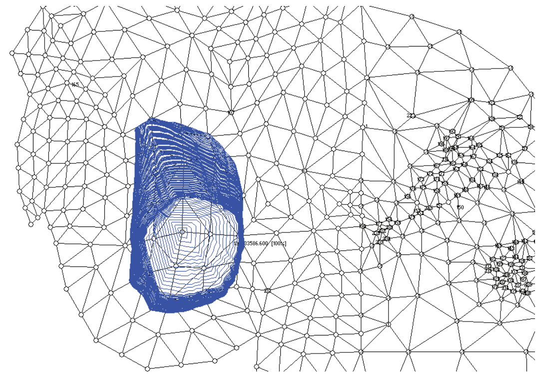
The reservoir for the geological structure is not homogeneous. There are geological faults, poor permeability of the interlayer between the individual zones of the formation and the like. In the process of gas injection at significant intervals, gas penetrates considerable distances from the well placement zone. Often it is important for the dispatch services to know what gas volumes are in each of the zones of the formation, and also what gas volumes and under what conditions and at what rate fall into the working zone. The volumes of gas flow between the zones depend on the volumes of injection and gas extraction.

In the software, methods for calculating the parameters of gas displacement from weakly permeable regions of reservoirs have been developed and implemented. As an example, let's take a non-uniform reservoir for permeability, porosity and power. It is necessary to displace nitrogen in the working area of natural gas with an inert gas from a weakly permeable zone of the formation. Let's believe that the process of nitrogen propagation passes without its mixing with natural gas, that is, resolving filtration of two gases is considered. Through some wells, nitrogen is injected, and through others natural gas can be extracted. The reservoir for capacity (the difference in the height marks of the upper and lower surfaces of the formation) is insignificant in comparison with other dimensions. Typical distances in the task are hundreds and thousands of meters, and time is months and years. The movement of gases is subject to Darcy's law. Gravitational forces are not taken into account.

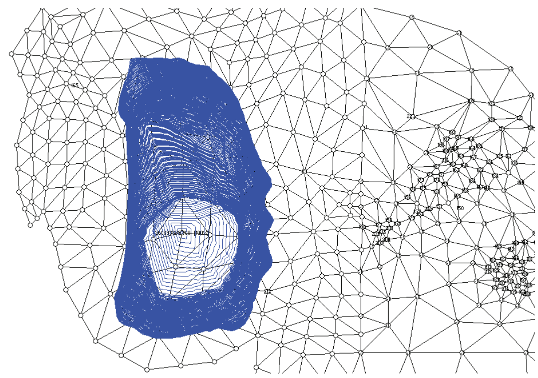
Gas withdrawal from underground storage facilities is carried out through n wells located at points (x_i, y_i) for a certain period of time $t \in [t_{1i}, t_{2i}]$, $(i = \overline{1,n})$. Numerical experiments are preceded by the adaptation of a mathematical model for calculating the nitrogen propagation regions to real gas-dynamic and filtration processes that occur in heterogeneous porous regions (reservoirs). The process of adaptation consists in finding the parameters of the permeability of reservoir layers, its individual blocks and poorly permeable layers of layers between separate layers. Experimenting on the software complex the adaptive parameters are constantly refined. One of the important and sufficiently convincing arguments regarding the adequacy of the model is the high accuracy of the calculated parameters of the dynamics of the pressure change in the neutral period (between the completion of the selection and the beginning of the gas injection).

The substitution of a buffer gas with nitrogen occurs during filtration and convective diffusion. In mathematical modeling of the filtration process, it can be assumed that the gas dynamic characteristics of nitrogen and natural gas differ insignificantly. The main goal of solving the filtration problem is finding a two-dimensional non-stationary distribution of the gradient of the gas flow velocities in the filtration region (Fig. 5).

As it is possible to see, on the 600th day of nitrogen injection, there is no breakthrough in the working area of the gas storage (well placement area).



a



b

Fig. 5. Area of distribution of nitrogen after pumping: *a* – 129.6 million m^3 nitrogen for 300 days (5 m^3/s); *b* – 260.0 million m^3 of nitrogen for 600 days (5 m^3/s). The contour of nitrogen distribution: *a* – on the 300th day after the start of operation of the gas storage; *b* – on the 600th day after the start of operation of the gas storage facility

In the process of operating UGS there are unusual situations – depressurization of the system. Here are some real examples. At one of the gas storage facilities, during the repair work, one of the wells is depressurized. The task is set: what volumes of gas for 66 hours have got into the external environment. The average reservoir pressure in the working zone is 42 atm.

The numerical experiment consists of the following steps:
- the coefficients of the filtration resistance of the bottomhole zone of the well are specified;
- the absence of gas flow through the loop of well No. 70 (closed the corresponding tap) is provided;
- the well is detached from the flow line, and the outlet pressure of the gas flare to the atmosphere in the range of 1–10 atm. is set at the output;
- the main factors influencing the amount of gas leakage are established;
- the sensitivity of the leakage parameters from the accuracy of setting the initial conditions is investigated.

The experiment shows that:
- the main factor of influence on gas leakage volumes – coefficients of the bottomhole zone filtration resistance and permeability of the near zone of the formation;
- the change in the outlet pressure in the indicated range (1–10 atm.) for leakage volumes doesn't significantly affect;
- the established leakage volumes per day are in the range of 0.2229–0.2344 million nm^3.

One of the results of numerical experiments is shown in Fig. 6.

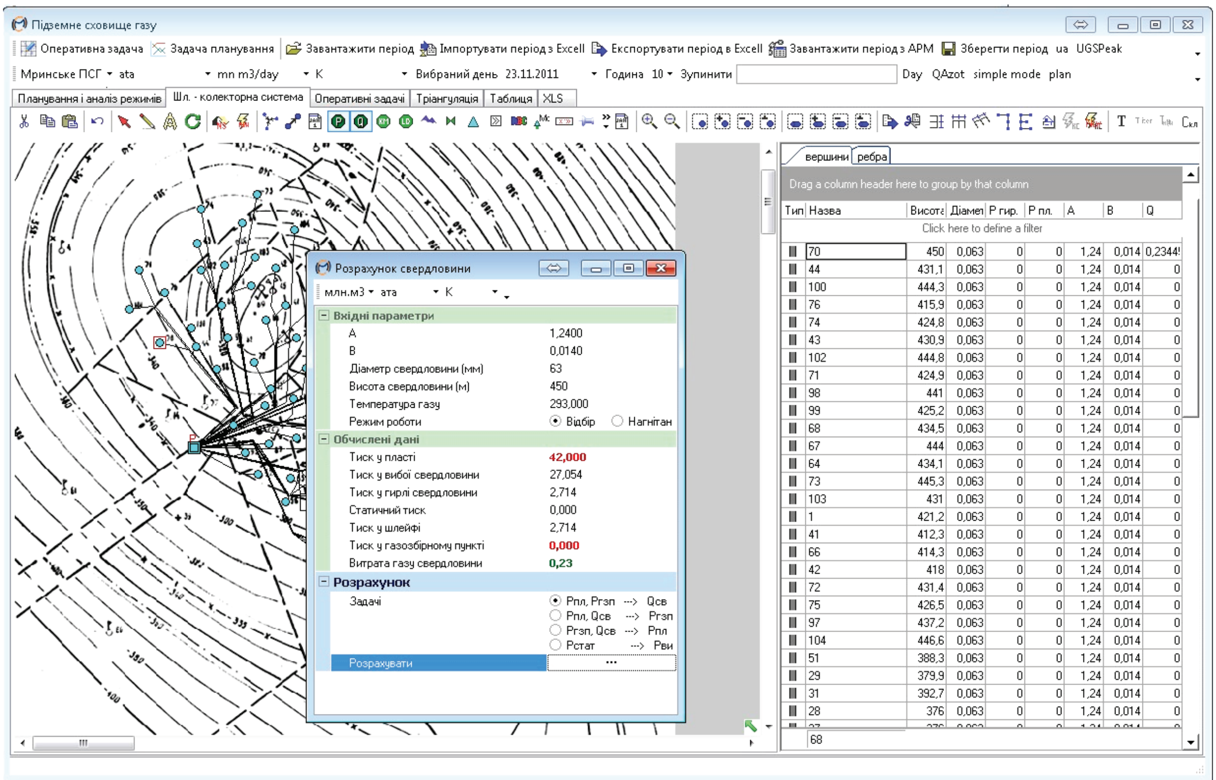


Fig. 6. Simulation results of leakage simulation from well No. 70

In recent years, there have been situations in which it is possible to organize the integrity of the GTS and the non-sealing of heating systems in large regions only in the process of implementing non-projected operating modes. To some of these modes of operation, the dispatch services are not prepared in advance, which required decisions on a significant time deficit. This makes it necessary to conduct research on the operation of individual objects in non-proprietary modes that are unusual for them.

7. SWOT analysis of research results

Strengths. The possibility of the fastest possible execution of computational experiments to find the optimal options for UGS operation and options for its reconstruction is realized. The qualitative and quantitative parameters of the software characterize it:

– completeness (maturity) for a set of solved tasks for dispatching control;
– fault tolerance in the field of correct functioning of object models (this area is somewhat more operational);
– ability to recoverability;
– time behavior of the software to produce the expected results, as well as to ensure the transfer of the required amount of data within the allotted time;
– the ability to solve problems with the use of a certain minimum amount of resources;
– the convenience of testing the test results and other types of verification that the changes made led to the desired results;
– ease of software installation (installability);
– the ability to coexistence with other programs in a common environment, sharing resources with them;
– the convenience of replacing another software with data for solving the same problems in a certain environment.

Weaknesses. To the essential weaknesses of the project is the insufficient level of ease of use of all the realized features of the developed software product. Currently, the WEB interface support of tasks and the system of actualization of their information support is developing, which did not require the user to have deep knowledge of the subject area.

Opportunities. Recently, the software has been partially integrated into the scheduling (prospective and operational) and operational maintenance of Ukrainian UGS facilities at the stages of gas injection and extraction. New tasks have been set and algorithmic support for the optimal operation of technologically coupled UGSs and UGS facilities in conjunction with the entire GTS has been developed.

Now the problem for Ukraine has become extremely important: forecasting the joint work of the gas transportation system and UGS facilities in conditions of poorly predicted sources and volumes of transit and import of gas. It is necessary to anticipate in advance all possible options for placing gas storage volumes by UGS facilities, the intensity of operation of each particular UGS during the gas withdrawal season. And also the reconstruction of the GTS and UGS for certain cases, including possible cases of occurrence of abnormal situations.

The technological objects of the gas transportation system and UGS are degrading. The task of determining the volume of modernization of the Ukrainian GTS, depending on the scenarios for their utilization, is considered, taking into account the residual resource of the objects as a function of time. Over all the recounted tasks are the work. The effect from use is significant, as the use of such developments ensures the energy security of the country.

Threats. In operating modes of off-line software, the main threat is the introduction of malicious input data to support the modeling process, and in other modes (on-line, real-time), the main danger is a failure in the telemetry system (SCADA type).

8. Conclusions

1. Scenarios for the operation of the software for various types of users and controls (geological service, controls of underground gas storage, management of operation of the CS, etc.) have been developed with access to relevant resources. This provided qualified support for the system in an up-to-date state and its operative operation in the conditions of variable modes of GTS operation.

Approbation of the software on the tasks of scheduling the operating modes (diurnal and seasonal) of individual UGS facilities and their aggregate, identifying the parameters of the object models, estimating the effect of reconstruction (modernization, replacement) of UGS facilities is carried out. The software quality is assessed by the service – a set of service functions and interface support for tasks, the quality of the code – the degree of logical division of the code into blocks, the completeness and speed of solving problems. The quality of the code allows to quickly form integrated program modules for solving a particular set of tasks. Service tools and an intuitive interface have provided minimal effort and time for solving basic task sets. The tasks of operational scheduling (daily) of UGS operations took up to a minute of time. The main time is generation of input data. Modeling of gas-dynamic and filtration processes that occur during the year in UGS facilities is several tens of seconds.

2. The functionality is implemented – automation of the processes of updating the information support, the creation of input data and the solution of problems. In addition, work with dynamic tables is provided, which are partially formed in the background in the process of solving optimization problems. A system of graphical support for the presentation and analysis of software performance is developed and implemented. A multi-user version of the system with subsystems for administration, data protection, permissions, priorities, etc. is implemented.

References

1. Prytula N. M., Pyanylo Ya. D., Prytula M. H. Pidzemne zberihannia hazu (matematychni modeli ta metody). Lviv: RASTR-7, 2015. 266 p.
2. Lavrivscheva K. M. Prohramna inzheneriia. Kyiv, 2008. 319 p.
3. Prytula N. M. Calculation of flow distribution parameters in gas-transport system (stationary flow case) // Fizyko-matematychne modeliuvannia ta informatsiini tekhnologii. 2007. Vol. 5. P. 146–157.
4. Three dimensional Geological Modeling by FOSS GRASS GIS: proceedings / Kajiyama A. // FOSS/GRASS Users Conference. Bangkok, 2004.
5. Prytula N., Prytula M., Boyko R. Mathematical modeling of operating modes of underground gas storage facilities // Technology Audit and Production Reserves. 2017. Vol. 4, No. 1 (36). P. 35–42. doi:10.15587/2312-8372.2017.109084
6. Official Website of Schlumberger. URL: http://www.slb.com/
7. Gafarov A. Sh. Osobennosti hidrodinamicheskoho modelirovania Gatchinskogo PHG // Vesti gazovoy nauki. 2012. Vol. 2 (10). P. 113–115. URL: http://www.vesti-gas.ru/sites/default/files/attachments/113-115-iz_matmodelirovanie-2012-v13-m-d.pdf
8. Modelirovaniie rezhymov roboty hazovoho promysla kak yedinoi termohidravlicheskoi sistemy / Rotov A. A. et al. // Gazovaia promyshlennost. 2010. Vol. 10. P. 46–50.
9. Brown K. G., Sawyer W. K. Practical Methods to Improve Storage Operations – A Case Study: proceedings // SPE Eastern Regional Conference and Exhibition, 1999. doi:10.2118/57460-ms
10. Expert System of UGS – An Efficient Tool for On line Performance Management and Optimization / Onderka V. et al. // 23rd World Gas Conference. Amsterdam, 2006. URL: http://members.igu.org/html/wgc2006pres/data/wgcppt/pdf/WOC%20Working%20Committees/WOC%202/Improvement%20of%20UGS%20performance/2.4EF.08.pdf
11. Zangl G., Giovannoli M., Stundner M. Application of Artificial Intelligence in Gas Storage Management // SPE Europec/EAGE Annual Conference and Exhibition. Vienna, 2006. doi:10.2118/100133-ms
12. Storing Natural Gas Underground / Bary A. et al. // Oilfield Review. 2002. Vol. 14, No. 2. P. 2–17.
13. Intelligent Well Technology in Underground Gas Storage / Brown K. et al. // Oilfield Review. 2008. Vol. 20, No. 1. P. 4–17.
14. Foh S. E. The Use of Inert Gas as Cushion Gas in Underground Storage: Practical and Economic Issues: proceedings // Gas Supply Planning and Management: 1991 and Beyond Conference. Lake Buena Vista, 1991. URL: https://www.osti.gov/servlets/purl/6028827
15. Zamishchennia bufernogo hazu azotom u plastah hazoshovyscha (modeli, metody, chyslovi eksperymenty) / Prytula N. et al. // Naftova haluz Ukrainy. 2013. Vol. 4. P. 32–39.

Prytula Nazar, *PhD, Department of Designing Systems of Optimal Scheduling and Forecasting Operating Modes of GTS, Research and Design Institute of Gas Transport of PJSC «Ukrtransgaz», Kharkiv, Ukraine, e-mail: nazar.prytula1@gmail.com, ORCID: http://orcid.org/0000-0001-9451-275X*

Prytula Myroslav, *PhD, Department of Designing Systems of Optimal Scheduling and Forecasting Operating Modes of GTS, Research and Design Institute of Gas Transport of PJSC «Ukrtransgaz», Kharkiv, Ukraine, e-mail: myroslav.prytula@gmail.com, ORCID: http://orcid.org/0000-0001-9259-4114*

Boyko Rostyslav, *PhD, Head of the Underground Gas Storage Department, Regional Pipeline Division «Lvivtransgaz» of PJSC «Ukrtransgaz», Lviv, Ukraine, e-mail: rboyko25@gmail.com, ORCID: http://orcid.org/0000-0002-6324-6847*