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Rational methods of operation of underground gas storages and mitigation of energy losses

Racjonalne sposoby działania podziemnych magazynów gazu z uwzględnieniem zużycia nośnika energii

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ABSTRACT: The fuel and energy complex of Ukraine, like most developed countries of the world, is a complex system of material production incorporating a set of many subsystems that cover the extraction, conversion, distribution, storage and consumption of energy. Ukraine's gas transportation system has an extremely complex system, which consists of gas pipelines of various purposes and capacities, compressor stations, compressor shops, gas distribution stations and underground gas storage facilities. Compressor stations, allied with underground storage, ensure full pipeline use, reliability of work, modes of regulation of transit flows and maintenance of uninterrupted supply. Their co-employment is considered one of the most effective methods of increasing reserves for reliable gas supply and efficiency of gas sales in the country and abroad. The use of storage reduces the unevenness of seasonal consumption and enables timely delivery. This is justified by the fact that during the year, gas production is uneven, as is consumption. In winter, the amount of gas extracted does not provide the amount of gas consumed. Therefore, underground storage facilities are an integral part of the gas transmission system, which must function efficiently. The Ukrainian gas transportation system is part of the European energy system, despite the fact that the country itself is not yet a member of the EU. To research the issues of improving the efficiency of the system and underground storage facilities, it is necessary to analyse the parameters of their work and study the problems of reducing costs during storage and transportation. In the work on the basis of the analysis of the cyclic operation of the Dashavsky underground storage, the energy approach to an estimation of losses of gas at storage is offered. This will streamline and specify the general ideas and the level of irreversible losses of natural gas as an energy source and will increase the efficiency of operation of the underground gas storage as a whole. At the same time, taking into account the energy characteristics of natural gas when forecasting its losses during storage will significantly affect the organisation and optimisation of maintenance of storage equipment and, in particular, the compressor station.

Key words: underground gas storages, cyclic operation, compressor station, gas losses, gas consumption.

STRESZCZENIE: Kompleks paliwowo-energetyczny Ukrainy, podobnie jak w większości krajów rozwiniętych, jest złożonym systemem produkcji materiałów, zespołem wielu podsystemów, które obejmują wydobycie, konwersję, dystrybucję, magazynowanie i zużycie energii. System przesyłu gazu na Ukrainie ma niezwykle złożoną strukturę, składającą się z gazociągów o różnym przeznaczeniu i pojemności, tłoczni, stacji dystrybucji gazu i podziemnych magazynów gazu. Tłocznie zapewniają przepustowość rurociągów, niezawodność działania, tryby regulacji przepływów tranzytowych oraz nieprzerwane dostawy realizowane za pomocą podziemnych magazynów gazu. Ich wykorzystanie uważane jest za jedną z najskuteczniejszych metod zwiększania rezerw, zapewniających niezawodne dostawy gazu oraz efektywność sprzedaży gazu w kraju i za granicą. Zastosowanie magazynu zmniejsza nierówności sezonowego zużycia i zapewnia terminowość dostaw. Jest to uzasadnione nierównomiernym wydobyciem oraz zużyciem gazu w ciągu roku. Zimą ilość wytworzonego gazu nie odpowiada ilości zużytego gazu. Dlatego podziemne magazyny stanowią integralną część systemu przesyłowego gazu, która musi sprawnie funkcjonować. Ukraiński system przesyłu gazu jest częścią europejskiego systemu energetycznego, mimo że sam kraj nie jest członkiem UE. Aby zbadać zagadnienia poprawy wydajności systemu i podziemnych magazynów, konieczne jest przeanalizowanie parametrów ich pracy oraz zbadanie problemów redukcji kosztów podczas magazynowania i transportu. W artykule, na podstawie analizy cyklicznej pracy podziemnego magazynu Daszawa, zaproponowano energetyczne podejście do oceny strat gazu podczas magazynowania. Uprości to ogólne idee i doprecyzuje poziom nieodwracalnych strat gazu ziemnego jako źródła energii oraz zwiększy efektywność działania wszystkich podziemnych magazynów gazu. Jednocześnie uwzględnienie charakterystyk energetycznych gazu ziemnego przy prognozowaniu jego strat podczas magazynowania w znaczący sposób wpłynie na organizację i optymalizację obsługi urządzeń magazynowych, a w szczególności tłoczni.

Słowa kluczowe: podziemne magazyny gazu, praca cykliczna, tłocznia, straty gazu, zużycie gazu.

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The aim and objectives of the study

Currently, energy security and diminishing dependence on neighboring countries have emerged in Ukraine. Ukraine's energy security should be understood as the state's ability to enable the efficient use of its own fuel and energy base, to optimise the diversification of sources and ways of supplying energy resources to Ukraine to ensure the vital functions of the population and the functioning of the national economy, and to prevent sharp price fluctuations in fuel and energy resources (Kryzhanivs'kyi et al., 2018).

Underground gas storage facilities are an integral part of the world's largest gas transportation system. Their work depends on the reliability and safety of the pipeline network. Currently, gas costs a lot and for its effective storage and sale, it is very important to minimise losses, especially when stored in the UGS (underground gas storage).

The main technological processes of cyclic exploitation of underground storage facilities are associated with the injection, removal and long-term storage of gas under pressure. The processes of injection, removal, stopping of compressor units, separation, cleaning and drying of gas are accompanied by periodic blowing. These types of operations are directly related to the losses of gas foreseen for production and technological needs (STP 320.30019801.020-2000).

Underground storage facilities are among the most effective and environmentally safe means of regulating unevenness and guaranteeing the gas supply of industrial and communal needs (Silva et al., 2013). However, the processes of creation and further exploitation of storage facilities entail gas costs. In relation to losses during transportation and extraction, they are smaller, partially offset and reduced as a result of the introduction of the latest technology. But the issue of studying gas losses during the operation of storage facilities in order to reduce them requires constant analysis in connection with the modern requirements for the gas transmission system (Filipchuk et al., 2018).

Due to the importance of the technical re-equipment and integration of Ukraine's gas transportation system (GTS) into a single European GTS and the directions of international cooperation, consideration should be given to analysing the problems of gas losses from underground storage facilities. This minimises the cost of holding gas in gas storage and increases the efficiency of their use.

An important aspect of reducing gas losses during storage is the optimisation of injection and selection modes using pressing compressor stations (PCS). Minimisation of energy consumption in the process of compressor injection and extraction of gas will reduce the amount of fuel gas, which can be considered as a reduction of gas losses during storage, considering natural gas as an energy source (Olijnyk and Chernova, 2017).

In addition to the costs involved in existing gas storage facilities, there are also formation processes associated with dissolution and diffusion. They do not go beyond the established ratios between active and buffer volumes of gas.

Materials and methods of research

In general (Methods..., 23.06.2008), the gas loss is divided into direct (due to the imperfection of the processes of extraction, transportation, distribution, storage and accounting), and indirect (caused, as a rule, by transformation of energy carriers in the production of thermal and electric energy and the technological use of natural gas) (Figure 1).

In the process of creation and subsequent cyclical exploitation of gas reservoirs in porous reservoirs, as well as in any energy-intensive production, there are gas costs for technological operations and their irreversible losses. They are relatively smaller than in production and transportation, and are partially offset and reduced as a result of the introduction of advanced technology (Chernova, 2016).

According to order No. 329 of Ukrtransgas, dated September 12, 2011, the structure of the PTL (production and technological losses) of gas during the operation of the UGS includes:

- technological costs of gas;
- technological leakage of gas;
- irreversible reservoir gas losses.

UGS technological expenses include:

- fuel gas for the operation of the gas pumping unit;
- the work of the gas preparation unit (UGG);
- starting, stopping and changing the operation of gas pumping units (GPU):
  - the work of the turbo detector,
  - for blowing off the circuit of the supercharger,
  - for the discharge of gas from the circuit of the supercharger,
  - the operation of the crane lining and pneumatic controllers (impulse gas);
- for operation and maintenance:
  - technological equipment, technological communications of gas pipelines, wells,
  - unloading and discharging from the communication booster compressor station (BCS), (STP 320.30019801.020-2000) technological equipment, technological communications of gas pipelines and wells,
  - pneumatic cylinders of overhead valves,
  - pneumatic regulators,
  - gas preparation units,
  - own power plants,
  - boiler houses;

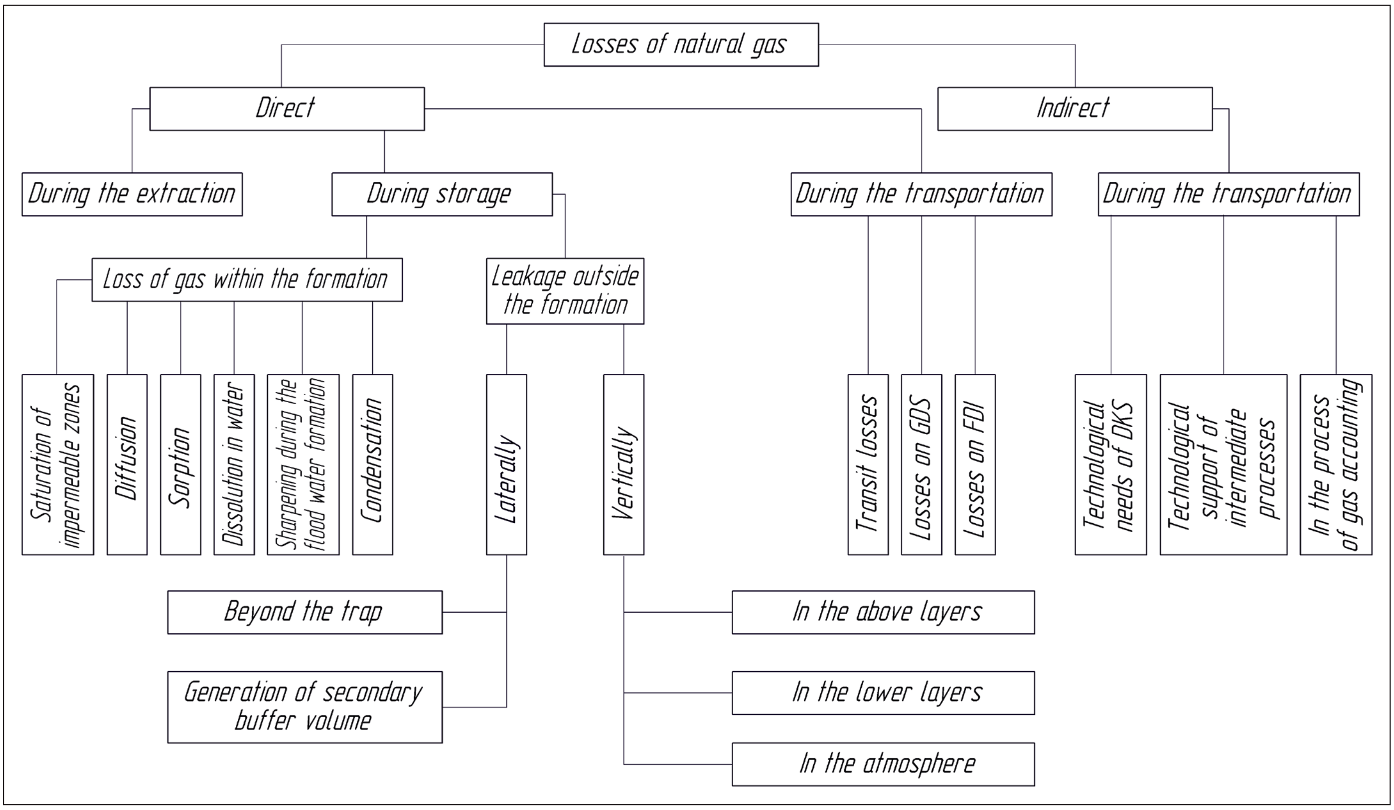

Figure. 1. Scheme of systematisation of losses of natural gas
Rysunek 1. Schemat systematyzacji strat gazu ziemnego

- on the process of degassing condensate;
- gas-dynamic and geophysical exploration of wells.

Gas losses due to technical reasons occur in virtually all of the existing UGSs, which are being constructed in aquifers and in depleted deposits (Methods..., 23.06.2008).

In the underground storage facilities, a matched compressor station is always required, as it serves for injection and removal of gas from the reservoir through the operation wells (Grudz et al., 2021). Since the gas is compressed at the compressor stations to a pressure of 7.5–10.5 MPa, it is heated to 343–345 K. As a result, the condensate passes into a gaseous state in which it enters the reservoir. At the same time, during formation, the formation pressure is reduced to 3.2–3.5 MPa, and the temperature is up to 278 K. Condensate, with such parameters, is partially applied to the surface of the formation, but the main part remains in the formation, filling the pores with heavy carbohydrates and changing the active porosity. The condensate itself is irretrievably lost. The average specific content of C5+ from gas is 12.76 kg/ths m^3, equivalent to a stable condensate corresponding to the content of 8.93 kg/ths m^3. According to the contents of the storage facilities, 17.4–19.5 billion m^3 of losses reach 160 thousand tons of condensate. An important problem is the increase of condensate saturation of pores. It has been established that when it is more than 30%, dynamic porosity is not significantly reduced, but the permeability is greatly reduced. In the case of a lack of pressure drop, the fallen condensate may cause colmatation of the pore space (Tymkiv et al., 2016).

Gas consumption for technological operations comes about due to the following:

- gas taps from GPU and their communications for unloading during preventive inspections;
- flushing of gas from dust collectors, separators, carbon adsorbers, ceramic filters and connecting gas pipelines and purging them with gas for the purpose of purification of contaminated solid particles and liquids, as well as for the installation of shutters before equipment that will not be used during the gas withdrawal from the UGS;
- gas tightening after the injection period from the plugs for the purpose of dismantling the stubs before the separators on the fracturing, which were not used when loading gas in the storage;
- steaming gas from the gas pipeline and the connecting gas pipeline in order to inspect the valves and diaphragms mounted on them.

To study this issue, many scientists have engaged in experimental studies of the modes of operation of the main gas collector of the gas collection and transportation system from integrated gas treatment plants (Chernova, 2020). It has been demonstrated that the liquid phase is accumulated in the pipeline due to the change in the thermobaric conditions of phase equilibria during the gas transport after the preliminary gas preparation. A complex of measures for liquid removal from the gas pipeline cavity without stopping the operation of the gas pipeline is proposed. Therefore, one of the first in the article of expenses and recorded losses is the fuel gas for the work of the GPU.

To assess the energy efficiency of BCS operation in real conditions of Bohorodchany UGS, an analysis of the capacity of gas pumping units was performed. The internal power of compressor cylinders N_c at each time of the gas injection period was determined by a mathematical model created by polynomial approximation of the load curves, which express the relationships between the parameters of the technological process of gas compression:

$$F(P_B, P_H, Q, R, n, x, N_i) = 0 \quad (1)$$

where:
P_B, P_H – pressure at the inlet and outlet of the BCS,
Q – productivity,
R – number of compressor cylinders,
n – crankshaft speed,
x – the degree of discovery of dead space,
N_i – indicator power.

Restrictions were imposed on the parameters of the GPU mode of operation:

- at the maximum pressure $P_H \leq P_{max}$;
- crankshaft speed $n_{min} \leq n \leq n_{max}$.

The effective power was based on the average indicator pressure in the power cylinders, which was determined based on the processing of indicator diagrams:

$$N_e = \frac{\pi D^2}{4} SnP_{cpi}$$

As a result, the effective efficiency of the GPU was calculated as a ratio:

$$\eta_e = N_i / N_e$$

The unproductive fuel gas consumption was established according to the value of the effective efficiency, which was compared with the actual one.

Results of research on modeling of filtering process

Figure 2 shows the dynamics of cost data, depending on the period (percentage section relating to month of the year beginning November to October).

According to the obtained dependences, it can be argued that the significant effect on the PTL value of the compressor station operation mode is confirmed by the provision on the low efficiency of the gas pumping units. In February, the decline in the value of these costs is almost to a minimum due to the cessation of the compressor station operations, and in January, when the growth of gas was by 72%, the higher value of the PTL having grown by 25%.

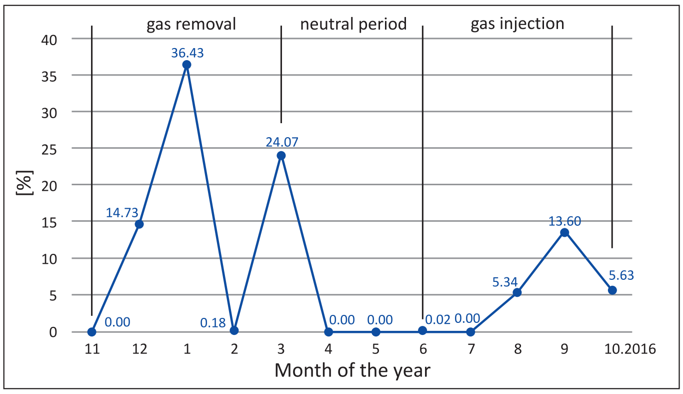

Figure 2. Dynamics of fuel gas consumption for GPU operation in 2016

Rysunek 2. Dynamika zużycia paliw gazowych na działalność GPA w 2016 r.

The structure of technical leakages of gas at the BCS of the UGS is the gas leak due to the design and physical wear of the equipment through:

- flange connections, sockets of overhead valves, etc.;
- the gas-oil seal of the shaft of the rotor of the supercharger;
- the seal gasket compressor (MMC).

Gas consumption for technological operations when gas is removed from storage are caused by:

- steaming of gas from dust collectors, contact columns of the drainage system of gas and separators;
- steaming of gas from plugs, connecting gas pipelines and gas pipeline-drainage;
- purging the dust from dust collectors;
- purge gas separators;
- in the study of wells with the release of gas into the atmosphere;
- when blowing up wells that came out of repair.

Losses of gas at gas distribution stations (GDS) are the largest since, according to the technological regime, there can be continuous gas emissions into the atmosphere. Stable gas leakage occurs when blasting wells, especially in the course of repair and restoration works of plugs and separators. Technological gas losses are conditioned by the necessity of causing BCS. It is believed that 10% of the volume of transportation is spent on the technological needs of the main and auxiliary processes. It is also necessary to note the losses in the accounting process. There are three factors of influence here: methodological, based on measurement methods; instrumental – limitations within measuring instruments; and the temperature of the accounting gas. With regard to the last, the change in temperature parameters ±30°C gives volume losses of ±1%.

Every year, for the quality work of the repository, major repairs of certain wells and their development are carried out. This cost item is also an important aspect, since its parameters depend on the skill and qualifications of the staff, which can have a significant impact on them. Technological expenses also take into account losses during major repairs. They are presented in Figure 3 (percentage section relating to month of the year beginning November to October).

The established dependence shows that repairs of this kind were carried out only during the period of gas pumping (the maximum amount of expenses is 39.62% – typical for August in the period of selection and a neutral period of work associated with major repairs.

It is also important to conduct an assessment of gas losses based on well analysis. The models of the filtration flow, taking into account the geometry of the regions and boundary conditions, the method of estimation of losses of hydrocarbons in the course of their flow through the well surface was proposed and implemented for the Dashava Storage (Olijnyk and Chernova, 2017).

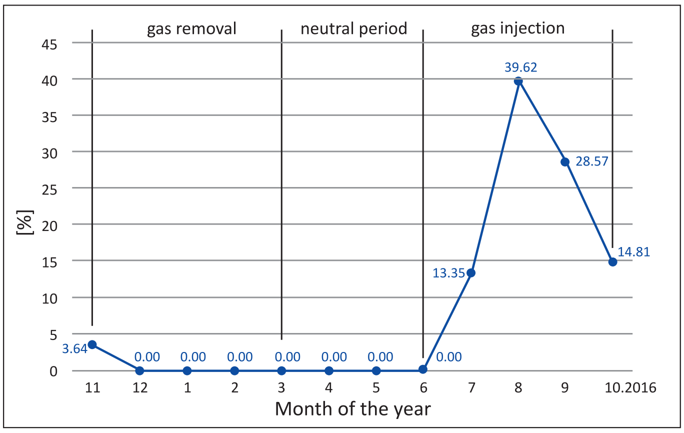

Figure 3. Dynamics of gas consumption during major repairs (shut-off and development of wells)

Rysunek 3. Dynamika zużycia gazu podczas kapitalnego remontu (zamknięcie i prace w odwiertach)

Non-repayable reservoir gas losses in the UGS are related to:

- disjunctive disorders passing through the reservoir and its roof;
- lithological windows in the roof of the reservoir;
- complications in the form of separate domes or structural nasos, separated from the main object by a deflection;
- old or abandoned wells that could not be detected during the preparation for the pumping of gas or poorly eliminated wells;
- wells in which poor cementing of casing columns exist, or those having leaking casing thread connections or where crushing and other defects have occurred;
- dissolution in reservoir waters, diffusion and sorption.

Particular attention should be paid to gas leaks from UGS, as there are large volumes of gas stored under pressure. Leakages are, however, everywhere: it is completely impossible to stop them completely. Therefore, it is necessary, based on the characteristics of the cyclical work of the storage, the characteristics of wells and the study of losses of previous cycles, to draw conclusions for their minimisation.

It is worth noting that the experience of underground storage of gas confirms the possibility of exploitation of wells with inter-column pressures up to 2 MPa and the flow of gas up to 100 m^3/day, that is, gas leakage is planned-predictable.

Gas losses within the formation are associated with the gradual saturation of impermeable zones of the formation, diffusion and sorption of gas, sputtering it in water during storage in the aquifer, and gas jamming in the event of a gradual flood formation. According to research, such losses do not exceed 1–1.5% of the active volume per cycle. Regarding the analysis of UGS in Ukraine, which has an active gas volume of about 32 billion cubic meters, such losses amount to 320–480 million cubic meters annually. Due to the political situation in the country, at present, the filling of underground storage facilities does not exceed 17–19.5 million m^3, and some underground storage facilities practically do not work. Thus, in accordance with the value of the active volume of gas loss within the formation, respectively, for Ukraine, UGS is less – 174–290 billion m^3. Obviously, in increasing reservoir pressure, the size of reservoir losses will increase.

During the operation of the UGS, processes of diffusion and dissolution of hydrocarbon components occur in the peripheral contact area and throughout the volume of the artificial gas deposit. In this case, the part of the buffer gas is represented by gas dissolved in formation water and sorbed by mountain rocks. Diffusion, solubility or all kinds of hydrogeochemical transformations of hydrocarbons occurring in natural deposits in geological time are not so characteristic of artificial deposits of underground gas storages, due to the short duration of the processes of diffusion and dissolution in the repositories, in comparison with the scale of the time of formation of deposits. Losses, as calculations shown by different methods, are relatively small and make up 1.0–1.5% of the volume of active gas. In addition, the amount of gas sorbed by rocks during the creation and operation of UGS is significantly less than the amount of gas dissolved in sewage water.

The gas dissolved in the reservoir water within the contamination of the gas content, is released when the reservoir pressure is below the pressure of saturation from the water in the free phase, thereby increasing the pressure in the deposit and preventing the possible watering of gas wells.

Consequently, the dissolved gas in the reservoir water within the contamination of the gas content performs the function of a buffer volume.

If the object of storage is the aquifer, then the operation of the storage facility further affects the loss of gas. By various methods, it is established that the rational mode of exploitation of underground storage facilities associated with aquifers and water pressure basins is work at a pressure of saturation of gas with water of 3–3.5 MPa. Under such conditions, the buffer volume of the gas is 23 million m^3, of which 3–3.5 million m^3 is dissolved in the reservoir waters of the gas.

A separate case of losses is the flow of gas into the higher horizons and the surface that is observed in individual wells (Chernova and Gershun, 2020). The migration of gas can lead to the formation of a secondary (man-made) deposit, from which it is impossible to extract. If it is economically inappropriate to take gas from an technogenic deposit with existing technology, and to take measures to prevent its further accumulation, the entire volume of this deposit should be attributed to reservoir losses and excluded from the balance of the storage. In the case of large quantities of gas and the possibility of industrial dumping (unloading), the volume of gas in the man-made deposit cannot be classified as a loss category, because part of it will be selected, and the other is the buffer volume.

A similar process takes place as a result of the expansion of an artificial gas deposit. In the presence of an upland reservoir, part of the buffer gas volume migrates. Due to minor gas saturation, such gas is not appropriate to be extracted and it is considered to be lost, or it is taken as a secondary buffer.

In physico-chemical terms, gas migrating from the main artificial reservoir is represented by:

- gas in a free state (secondary man-made gas deposits);
- the gas dissolved in the reservoir waters;
- gas sorbed by mountain rocks.

The internal volume of the buffer gas is also related to the internal pressure. Consequently, reservoir losses include:

- gas located outside the trap and isolated from the main deposit of the UGS;
- gas that migrates in the above located aquifers and does not participate in the technology of gas selection and has no effect on the operation of the storage.

The gas contained in dense collectors, which has a weak hydrodynamic relationship with the main gas storage, as well as the gas contained in the dissolved form in the reservoir waters in the zone of two-phase filtration within the contamination of the gas content, is considered to be the buffer volume. It can be divided into two components:

- gas that can be taken from an underground storage facility in the event of an emergency need for additional supply to the consumer or in the event of the elimination of UGS;
- gas that is economically inappropriate to be removed from the reservoir due to existing methods.

The causes of reservoir gas losses are divided into geological and technical, which are manifested independently or jointly. Plant gas losses due to geological reasons are inherent in repositories with water pressure regimes and constructed in difficult geological conditions. (Methods..., 23.06.2008). For geological reasons, the following are noted as causes of reservoir gas losses:

- the presence of tectonic violations;
- lithological "windows" in the containment that directly overlaps the reservoir.

For the purpose of the analysis of irreversible reservoir losses, we used real data drawn from the Dashavsky underground gas storage, which is located in the Stryj district of the Lviv region, at a distance of 15 km from the city of Stryi, and was created in 1974 in depleted deposits of the same name gas field (Chernova and Gershun, 2020). The active layers for storage of gas are two horizons of the Lower Dasha sandstones of the Sarmatian stage of the Neogene ND-8 and ND-9. The capacity of the Dashavsky storage is 5.26 billion m^3 of gas, of which 2.15 billion m^3 is an active volume. The amplitude of the change in reservoir pressure varies from 1.9 to 4.3 MPa. The area of gas is 46 km^2, the average effective thickness is 10.8 m.

Figure 4 shows a graph of the dependence of irreversible reservoir losses in the Dashava Storage in 2016 (percentage section relating to month of the year beginning January to December).

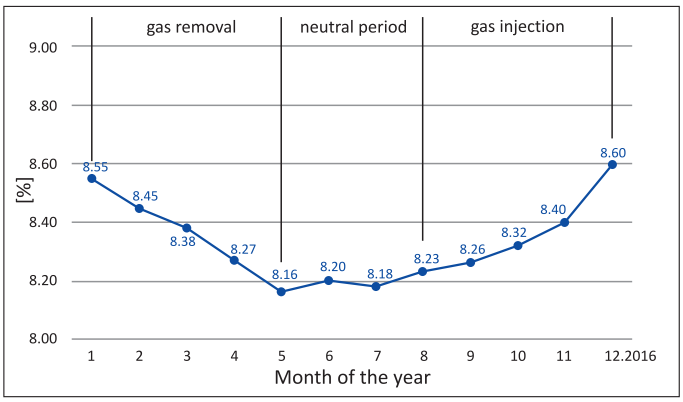

Figure 4. Dynamics of irreparable reservoir losses

Rysunek 4. Dynamika nieodwracalnych strat formacji

According to the schedule, the loss data directly depends on the amount of gas in the storage. The greater the amount of gas, the greater the formation pressure. At the same time, this leads to an increase in the size of reservoir flows. Therefore, the smallest of their values are characteristic for the end of the withdrawal period and the neutral period. With the start of loading they begin to grow.

Discussion of results of modelling the filtration process

Consequently, irreversible reservoir gas losses in the UGS are related to:

- disjunctive disorders passing through the reservoir and its roof;
- lithological windows in the roof of the reservoir;
- complications in the form of separate domes or structural nasos, separated from the main object by a deflection;
- old or abandoned wells that could not be detected during the preparation for the pumping of gas or poorly eliminated wells;
- wells in which the cementation of the casing columns is poor or those having leaking threaded casing column connections or crushing of their walls and other defects;
- dissolution in reservoir waters, diffusion and sorption.

Non-repayable stock losses can be caused by:

- emergency flooding in the upper horizons and on the surface (for technical reasons);
- flows beyond the limits of the trap caused by a high pumping rate or increase in its total volume;
- formation of isolated gas deposits within the limits of the trap in places, the presence of which was not revealed during designing;
- flowing in the upper horizons due to geological reasons (not recognized at the design stage).

Irreparable reservoir losses include gas that:

- is located within the trap and hydrodynamically isolated from the main deposit;
- is located outside the trap and is not hydrodynamically connected with the main deposit;
- found in the upper horizons and does not enter the main deposit;
- migrated into the atmosphere through rocks or objects of mining activity;
- is dissolved in reservoir water outside the contour of gas content;
- is adsorbed by the rock structures.

An analysis of the work at the Dashaevsky underground storage system that includes performance indicators, is presented and described in a previous paper.

To assess gas consumption for production and technological needs, we built the dynamics of gas consumption in all the articles described above (Figure 5) (percentage section relating to month of the year beginning November to October).

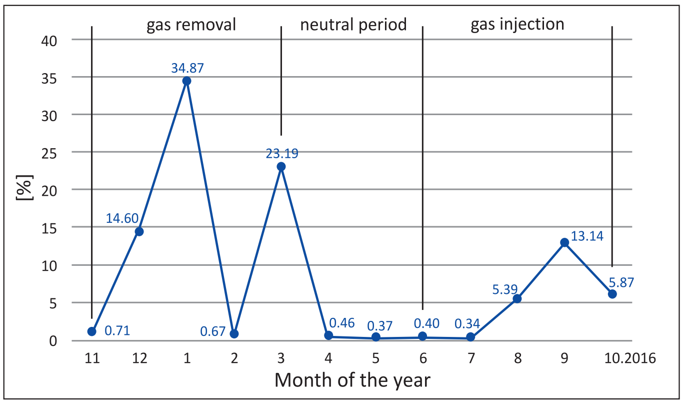

Figure 5. Dynamics of gas consumption for production and technological needs

Rysunek 5. Dynamika zużycia gazu na potrzeby produkcyjne i technologiczne

According to the data presented in the graph, it can be concluded that the data of the PTL in 2016 confirm the operation of the aggregates in January and March. In February, sampling was not carried out. As stated in the instructions of the central dispatching department, in this month, for the efficient operation of the gas transmission system, the supply of gas from this storage facility was not required, and therefore the costs without the work of the aggregates were 0.67%.

The established patterns allow optimisation of compressor station operation during the period of compressor selection and gas injection that will minimise fuel gas consumption and, consequently, reduce gas losses during storage.

The main factors determining, in the general case, all kinds of gas losses, including that from the reservoir are:

- mining and geological conditions of creation and operation;
- technical condition of wells and technological equipment;
- quality and timeliness of carrying out of repair works and preventive measures;
- efficiency of control and observation in the process of creation and operation of gas storage facilities.

The volumetric efficiency of the UGS will be introduced to evaluate the gas selected from the gas storage in relation to the volume of injection.

As is known, the gas, which is periodically pumped and taken out of the storage is called active. Therefore, when removing, the balance of gas should be maintained. However, this balance cannot be met due to gas flooding in the reservoir and their dissolution in contour waters, as well as losses in surface equipment.

For perfect storage without gas loss:

$$\eta = \frac{V_{out}}{V_{in}} = 1$$

However, in practice, in the operation of the UGS, this ratio, as a rule, is less than one.

The volume of pumped gas is therefore:

$$V_{in} = \Omega \frac{p^*_{\max} - p^*_{\min 0}}{p_{st}} \cdot \frac{T_{st}}{T_{for 0}} \quad (2)$$

where:

$p^* - p/z$ – correct pressure,

p_{st}, T_{st} – standard terms.

While the volume of selected gas is:

$$V_{out} = \Omega \frac{p^*_{\max} - p^*_{\min 1}}{p_{st}} \cdot \frac{T_{st}}{T_{for 1}} \quad (3)$$

For the gas storage mode, that is why:

$$\eta_0 = \frac{p^*_{\max} - p^*_{\min 1}}{p^*_{\max} - p^*_{\min 0}} \cdot \frac{T_{for 0}}{T_{for 1}} \quad (4)$$

and:

$$\eta_0 = \frac{1 - p^*_{\min 1} / p^*_{\max}}{1 - p^*_{\min 0} / p_{\max}} \cdot \frac{T_{for 0}}{T_{for 1}}$$

Here:

$p^*_{\min 0}$ – minimum formation pressure at the start of loading,

$p^*_{\min 1}$ – minimum reservoir pressure at the end of the next sampling.

For water pressure and elastic modes, Ω = const, hence:

$$\eta_0 = \frac{\Omega(t) 1 - p^*_{\min 1} / p^*_{\max}}{\Omega(t) 1 - p^*_{\min 0} / p_{\max}} \cdot \frac{T_{for 0}}{T_{for 1}} \quad (5)$$

In the ideal situation, $p^*_{\min 0} = p^*_{\min 1}$, however, in practice, the minimum formation pressure over the years varies due to the non--identity of the volume of injection and removal and gas losses.

Considering the process of pumping gas (Olijnyk et al., 2013), well performance is related to the pressure described by the equation:

$$p^2_{sque} - p^2_{sq} = aq + bq^2 \quad (6)$$

where:

p_{sque}, p_{sq} – squeezing and squatting,

q – well flow rate,

a, b – coefficient of filtration resistance.

Moreover, vibe and formation vice related correlations are:

$$p^2_y \cdot e^{2S} = p^2_w + Qq^2$$
$$S = 0{,}003415 \frac{AL}{ZT} \quad (7)$$
$$Q = 0{,}00133\lambda \frac{z^2 T^2}{d^5} (\mathrm{e}^{2S} - 1)$$

Downhole pressure of working wells is called dynamic, stopped – static (well pressure that idles for a long time is called a reservoir).

Due to the fact that the productive formations lie not only horizontally, the downhole pressure in hydrodynamic calculations is adjusted to any horizontal area, taking into account the pressure on the column of formation fluid between this area and the face.

For the system of superficial distribution of gas, which consists of a collector and loops, we write:

For the loop:

$$p^2_n - p^2_y = \frac{\lambda_l \Delta z T L_l}{A^2 d^5_l} q^2 = c_l q^2 \quad (8)$$

For the collector:

$$p^2_n - p^2_y = \frac{\lambda_\kappa \Delta z T L_\kappa}{A^2 d^5_\kappa} \left(\sum_{i=1}^{n} q \right)^2 = c_\kappa \left(\sum_{i=1}^{n} q \right)^2 \quad (9)$$

If we consider the performance of all wells to be the same, then:

$$\sum_{i=1}^{n} q_i = n \cdot q \quad (10)$$

Taking into account equality (10), the equation (9) has the form:

$$p^2_\kappa - p^2_n = c_\kappa n^2 q^2 \quad (11)$$

Equations (7), (8), (9) and (10) then form the system from which we obtain:

$$p^2_\kappa - p^2_y = A_\kappa n^2 q^2 + c_l q^2$$
$$p^2_\kappa = p^2_{for} e_\kappa n^2 q^2 + c_l q^2 + (aq + bq^2 + Qq^2) e^{-2S} \quad (12)$$

It is evident that there is pressure at the beginning of the collector, that is, at the exit of the climbing COP. If the pressure is steady at its entrance, the degree of pressure increase of the COP will be:

$$E^2 = \frac{1}{p^2_{beg}} \begin{bmatrix} p^2_n e^{-2S} + c_\kappa q^2 n^2 + c_l q^2 + \\ +(aq + bq^2 + Qq^2) e^{-2S} \end{bmatrix} \quad (13)$$

If for a certain moment or period to download, $E \leq 1$, then there is download without compression. At $E \leq 1$, the compressor station is included in the work. The amount of pumping is then:

$$Q_{in} = Q_1 - Q_2 \quad (14)$$

where:

Q_1 – the amount of gas entering the underground storage of gas,

Q_2 – fuel gas consumption on compressor loading.

Thus, one of the ways to increase the volumetric efficiency of the storage facility is to reduce fuel consumption by combustion.

Technical and economic indicators (Kryzhanivs'kyi et al., 2013, 2018) of the process of gas injection into the storage by compressor method in 2016 were compared with similar indicators in 2015. In 2016, the period of compressor gas injection lasted 94 days, and in 2015 – 111 days (from July 8 to October 27, 2015). Compressor injection in 2015 and in 2016 began at a reservoir pressure in the storage of 6.45 MPa and ended in 2016 at a reservoir pressure of 8.45 MPa, and in 2015 – at a pressure of 108.9 MPa. At the same time, 643.6 million m^3 of gas were pumped into the storage by the compressor method in 2016, and 737.1 million m^3 of gas in 2015. The average daily injection of gas into the reservoir in 2016 amounted to 6.847 million m^3 per day compared to 2015 at 6.64 million m^3 per day - an increase by 15.1%. This is explained by the fact that at lower formation pressures there was a lower degree of increase in the pressure of the CS, which led to an increase in the productivity of a single PGPU. Fuel gas consumption per 1000 m^3 of injection in 2016 was 6.05 m^3/1000 m^3 and, compared to 2015 (6.238 m^3/1000 m^3), decreased by 3.1%.

The cost of gas compression (Zelinska et al., 2020) for each year was defined as the sum of the compression costs, and the compression costs included the cost of fuel gas, the cost of materials and reagents (according to actual data), the salary of service personnel and the cost of servicing the PGPU. As a result of calculations, the cost of gas compression in 2016 amounted to 47.65 UAH/1000 m^3, and compared to 2015 (50.34 UAH/1000 m^3), there was a decrease in the cost of compression by 2.2%, which indicates the effectiveness of the measures provided by the proposed methods of forecasting modes and maintenance of gas pumping station in the conditions of compressor stations of underground gas storages.

The established patterns allow to optimise the operation of the compressor station during the period of compressor selection and injection of gas, which will reduce fuel gas consumption and, consequently, reduce gas losses during storage.

The application of the method will also enable a reduction in the average fuel gas consumption from 4598 thousand m^3/h, to 3891 thousand m^3/h. Therefore, this will diminish the average fuel gas consumption by 707 thousand m^3/h or 15.38%. The reduction of the average fuel gas consumption leads to a decrease in the cost of the annual gas volume from UAH 27,949.6 thousand to UAH 23,665.7 thousand, that is, by UAH 4,283.9 thousand (or by 15.3%).

Conclusions

The created mathematical model of the technological process at the UGS has allowed determining the nature of the change in energy consumption by injection and compressor gas selection, depending on the parameters of the storage and operating conditions of the booster compressor station. We demonstrated that energy consumption varies widely, which in turn results in a wide range of fuel gas consumption, and leads to increased energy consumption.

Thus, the proposed energy approach to estimating gas losses during storage will make it possible to streamline and specify the general perceptions and the level of irreversible losses of natural gas as an energy carrier that will increase the efficiency of operation of underground gas storage in general. Taking into account the energy characteristics of natural gas in predicting its losses during the period of storage will significantly affect the organisation and optimisation of maintenance of the equipment of the storage facility and, in particular, the compressor station.

References

Chernova O.T., 2016. Characteristics of the formation of the reservoir system of Dashav underground storage during the period of operation. Exploration and development of oil and gas fields. *All-Ukrainian Quarterly Scientific and Technical Journal*, 2(59): 64–71.

Chernova O.T., 2020. Analysis of typical technological and assembly schemes of strapping wells of underground storage facilities with anti-ejection equipment. *Methods and Devices of Quality Control*, 2(45): 13–25. DOI 10.31471/1993-9981-2020-2(45)-13-25.

Chernova O.T., Gershun B.I., 2020. Analysis of growth drive breakdown by the increase of the Dashav UGS fountain pipes. *Methods and Instruments of Quality Control*, 1(44): 76–88. DOI: 10.31471/1993-9981-2020-1(44)-76-88.

Filipchuk O., Grudz V., Marushchenko V., Myndiuk V., Savchuk M., 2018. Development of cleaning methods complex of industrial gas pipelines based on the analysis of their hydraulic efficiency. *East European Journal of Advanced Technologies*, 2(8 (92): 62–71. DOI: 10.15587/1729-4061.2018.126590.

Grudz V., Grudz Ya., Zapuklyak V., Poberezhny L., Tereshchenko R., Wójcik W., Droździel P., Kalimoldayev M., Kalizhanova A., 2021. Forecasting reliability of use of gas-transmitting units on gas transport systems. 1st Edition. *Mechatronic Systems*. DOI: 10.1201/9781003224136.

Kryzhanivs'kyi E.I., Hrabovskyi R.S., Mandryk O.M., 2013. Estimation of the serviceability of oil and gas pipelines after long-term operation according to the parameters of their defectiveness. *Materials Science*, 49(1): 117–123. DOI: 10.1007/s11003-013-9590-6.

Kryzhanivs'kyi E.I., Hrabovskyi R.S., Vytyaz O.Y., 2018.Consideration of the geometry of corrosion-fatigue cracks in assessing residual life of long-term operation objects. *Materials Science*, 54(5): 647–655. DOI: 10.1007/s11003-019-00229-8.

Olijnyk A.P, Chernova O.T., 2017. Estimation of gas losses based on the character of the state of wells of Dashava Storage. *Eastern-European Journal of Enterprise Technologyologies*, 6/8(90): 25–32. DOI: 10.15587/1729-4061.2017.116806.

Olijnyk A.P, Steyer L.O, Klapouschak O.I., 2013. Mathematical modeling of filtration processes in problems of evaluation of level and quality of groundwaters. *Eastern-European Journal of Enterprise Technologies*, 1(4 (61): 15–18. DOI: 10.15587/1729-4061.2013.9142.

Silva E.J.G., Tirabassi T., Vilhena M.T., Buske D., 2013. A puff model using a three-dimensional analytical solution for the pollutant diffusion process. *Atmospheric Research*, 134: 131–136. DOI: 10.1016 / j.atmosres.2013.07.009.

Tymkiv D.F, Kostiv Y.V, Zayets V.O., 2016. Methodology for determining gas losses during the creation and operation of underground gas storage facilities. *Oil and Gas Energy*, 1(25): 49–57.

Zelinska H., Fedorovyc I., Andrusiv U., Chernova O., Kupalova H., 2020. Modeling of the Gas Transmission Reliability as a Component of Economic Security of the Ukrainian Gas Transmission System. *Machine Learning for Prediction of Emergent Economy Dynamics Proceedings of the Selected Papers of the Special Edition of the International Conference on Monitoring, Modeling & Management of Emergent Economy* (M3E2-MLPEED 2020), Odessa, Ukraine, Arnold Kiv (Ed.): 415–433. http://ceur-ws.org/Vol-2713/paper46.pdf.

Legislative acts and normative documents

Methods for determining the production and technological costs of natural gas for its production, transportation by main gas pipelines and operation of underground storage facilities. NAKAZ 23.06.2008. No. 340 <http://surl.li/bajlq>.

STP 320.30019801.020-2000. The standard of the enterprise of the provision on the organization of commissioning works on the equipment of compressor stations of the main gas pipelines which is put into operation. Approved and put into effect by order of 16.11.2000. No. 251 <http://surl.li/bajlv>.

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