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THE OPTIMIZATION OF OPERATING MODES OF TECHNOLOGICAL EQUIPMENT FOR UNDERGROUND GAS STORAGE

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Statement of the problem. The paper considers the process of regime adjustment of the gas preparation section of the Yelshansk underground gas storage. Instead of the obsolete gas preparation section, a new gas treatment complex was constructed and new equipment was commissioned. However, commissioning identified a number of unresolved problems requiring optimization.
Results. The issues arising in the operational mode were eliminated by means of introducing a new section of complex gas treatment. In order to improve the quality of the gas prepared for transportation, analytical and technical-economic comparison of different modes of operation of the fire regenerator was carried out.
Conclusions. Based on the results of the research, an optimal method of adjusting the technological mode of operation of the gas preparation section was set forth. It allows material and financial resources to be saved.

Keywords: underground gas storage, equipment, gas preparation, absorber, fire regenerator, fuel gas.

Introduction. The objective of designing underground gas storages is to increase the reliability of gas distribution system by controlling seasonal consumption of gas fuel by different categories of consumers [10, 13, 22, 24, 29].

There have been a lot of research attempts here and abroad at studying existing technologies of gas transportation preparation and optimization of storages in order to improve the quality and efficiency of fuel [2, 3, 11, 15, 23, 25, 27, 28, 30, etc.]. As research results suggest, disruptions of technological operation have a negative impact on gas-pumping aggregates, separation devices as they cause a 10 to 15 % reduction in their efficiency factor [5, 9, 17, 20].

Search for new ways of optimizing industrial safety maintenance costs as well as lower rates of faulty decision-making regarding the operation of all underground gas storages is crucial for economic efficiency of energy complexes [1, 4, 6—8, 14, 17—19, 21, 26, 31 и др.].

The Yelshano-Kyurdyumskoe underground gas storage is designed to control seasonal gas consumption in the depleted gas and oil field of the same name [12]. Since 1966 depleted fields of the Tula region and Bobrikovsk-Kyzelevsk complex have been operated as independent gas storages. The Yelshano-Kyurdyumskoe gas and oil field is located in the Leninskiy District of Saratov, Saratov and Tatischevskiy districts of Saratov region. Orographically the horizon lies in the right bank of the water reservoir of the Volga River. The surface of the area of the storage has a permanent bend from the South West to the North East. The relief of the area is quite scattered with significant differences at the absolute points (from 50 to 125 m).

One of the features of the operation of the storage is an extremely even distribution of the wells throughout the structure. The main causes are as follows: the roof of the field is occupied by gardens, in the South there are residential areas, in the West there are no collectors in the Bobrikovsk (main) region and the collectors of the Kyzelevsk region have low filtration and capacity characteristics and thus provide no high well flow rates. Therefore the operating wells are located in the eastern, south-eastern and north-western parts of the structure.

1. A brief history of the opening and operation of the Yelshano-Kurduymskiy field. The Yelshano-Kurdumskiy structure was discovered in 1940 as part of a geological survey. In 1941 seismic work was performed and welling got underway resulting in an industrial gas presence of Vereian horizons (an open fountain was opened). Following the 1941—1948 geological surveys gas deposits of the Vereian, Melekessk, Cheremshano-Prikamsk complex, gas and oil fields of the Tula horizon, the Bobrikovsk-Cherepetsk-Kyzelevsk complex. The gas presence of deposits of the Bobrikovsk, Kyzelovsky and Cherepetskiy horizons was identified in 1943 with the well № 12. As the well was being prepared to be examined, some washing-out liquid was resulted which resulted in an open fountain. The mine was surveyed and its contouring continued accompanied by its development into a field. Oil fringe was found in 1945, in 1946 oil started being mined from the oil fringe with gas extracted from a gas cap.

From then on exploration drilling began for contouring the oil fringe in parallel with exploration gas drilling. Exploration oil drilling finished in 1951. By that time the main well stock had been drilled. In 1949 in order to sustain the formational pressure in the gas cap, some of the gas well stopped being explored and in 1952 the exploration of the gas cap was completely cut short [12].

Originally the oil wells were operated as a fountain but gradually as the formational pressure dropped, bottomhole pumping was introduced. The gas cap of the Bobrikovskiy, Kyzelevsk and Cherepetsk horizons was developed by 19 wells, the oil fringe was operated by 67 wells. In order to sustain the formational pressure as well as consider the possibility of designing an underground gas storage in this field, in 1960 and 1961 there was a trial pumping of gas into the wells located within the gas cap. Since 1966 along with the oil mining gas had been routinely pumped followed by its section during the winter season [12].

The operation of the oil fringe continued up until 1985. As of now, in the Yelshano-Kurduymsk area more than four hundred well have been drilled for various purposes. The Yelshano-Kurduyskaya anticline was established as part of the expansive Yelshano-Kurduymsk raise and has a distinct representation in the landscape these days. The structure spans 12 km from North to East and 8 km from North to West. The raise amplitude in the Bobrikovsk, Kyzelovsk and Cherepetsk horizons is 100 m.

2. Lithological and stratigraphic characteristics of collecting rocks. In the Yeshano-Kurdyumsk underground gas storage there are two independent gas storages, i.e. depleted fields of the Bobrikovsk and Kyzelovks horizons which are significantly different in their lithology and petrophysical characteristics. One of the distinct features of designing a reservoir of the Bobrikovsk-Kyzelovsk field is its “two-storeyed” structure. The upper level is a terrigenous one (Bobrikovsk) and the lower one is a carbonate one (Kyzelovsk). The collecting layers of the Bobrikovsk horizon are mutually connected and the areas of the girth between the Bobrikovsk and Kyzelovks horizons is not consistent resulting in a “gap” between them. Therefore these fields can be considered as a single reservoir.

The Bobrikovsk horizon is represented with sand and clay rocks with the thickness from 2 to 13 m. The collectors are sandstone with the thickness of collectors varying from 0 to 9.3 m.

The fields of the *Kyzelovsk horizon* are represented with carbonate rocks with two distinct types of lithological and physical characteristics: the upper (productive) abd lower (unproductive) one with the total thickness from 7.3 to 20.0 m. The thickness of the productive pack ranges from 6.0 to 17.0 m.

The Tula horizon. The field of the horizon was introduced into gas mining in February, 1948. In 1958 the gas field of the Tula horizon was almost depleted and thus a decision was made to employ it as underground gas storage. The deposits of the Tula horizon are made up of clay containing sublayers of sandy stone and limestone. The total thickness of the Tula horizon ranges from 22 to 41 m.

3. Major technical and economic characteristics of the object. The industrial activities in the Yelshankiy underground gas storage involve continuous operation of technological gas-pumping equipment in an underground gas storage, its selection and transportation to consumers. The major parameters of the operation of the Yelshankiy underground gas storage in the horizons are given in Table 1.

Table 1

Characteristics of the operation of the underground gas storage in the horizons

Characteristics	Bobrikovsk-Kyzelovsk-Cherepetsk horizon	Tula horizon	Total
Total volume of gas, mln m^3, including active volume, mln m^3, buffer volume, mln m^3	4 979.2 2 710 2 269.2	534 300 234	5 513.2 3 010 2 503.2
Maximum daily productivity, mln m^3/day, of the finished gas, selected gas	21 24.72	3.4 7.2	24.4 31.92
Maximum formational pressure in the area of operational wells, MPa	10.47	8.41	10.47
Minimum formational pressure in the area of operational wells, MPa	3.78	2.0	3.78
Maximum gas pressure at the entrance of the CS (during selection), MPa	8.3	7.58	8.3
Minimum gas pressure at the entrance of the CS (during selection), MPa	1.8	1.996	1.996
Maximum gas pressure at the exit of the CS (during pumping), MPa	10.47		
Minimum gas pressure at the exit of the CS (during pumping), MPa	7.48		
Number of operational wells	129	21	150
Mode of operation of an enterprise	Twenty-four-hour		

4. Description of a technological process and technological schemes. Drying carbohydrate gases is an important part of preparing natural gas for transportation along the pipelines and to consumer [10, 13, 15]. The depth of drying is determined with particular industrial requirements.

In a technological process on a combined setup for gas drying and purification the absorption process using a diglycol solution was used. The absorption as part of a complex preparation of gas involves two phases, i.e. a liquid one (diglycol) and gas one (moist and gas) and the substance is converted from the gaseous into the liquid phase. Absorption is thus a type of mass transfer (mass exchange). The liquid phase consists of an absorber and absorbent. An absorber is a solution (a diglycol solution) of active components, i.e. diglycols taking part in a chemical reaction with an absorbent (gas). Absorption is cost-effective for preparing (drying and purification) of large natural gas flows. The use of liquid absorbents for drying gas compared to solid ones has the following advantages:

— possibility of drying gases that are included in substances that intoxicate solid absorbents;

— continuous process;

— simple automatic management system;

— drying of gas till a lower dew point.

During absorption of moist from gas the process will continue till partial pressure of absorbed moist in the gas reaches that over the liquid. The moist absorbed from it as a result of subsequent desorption taking place as an absorber is heated, the pressure in the system drops or blowout gas is supplied. Moisture is released from the solution and enters the gaseous stage as its equilibrium pressure is higher than that in the desorbed absorber (diglycol). Desorption is the most complex stage in a technological scheme of drying of gas that requires considerable amounts of energy.

A combination of absorption and desorption allows an absorber to be multiply used and release a pure absorbed component. For that after the absorber (saturated diglycol) a solution undergoes desorption where a component is extracted and the regenerated solution (a diglycol solution) free from the component returns for absorption into a mass-exchange device, i.e. an absorber. For such a scheme the solution circulates in the system as an "absorber-desorber-absorber" (in circle) with absorber not being used. There are some absorbent losses caused by a mechanical blow of the absorbent in the absorber by a gas flow and thermal decomposition on the surface in the regenerator with possible leaks in the system due to leakage of flanged joints and gland seals. Losses per a unit of time are immeasurably small compared to those in the solution circulating in the system.

As absorption takes place, there is mass exchange on the surface of phase contiguity (liquid — gas). Therefore absorption devices have a developed gas-liquid contact surface.

5. Collection of gas selected from underground gas storages. Collection of gas from the Tula and Bobrikovsk-Kyzelovsk horizons takes place according to the X-ray scheme in the following way. The gas coming to the bottom of an operating well under the effect of a pressure drop in the layer goes up the fountain pipes to the mouth of the well. From the wells gas comes into individual overlapping gas pipelines joining the mouths of the wells with the gas collection station through the mouth equipment, fountain reinforcement and pipeline binding.

In gas regulating station 1 gas comes along the overlapping gas pipelines from 28 wells, in gas regulating station 2 from 41 wells, in gas regulating station 3 from 60 wells, gas regulating station "Tula" from 22 wells.

In the input lines from each well there is:

— switching of the wells into the line of pipeline purging into a candle of manual multipurpose reinforcement;

— freeing of the system from gas into a candle of manual multipurpose reinforcement;

— instalment of gas regualting devices, gas consumption control, cutoff multipurpose reinforcement;

— switching of weach well into a separator for measuring gas consumption;

— reverse technological lines;

— dumping the liquid from the separators into the drainage vessel;

— purging of each overlapping pipeline and freeing of the technological system from gas.

In the gas regulating station gas comes into underground gas collectors for complex preparation and then along the input collectors it is transported into the gas collector from where it is distributed along four technological lines for gas distribution and separation and finally it is supplied to the technological lines to be cleaned and dried. Cleaned and dried according to the Gazprom Specifications 089-2010, it is supplied into the main gas pipelines.

For automatic maintenance of gas consumption in the technological line there are special devices and crane-controllers at the outlet.

6. Experimental operation. Issues. During experimental operation of the area for preparation of gas from the underground gas storage, a number of issues that affected the technological as well as economic aspects of the process were identified:

— failure of a fire glycol regenerator due to depressurization and deep failure of a thermosiphon owing to overheating. As a result, large-scale repairs of the fire regenerator had to annually take place;

— pollution and salinification of diethylene diglycol due to ineffective operation of separators of the first stage purification and diethylene diglycol filters. As a result, it was necessary that the diglycol system is completely replaced at least every other year;
— pollution of internal elements of absorbers, which resulted in the reduction of the efficiency of mass-exchange plates. As a result, this affected the performance of absorbers, which had a negative impact on the technological process;
— clogging of heat-exchange device pipes resulting in the reduction in the efficiency of heat exchange, higher consumption of fuel gas onto the fire glycol regenerator for specified parameters of glycol.

The combination of all of these contributed to an overall reduction in the efficiency of gas preparation, which had a negative effect on the specified parameters of the dew point temperature. Table 2 shows the overall data on economic costs for operating a gas preparation station.

Table 2

Overall data on economic costs for operating a gas preparation station

Type of work	Time of work, year^{-1}	Amount of completed work	Price of work, mln rub	Cost of work, mln rub
Large-scale repairs of a fire glycol regenerator	1	1	4.5	4.5
Steaming and checking of the absorbers	1	5	0.1	0.5
Repairs and checking of pumping equipment	1	5	0.3	1.5
Replacement of diethylene diglycol	0.5	1	2.6	1.3
Total	7.8			

As part of renovation of industrial gas structures, a new station for complex gas preparation was built. Two stages of gas separation (primary gas separators and gas separators with a washing section), complex purification of diethylene diglycol (coal filter, cartridge filter, magnetic processing tool), improved mass-exchange plates of absorbers and fire glycol regenerators allowed the specified temperature of the dew point to be reached while reducing operating costs of gas preparation stations.

During the precommissioning work it was shown that the entire volume of diethylene diglycol going through a pump came into the fire regenerator. As a result, even under a load of one absorber the fire regenerator regenerated 10 m^3/h of diethylene diglycol. This led to a high consumption of gas fuel. For the sake of optimization it was suggested that the consumption of diethylene diglycol was reduced and thus that of gas fuel for the fire regenerator.

7. Analytical comparison of the operating modes. For analytical comparison of the operating modes of a volume of gas fuel for a large and small consumption of diethylene diglycol let us calculate the consumption of gas fuel. The initial data for calculating the consumption of fuel gas for the fire regenerator for the consumption of DEG_{10} = 10 m^3/h and the amount of fuel gas necessary to regenerate 2 m^3/h of DEG, DEG_2 are given in Table 3.

Table 3

Initial calculation data

Value	Designation	Size	Values for DEG_{10}	Value of DEG_2
Initial consumption of the heated DEG	$G_{DEG}{}^{I}$	m^3/h	10	2
Temperature of the surrounding air	$t_{н.\ в.}$	^{0}C	−20	
Coefficient of the air consumption for the burner	α_m	—	1.02	
Heat capacity of saturated diethylene diglycol	C_{SDEG}	kJ / kg×K	2.85	
Temperature of SDEG at the vapour outlet	$t^{/}$	°C	135	
Temperature of the diethylene diglycol solution at the outlet of the vapour	$t^{//}$	°C	163	
Temperature of the escaping gases	$t_{ух}$	°C	420	

Let us calculate the heat productivity of the vapour, kWatt:

$$Q_П = G_{ДЭГ} \cdot C_{ДЭГ} \left(t^{//} - t^{/}\right) + G_В \cdot C_В \,, \tag{1}$$

where G_{DEG} is the consumption of the heated DEG; C_{SDEG} is the heat capacity of the SDEG; $t^{//}$ is the temperature of the diethylene diglycol solution at the outlet of the vapour; $t^{/}$ is the temperature of the SDEG at the inlet of the vapour; G_B is the consumption of the escaping gases; C_B is the heat capacity of the escaping gases.

In order to calculate the heat of fuel combustion a number of parameters has to be determined [16]. The volume of the air that is theoretically needed for complete combustion of 1 m^3 of fuel gas:

$$V_0 = 0.0476 \cdot \left[0.5 \cdot (H_2^{тл} + CO^{тл}) + 1.5 H_2S^{тл} + 2CH_4^{тл} + \sum\left(n + \frac{m}{4}\right) C_n H_m^{тл} - O_2^{тл}\right], \tag{2}$$

where H_2, CO, H_2S, CH_4 are volumetric proportions of fuel gas.

The volume of nitrogen that is theoretically necessary for complete combustion of 1 m^3 of fuel gas:

$$V_{N_2} = 0.79V_0 + 0.01N_2^{тл}. \quad (3)$$

The volume of carbon dioxide that is theoretically necessary for complete combustion of 1 m^3 of gas fuel:

$$V_{CO_2} = 0.01\left[H_2^{тл} + H_2S^{тл} + CH_4^{тл} + \sum nC_nH_m^{тл}\right]. \quad (4)$$

Then the volume of dry smoke gases in the combustion products during complete fuel combustion is given by the formula:

$$V_{СГ} = V_{N_2} + V_{CO_2} + (\alpha_m - 1)\cdot V_0. \quad (5)$$

The volume of water vapour is respectively:

$$V_{H_2O} = 0.01\left[H_2^{тл} + 2CH_4^{тл} + \sum \frac{m}{2}C_nH_m^{тл}\right] + 0.0161\alpha_m V_0, \quad (6)$$

where α_m is the coefficient of air consumption in the burner.

Therefore the total volume of smoke gases is given by the formula:

$$V_Г = V_{сг} + V_{H_2O}. \quad (7)$$

For calculating the amount of heat released during the fuel combustion we calculate the lowest heat of fuel combustion using the formula:

$$Q_н^р = 0.01\sum C_i^{тл} Q_{н_i}^р, \quad (8)$$

where $C_i^{тл}$ is the specific heat capacity of the fuel; $Q_{н_i}^р$ is the specific heat of the fuel combustion.

Along with that the physical heat introduced with the fuel is

$$Q_{ТЛ} = \left(c_{CH_4}\right)\cdot t_{тл}, \quad (9)$$

where c_{CH_4} is the specific heat capacity of methane; $t_{тл}$ is the temperature of the fuel gas (15 °C).

The physical heat introduced with the air is

$$Q_{в.вн.} = \alpha_m V_0 i_в, \quad (10)$$

where $i_в$ is the enthalpy of the atmospheric air.

Therefore the available amount of heat of the fuel combustion is

$$Q_р^р = Q_н^р + Q_{тл} + Q_{в.вн.}. \quad (11)$$

The adiabatic temperature of the fuel combustion determined using the method of sequential approximations:

$$t_a = \frac{Q_p^p}{V_{N_2}C_{N_2} + V_{CO_2}C_{CO_2} + V_{H_2O}C_{H_2O} + V_{H_2}C_{N_2} + (\alpha_m - 1)V_0 C_в}. \quad (12)$$

The enthalpy of smoke gases at the outlet of the vapour is given by the formula:

$$i_{ух} = V_{N_2}J_{N_2} + V_{CO_2}J_{CO_2} + V_{H_2O}J_{H_2O} + (\alpha_m - 1)V_0 J_в, \quad (13)$$

where $J_{N_2}, J_{CO_2}, J_{H_2O}, J_в$ are specific enthalpies of the elements included in the escaping gas and air necessary for complete combustion of 1 m^3 of fuel gas respectively.

The thermal coefficient of the efficiency of the vapour is

$$\eta = \left(1 - \frac{i_{ух}}{Q_p^p}\right)\phi_\Sigma, \quad (14)$$

where ϕ_Σ is the coefficient of the efficiency of the vapour.

The heat capacity of the smoke gas in the temperature range ($t_a - t_{yx}$) is

$$c_p = \frac{Q_p^p - i_{ух}}{t_a - t_{ух}}. \quad (15)$$

The consumption of fuel gas considering the above formulas and calculations is

$$B = \frac{Q_п + (c_{ух} \cdot V_Г)}{Q_p^p \cdot \eta} \quad (16)$$

The results of the calculations are summarized in Table 4.

Table 4

Results of the comparative calculation

Value	Designation	Size	Values for DEG$_{10}$	Value for DEG$_2$
Effective heat productivity of the vapour	$Q_П$	kWatt	937.96	335.56
Theoretical volume of the air necessary for complete combustion of 1 m^3 of fuel gas	V_0	m^3/m^3	9.52	
Volume of nitrogen theoretically necessary for complete combustion of 1 m^3 of fuel gas	V_{N_2}	m^3/m^3	7.52	
Volume of carbon dioxide theoretically necessary for complete combustion of 1 m^3 of fuel gas	V_{CO_2}	m^3/m^3	1	
Volume of dry smoke gas in the combustion products of fuel	$V_{СГ}$	m^3/m^3	8.71	

End of Table 4

Value	Designation	Size	Values for DEG_{10}	Value for DEG_2
Volume of water vapour	V_{H_2O}	m^3/m^3	1.15	
Total volume of smoke gases	$V_Г$	m^3/m^3	9.86	
Lowest heat of fuel gas combustion	$Q_н^р$	MJ/m^3	39.82	
Physical heat introduced with fuel gas	$Q_{ТЛ}$	MJ/m^3	0.033	
Physical heat introduced with the air	$Q_{в.вн.}$	MJ/m^3	−0.25	
Available heat of fuel combustion	$Q_р^р$	MJ/m^3	39.6	
Adiabatic temperature of fuel combustion	t_a	$°C/m^3$	1950	
Enthalpy of smoke gases at the outlet of the vapour	$i_{ух}$	kJ/m^3	8994	
Thermal coefficient of the efficiency of the vapour	η		0.734	
Thermal capacity of smoke gases	c_p	$kJ/m^3 \times K$	20	
Fuel gas consumption	B	m^3	0.0402	0.0183

Therefore for regenerating 10 m^3/h of DEG 144ю72 m^3/h of fuel gas is required and for regenerating 2 m^3/h of DEG 65ю88 m^3/h of fuel gas is required.

8. Technical and economic calculation. In order to determine the costs for regenerating glycol it is necessary to calculate what time (hours per year during a season) the fire regenerator operates, h/year:

$$r_{общ} = z_{от.пер.} \times 24 = 4344,$$

where $z_{от.пер}$ is the number of days of the heating season.

Then the total fuel gas consumption for regeneration of 2 m^3/h of DEG during a heating season is, m^3/year:

$$B^2{}_{год} = B_2 \times r_{общ} = 286183,$$

where B_2 is the consumption of fuel gas per second that is necessary for the regeneration of 2 m^2/h of DEG; $r_{общ}$ is the number of hours of the heating season.

Let us calculate the consumption of the fuel gas supplied into a flame tube for regenerating 2 m^3/h of DEG, thousand rub/year:

$$И_T^2 = B_{год}^2 \times Ц_T = 396.8,$$

where $B_{год}^2$ is the total fuel gas consumption for regenerating 2 m^3/h of DEG; $Ц_T$ is the cost of the fuel gas (1.386 thousand rub/1000 m^3).

The total fuel gas consumption for regenerating 10 m^3/h of DEG for the heating season is, m^3/year:

$$B_{год}^{10} = B_{10} \times 3600 \times r_{общ} = 628664,$$

where B_{10} is the consumption of fuel gas necessary for regenerating 10 m^3/h of DEG.

The costs of the fuel gas supplied into the flame tube for the combustion for regenerating 2 m^3/h of DEG is, thousand rub/year:

$$И_T^{10} = B_{год}^{10} \times Ц_T = 871.643,$$

where $B_{год}^{10}$ is the total consumption of the fuel gas for regenerating 10 m^3/h of DEG.

Therefore the saved regeneration costs are, thousand rub/year:

$$\Delta И = И_T^{10} - И_T^{2} = 474.843.$$

Conclusions

1. An analytical analysis of the operation of the fire glycol regenerator for different operation modes (during loading of all the absorbers and of one absorber). The calculations of the economic efficiency showed that the reduction in the consumption of diethylene diglycol for regeneration allows around 470.000 rubles per collection season to be saved.

2. This operation mode can be achieved in two ways: by installing a by-pass line at the inlet pump and frequency controller at the inlet pump. The use of the first option would allow one to reduce the consumption of diethylene diglycol required for regeneration and the use of the second one, apart from reducing the consumption of diethylene diglycol, would provide a longer life cycle of the pump and trouble-free life.

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