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CALCULATION OF UNDERGROUND GAS STORAGE OPERATING MODES

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Abstract: Optimal operation of an underground gas storage (UGS) requires modeling of gas-dynamic and filtration processes that take place in its facilities as a single hydraulic system. Simulation of gas storage is somewhat different from the simulation processes in natural gas production. Filtration and gas-dynamic processes that take place in the UGS is more dynamic and therefore essentially depends on the UGS bed parameters such as permeability, anisotropy, and input data uncertainty. As a consequence, the study of these processes requires the construction of highly accurate models and rapidly converging methods for their implementation. The paper discusses the problem of an optimal operation of storage facilities in the composition of the gas transmission system of Ukraine. We show in this article mathematical models and appropriate statements of mathematical optimization problems of gas storage facility operation. We have conducted numerical study and testing of the developed algorithms and the software.
Keywords: gas transmission system, underground gas storage, numerical methods, gas storage reservoir, piping diagram

1. INTRODUCTION

Optimal operation of an underground gas storage (UGS) requires modeling of gas-dynamic and filtration processes [1] that take place in its facilities as a single hydraulic system [2]. Simulation of gas storage is somewhat different from the simulation processes in natural gas production. Filtration and gas-dynamic processes that take place in the UGS is more dynamic and therefore essentially depends on the UGS bed parameters such as permeability, anisotropy, and input data uncertainty. As a consequence, the study of these processes requires the construction of highly accurate models and rapidly converging methods for their implementation. The piping diagram that links storage facilities with gas transmission system (GTS), allows multi-variation of their compatible operation.

2. OPERATING MODES OF GAS STORAGE FACILITIES

Operating modes of gas storage facilities are variable and poorly predictable. The main objective of the gas storage operation is removing the imbalance of gas in the gas transmission system during large gas inflow or outflow. During cold snap on a large area of a country there is a need for maximum capacity of gas storage operation (peak capacity modes).

Bilche-Volytske structures measures 7km by 12 km and Ugerske measures 3km by 13km [5]. As a facility for gas storage used depleted gas reservoirs. On Ugerske's square XVI horizon has a relatively better collecting properties. Sandstone thickness is 91% of the total thickness of the horizon.

Porosity ranges from 5% to 31% and on average equals 25%. In the productive horizon Bilche-Volytske reservoir effective thickness of sandstones are on average 60-77% of the total thickness of the gas-saturated horizon. The average porosity is 21.4%. Reservoirs are massive, are at a depth 900-1080 m. Thus, the geological structure of Ugerske and Bilche-Volytske reservoirs are difficult. These features can not influence the technological parameters and tightness of the gas storage facility that created in the XVI horizon.

3. MATHEMATICAL MODELS OF FACILITIES

Basic mathematical models of UGS are: a filtration reservoir model, a model of well bottoms, a gas-dynamic model of a well and a gas gathering system, a discrete-continuous model of the compressor station (CS). The developed software (models, methods and algorithms) allow to include models of all existing facilities that are present on the detailed piping diagrams into the calculation process of UGS operations and facilities that affect gas flow distribution in the processing chain composed of a reservoir and pipeline. The scheme of the process chain composed of a reservoir and pipeline, as well as the ICS (injection compressor station), presented as a graph $G_s(E,V)$ in which each edge $(i,j)\in V$ has its own type. In the process chain composed of a well bottom and gathering system $(i_{\Gamma i}, i_{zi}, i_{si}, i_{0i}, i_{shi})$ $(i=1,...,n)$ we will recognize these types of edges: a well bottom $(i_{\Gamma i}, i_{zi})$, well (i_{zi}, i_{si}), wellhead connections or a well collector (i_{0i}, i_{shi}). A well bottom area is considered to be homogeneous in a permeability parameter. All vertices $i_{\Gamma i}$ belong to a circular contour Γ_i – the area of a well bottom. The pressure in such a vertex is called a reservoir pressure for a i - well. A piping diagram, which includes a gas gathering system, a gas gathering station, an injection station and gas pipes, is a graph that has other types of edges too. Each edge type has its own mathematical model of the gas flow. A piping diagram of the CS is also presented as a graph $G_k(E,V)$. Part of the edges of the graph $G_k(E,V)$ is oriented. Each edge of the graph is a facility or a hydraulic equivalent.

3.1. A mathematical model of the reservoir

The majority of UGS reservoirs have a small height and relative slight slope, and therefore they can be considered flat and horizontal. As shown by numerical experiments, such an assumption in many cases is warranted.

A UGS reservoir will be regarded as a two-dimensional planar domain $\Omega \subset R^2$. A set of points (wells) with coordinates $\{x_i, y_i\}$, $i=1,\ldots,n$ and the pressures p_i at these points are given on Ω.

The border Σ of the area Ω is divided into two $\Sigma = \Sigma_1 \cup \Sigma_2$, where Σ_2 - the outer boundary of the area Ω; Σ_1 - Combining the boundaries of domains $\Omega_i \in \Omega$ that spans the coordinates of points with known values of pressures p_i.

We have to find a solution to the equation $p(x,y,t)$ on Ω:

$$\frac{\partial}{\partial x}\left[\frac{kh}{\mu z}\frac{\partial p^2}{\partial x}\right]+\frac{\partial}{\partial y}\left[\frac{kh}{\mu z}\frac{\partial p^2}{\partial y}\right]=2\alpha mh\frac{\partial}{\partial t}\left[\frac{p}{z}\right]+2q(t)hp_0 \tag{1}$$

which describes the filtering flow in porous heterogeneous environment with the following boundary conditions.

On $\Sigma_1 = \bigcup_{i=1}^{n}\Gamma_i$ the Dirichlet boundary condition is satisfied

$$p(x_i,y_i)=p_i,\ \ (x_i,y_i)\in\Gamma_i\ \ i=1,\ldots,n, \tag{2}$$

and on Σ_2 the Neumann condition

$$\Phi p(x,y)=0,\ \ (x,y)\in\Sigma_2; \tag{3}$$

where

$$\Phi p \overset{def}{=} \frac{k\cdot h}{\mu\cdot z}\frac{\partial p}{\partial x}\nu_x+\frac{k\cdot h}{\mu\cdot z}\frac{\partial p}{\partial y}\nu_y;\ \ \nu_x=\cos(\nu,x),\ \ \nu_y=\cos(\nu,y),$$

ν - the outward normal to the domain $\Omega \subset R^2$; $k(x,y,p), m(x,y), h(x,y), \alpha(x,y)$ - coefficients of permeability, porosity, gas-saturated thickness of the reservoir and the coefficient of gas saturation, respectively; z - Compressibility factor; μ - The dynamic viscosity; $q(t)$ the density of the gas withdrawal; p_0 -Air pressure under normal (standard) conditions.

Withdrawal (injection) of gas from an underground storage facilities are made through n. wells, which are located at points (x_i, y_i) during a period of time $t \in [t_{1j}, t_{2j}]$, $(j=\overline{1,J})$. Withdrawal density is determined by the formula:

$$q(t)=\frac{1}{V}\sum_{i=1}^{n}q_i\delta\left(x-x_i^0\right)\left(y-y_i^0\right)\left[\eta\left(t-t_{1i}\right)-\eta\left(t-t_{2i}\right)\right]. \tag{4}$$

In the last formula q_i - gas withdrawal from $i-$ well, $\delta(x)$ - Dirac delta function, $\eta\left(t-t_{ji}\right)$ - Heaviside step function, V - the total volume of gas.

The solution for the problem (1) - (3) is constructed using finite element method (FEM).

3.2. Mathematical model of a well bottom

Well bottoms account for a significant portion of the total loss of pressure in the reservoir [3,4]. Gas flow depends on the degree and nature of the reservoir opening (degree is concerned with the height of the reservoir opening, and the reservoir nature is concerned with possible inclusion of additional hydraulic resistance, it can be, for example, perforated production string). Often the inflow models must also take into account reservoir anisotropy.

Under condition of spherical inflow law gas pressure distribution in well bottom satisfies the equation [1].

$$-d\left(\frac{p}{p_0}\right)^2=\frac{\mu}{\pi hkp_0}\ \frac{q_0}{F}\ dF+\beta\frac{\rho_0}{\pi p_0 dh}\ \frac{q_0^2}{F^2}\ dF,\quad \beta=\frac{12\cdot 10^{-5}d^3}{mk^{3/2}} \tag{5}$$

wherein p_0, q_0, ρ_0 - the pressure, flow rate and density of the gas in normal conditions, d - a grain diameter of rock, m - reservoir porosity, k - permeability diffusion area, F - the filtering surface area, h - reservoir thickness.

4. PROBLEMS AND METHODS FOR THEIR SOLUTION

There is a set of direct and inverse operating problems that need to be solved. Direct problems include those for which the calculation process is carried out in a direction from the reservoir to the entrance of the ICS whether the entrance of the gas pipeline. If the input data is the input pressure or flow rate of ICS (in pipeline), and it is necessary to calculate the pressure on the reservoir inflow boundary of wells, then the problem will be called inverse. All problem statements are carried out for the isothermal case.

≡ **Solved problems**

Operating mode of UGS calculates after the identification of reservoir parameters, filtration coefficients of well bottoms, coefficients of hydraulic resistance of gas flow in the well and in the wellhead connections. When calculating the operating mode of the well provided the opportunity to take into account restrictions on the maximum flow rates and depression in the well bottom. Developed methods for solving a quite complete set of direct and inverse problems.

For a given value - average reservoir pressure in the withdrawn area; reservoir pressure for each well, the total flow rate of wells, flow rate for each well, as well as one of the variables on gas gathering station (GGS):- pressure or flow rate, the software finds flow rate of each well, the flow rate or pressure on GGS.

Reservoir pressure distribution is greatly affected by the reservoir parameters (porosity, permeability, effective power, geological, geometric, etc.) which are known for the most part fairly approximately. And because often enough input parameters satisfy the appropriate mathematical equations and systems also approximately. It should be used at the stage of defining and solving problems.

≡ **Methods of solving problems**

To find the pressure distribution in the gas storage reservoirs used finite element method. Systems of linear equations are solved by the developed method, which takes into account a significant sparseness of the corresponding matrices. This allowed more than two orders faster obtain a solution, which, in turn, allowed for tens of seconds to simulate filtration processes in dozens of square kilometers and at intervals for several years.

≡ **Calculation of operation of gathering systems, wells and well bottoms**.

To calculate the operation of a gathering system and their wells with well bottoms as a single hydraulic system proposed original methods for solving nonlinear systems. Developed and implemented methods, algorithms and software allow you to solve systems with different mathematical representation of equations. Convergence of the method is provided in the entire domain of really possible modes.

Calculation of the initial distribution of pressure in the reservoir is carried out for values of pressure measured in certain wells with simultaneous identification of the parameters of inhomogeneous reservoir. The pressure distribution in the reservoir and flow rates of wells calculated under conditions of non-stationary gas filtration.

≡ **Calculation of operating modes of injection compressor stations (ICS)**

Hydraulic calculation of multi shop compressor stations with heterogeneous gas compressor units (GCU) allows you to take into account the individual characteristics of each. The main task is using input parameters and output gas pressure parameter of a compressor station to find the parameters of operating modes (diagrams of operation of shops, the number of GCUs at each stage of compression, compressor revolutions and setting of centrifugal superchargers).

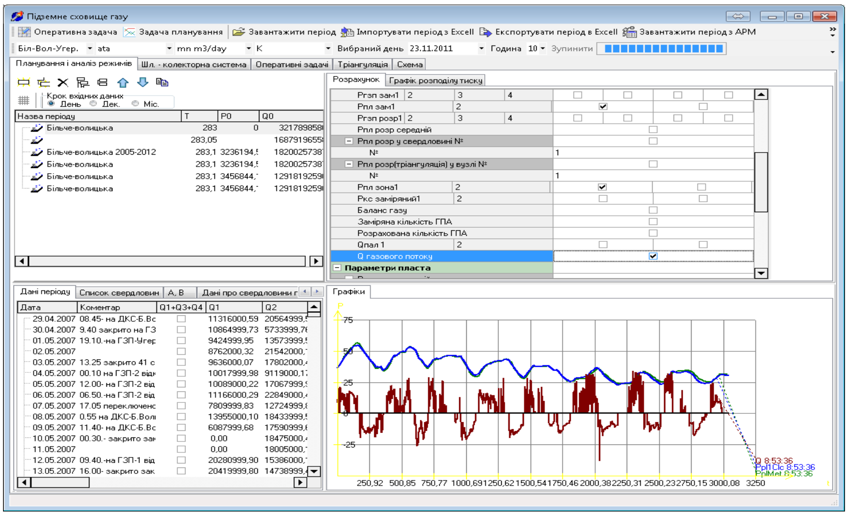

Figure 1. The main form of the software and the tab "Processing of measurements."

5. NUMERICAL EXPERIMENTS

The designed software "UGS operating mode" allows the adaptation of models of facilities at considerable intervals of time. To this effect, implement the ability to visualize the calculated and measured data, which allows you to quickly assess the impact of changes of certain parameters on a change of the reservoir pressure. The software " UGS operating mode " is implemented in an environment DELPHI and has a convenient user interface that meets the basic requirements for a graphical interface.

Calculation of a reservoir pressure and a pressure on a GGS (Gas gathering station) of Bilche-Volytske UGS for four periods of gas injection and withdrawing is presented in Figure 1. The top two graphs are calculated and measured reservoir pressure in a work area, and the lower one is injection (above the axis) and withdrawal (lower axis) of gas.

Example 1. The maximum withdrawal of gas at a pressure of 40.0 ata in pipeline.

Table 1. The maximum withdrawal of gas, according to Example 2

	Average pressure in the work area of Bilche-Volytske UGS (ata)	Average pressure in the work area of Ugerske UGS (ata)	Daily withdrawn from Bilche-Volytske UGS (Mm^3/day)	Daily withdrawn from Ugersko UGS (Mm^3/day)	Total withdrawn (Mm^3/day)
1	55.0	36.0	123.8	20.9	144.6
2	52.0	35.0	115.0	19.9	134.9
3	49.0	34.0	106.2	18.9	125.1
4	46.0	33.0	97.3	17.9	115.2
5	43.0	32.0	88.2	16.8	105.1
6	40.0	31.0	78.9	15.8	94.7
7	37.0	30.0	69.3	14.7	84.0
8	34.0	29.0	59.3	13.6	72.9
9	30.5	28.0	46.9	12.4	59.3
10	27.5	27.0	35.1	11.2	46.3
11	24.5	26.0	21.1	9.9	30.9
12	21.0	24.5	7.1	7.64	14.7

Example 2. Gas volumes which inflow in a gasmain without operating CS at average pressure in the work area of Bilche-Volytske UGS of 55 ata and pressure in the work area of Ugerske UGS of 36 ata.

Table 2. Gas volumes, according to Example 2

	Pressure in the gas gathering station of Bilche-Volytske UGS (ata)	Pressure in the gas gathering station of Ugersko UGS (ata)	Daily injection from Bilche-Volytske UGS (Mm^3/day)	Daily injection from Ugersko UGS (Mm^3/day)	Total injection (Mm^3/day)
1	50.0	30,0	6.83	5.56	12.39
2	47.5	27.5	35.81	8.79	44.6
3	45	25	57.52	11.42	68.94
4	42.5	22.5	75.23	13.61	88.84

Example 3. Gas volumes which outflow from a gasmain without operating CS at average pressure in the work area of Bilche-Volytske UGS of 22 ata and pressure in the work area of Ugerske UGS of 22 ata.

Table 3. Gas volumes, according to Example 3

	Pressure in the gas gathering station of Bilche-Volytske UGS (ata)	Pressure in the gas gathering station of Ugersko UGS (ata)	Daily withdrawn from Bilche-Volytske UGS (Mm^3/day)	Daily withdrawn from Ugersko UGS (Mm^3/day)	Total withdrawn (Mm^3/day)
1	22.5	22.5	13.95	4.65	18.6
2	25	25	28.10	7.45	35.55
3	27.5	27.5	41.73	10.21	51.94
4	30	30	55.03	12.94	67.97

6. CONCLUSIONS

Carried numerical experiments confirmed that significant random reservoir pressure perturbation with a mean of zero over a wide range does not alter the calculated output parameters of the CS. This justifies certain conclusions that are formulated above. Reservoir pressure distribution all over the reservoir is formed over a considerable period of time. The reconstruction of the pressure needs modeling of UGS over a certain time (three - five years). The distribution of reservoir pressure is influenced by both operating modes of withdrawn and injection and also distributed parameters of porosity, permeability and geometrical parameters of the reservoir. Most of these parameters are known only approximately. Establishing distribution of reservoir pressure is carried out simultaneously with the identification of distributed parameters of the reservoir. This way possible to achieve coincidence between the calculated and measured average reservoir pressure in the area of withdrawn and injection. The question about unique identification is open (one filtration equation and a lots of parameters that need to be identified).

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