ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
Tome XIII [2015] – Fascicule 3 [August]
ISSN: 1584-2673 [CD-Rom; online]
a free-access multidisciplinary publication of the Faculty of Engineering Hunedoara

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OPTIMIZATION OF ENERGY COSTS FOR GAS TRANSPORTATION IN COMPLEX GAS TRANSMISSION SYSTEMS

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Abstract: In this paper the process of gas movement is modeled in the section of the gas transmission system which consists of two branches of the gas main and underground gas storage with its booster compressor station. At the ends of these branches there are three compressor stations. Under the given conditions for the values of pressure and gas volumes at the inlet and the outlet of the system, the dependence of the fuel gas total consumption on coefficients of gas compressibility at the compressor station and on the place of connection of the underground gas storage to the gas main is studied at each compressor station. A method is suggested to determine such operational parameters of the system for which the total amount of fuel gas will be minimal in the case of the satisfaction of the imposed boundary conditions.
Keywords: gas transmission system, gas movement modelling, booster compressor station

1. INTRODUCTION

Underground gas storages (UGS) are used to eliminate the imbalance in the gas transmission system (GTS) in autumn and winter [2-4]. UGS operating is characterized by both the periodicity and the unevenness of processes of gas injection and its withdrawing. Such UGS operating complicates the mathematical model of its functioning in general. In the literature, there are a significant number of works concerning mathematical modeling of individual technological objects (pipes, valves, etc.) as the linear part of the GTS as well as UGS (beds of underground storages, drilling zones, and borehole walls, etc.) [1-8]. The regimes of individual underground gas storage facilities as well as their operating as a part of the gas transmission system are studied less thoroughly. However, in the total, the operating of underground gas storages depends on the gas transportation along the whole GTS. In this regard, there is a need for a detailed study and modeling of joint work of the underground gas storage and the gas transmission system. The movement of gas in the UGS bed should be modeled in non-steady regime, while the process of gas moving in other technological objects of UGS (wells, trails, etc.) is described by stationary models with adequacy sufficient for practice. As for the gas flow in gas mains (GM), it makes sense to study the non-stationary regime of gas movement not within the whole GTS, but in its part where the flow disturbances occur. This choice is due to the fact that non-stationary process quickly damps due to the properties of gas, especially due to its compressibility. The flow disturbance rarely vanishes (emergencies, the necessity to change the volumetric consumptions, etc.). During its main time, the GTS is operating in steady state.

2. THE AIM AND OBJECT OF THE STUDY

The aimof this work is to develop a mathematical model of joint operating of the underground gas storage and the gas transmission system to study the effect of the ways of connection of the UGS to GM on energy costs of gas transportation with taking into account hydraulic linking of the system UGS bed-MG.

Object of the studyis a mathematical model of gas movement process in a system which consists of the part of GM (Fig. 1) where there are three compressor stations (CS) connected with the I and II pipelines and underground gas storage with its booster CS. The mathematical model of this system is formed of models of technological objects that at the splice points are in compliance with the basis of the relevant laws of physics [1, 2]. Note that the boundary conditions of the corresponding problems of mathematical physics are based on measured data or under conditions of conjugation.

2.1. Outputrelations

1. The equation of the gas filtration process in a complex porous medium has the form [2-4]

$$\frac{\partial}{\partial x}\left(\frac{kh}{\mu z}\frac{\partial p^2}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{kh}{\mu z}\frac{\partial p^2}{\partial y}\right)=2mh\left(\frac{\partial}{\partial t}\left(\frac{p}{z}\right)+2qp_{am}\right), \qquad (1)$$

where k, m, h are the coefficients of permeability, porosity, the effective gas saturation of the bulk of the bed; p is the pressure at the point of the bed with coordinates (x, y) at the instant of time t; μ, z are the coefficients of dynamic viscosity and compressibility of gas, respectively; q the density of the gas withdrawing.

The solution of Eq. (1) under certain naturally specified conditions is presented in [2, 4].

2. Gas filtration in the medium in the case of violation of the Darcy's law (drilling well) is modeled according to a spherical law of gas inflow, which is described by Eq. [2]

$$\frac{\partial P}{\partial r} = -\frac{\mu}{\kappa} v + \beta^* \rho |v|^2, \qquad (2)$$

where $1/\beta^*$ is the coefficient of macro-roughness, v and ρ are filtration rate and gas density.

The solution of Eq. (2) is given in [4].

3. The gas movement in a pipeline under unsteady non-isothermal regime is described by the interrelated system of differential equations in partial derivatives

$$\begin{aligned} &\frac{\partial(\rho v)}{\partial t} + \frac{\partial}{\partial x}\left(p + \rho v^2\right) = -\rho\left(\frac{\lambda v|v|}{2D} + g\frac{ds}{dx}\right), \\ &\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0, \\ &\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x}\rho v\left(E + \frac{p}{\rho}\right) = \frac{4\alpha(T_{гр} - T)}{D} - \rho v g\frac{ds}{dx}, \end{aligned} \qquad (3)$$

where α is the coefficient of heat transfer between the pipe and the soil; $T_{гр}$ is the temperature of the soil; s is the curve that describes the relief of the pipeline route; $E = i - P/\rho + v^2/2$ is the total energy of the gas mass unit [1, 5-8].

The third equation in the system (3) defines the balance of the gas thermal energy. It is known [1] that with the lapse of time, the temperature field around the pipeline is determined quickly enough. Assuming that the temperature of the gas in the pipeline does not depend on time, the system (3) breaks up into the interrelated system of two equations and the equation describing the temperature distribution along the pipeline [1, 3]. Note that this approach allows us to solve a number of practically important problems.

4. The work of a compressor station depends on its capacity which is calculated according to the formula [1, 2, 5] $N = \xi z R Q T_1\left(\varepsilon^{\vartheta/\eta_{пол}} - 1\right)/\vartheta$. Here Q is the gas consumption of CS (m³/24h), $\vartheta = \left(1 - \lg(T_2/T_1)/\lg\varepsilon\right)^{-1}$ is the polytropic index, $\varepsilon = p_2/p_1$ the coefficient of gas compression, p_1 is the gas pressure at the inlet of CS, p_2 the gas pressure at the outlet of CS, T_1 is the gas temperature at the inlet of CS, T_2 is the gas temperature at the outlet of CS, $\eta_{пол} = (\vartheta(\gamma - 1))/(\gamma(\vartheta - 1))$ is polytropic performance efficiency, γ is the indicator of adiabatic process, ξ is the dimensional coefficient.

5. The drop of pressure at local resistances is determined according to the formula [1, 2] $\Delta p = \rho v^2 \xi/2$, ξ is the the coefficient of local resistance. For closure of the system of equations, let us use the equation of gas law $p = \rho z R T$ (R is the gas characteristic). Other parameters of the calculation (coefficients of gas compressibility and hydraulic resistance, Reynolds' numbers) are determined according to formulae known in the literature [1, 2]. In particular, changes in gas temperature along the pipeline in the isothermal case is as follows

$$T(x) = T_{01} + T_{02}e^{-ax}. \qquad (4)$$

Here

$$T_{00} = \frac{1}{aL}\left(\Delta p\left(D_i - \frac{1}{C_p \rho_0}\right) + \frac{g\Delta s}{C_p}\right),$$

$$T_{01} = T_г - T_{00}, \quad T_{02} = T_0 - T_г + T_{00}, \quad \Delta p = p_0 - p_k; \quad a = \frac{\alpha_{gr}\pi D}{C_p M},$$

T_0 is the gas temperature at the inlet of the pipeline; $T_г$ is the temperature of the soil; D_i is the Joule-Lenz'scoefficient; p_0 is the gas pressure at the inlet of the pipeline; p_k is the gas pressure at the outlet of the pipeline; ρ_0 is the density of gas under standard conditions (p_{st} = 0,1033 MPa, T_A = 293 K); x is the moving coordinate $x \in [0, L]$, L is the length of the pipeline; D is the internal diameter of the pipeline; α_{gr} is the coefficient of heat transfer between gas and the soil; C_p is the specific heat of gas at constant pressure. In the formula (4), there is taken into account the effect of Joule-Lenz and the temperature change due to friction.

2.2. Formulation of the problem

Having formulated mathematical model of the system, to calculate the values of the geometrical and regime parameters of its work, for which the minimum amount of fuel gas consumption is.

2.3. The input data

The input data are: the pressure p_{11} and volumetric gas consumption Q_1 at the inlet of the I-st CS; the pressure p_{33} and volumetric gas consumption $Q = Q_1 + Q_2$ at the outlet of the III-d CS; Q_2 is the volume of gas that comes from underground storage and the average pressure of the bed p_n.

3. SOLUTION PROBLEM

We consider two ways to attach UGS to the system. The first one is at the outlet of CS_2 (Fig. 1); The second one is at the inlet of CS_2 at arbitrary point between CS_1 and CS_2 (Fig. 2).

Let us introduce the notation

$$\Theta_1(T_1) = \frac{0.02064}{1.16\eta_{emy}Q_n}\left[\frac{3}{4} + 0.025\frac{p_a}{1.033K_3}\sqrt{\frac{T_1}{288}}\right], \quad \Theta_2(T_1) = \xi\frac{zR}{m}T_1,$$

$$\eta = \vartheta/\eta_{пол}, \quad \Theta_3(T_1) = \Theta_1\Theta_2, \quad \Theta_4(T_1) = \lambda z\frac{RT_1L}{D}\left(\frac{\rho_0}{S}\right)^2 .$$

Parametres Θ_i ($i = 1,2,3$) and η are related to CS, while Θ_4 is related to the linear section between two neighbour CS, K_3 is the coefficient that characterizes the workload of the CS.

The correlations above make it possible to calculate the amount of fuel gas needed to maintain the input and output parameters of the system. If $q_{ni} = \theta_{3i}(T_{si})\left(\varepsilon_i^{\eta} - 1\right)Q_i$ is the value of fuel gas for the i-th CS [2], then the total amount of fuel gas for four CS is the sum of

$$q = q_{n1} + q_{n2} + q_{n3} + q_{n4} .$$

1. Consider the option when from underground storage facilities gas comes into the gas main at the outlet of the second CS (Fig. 1, Problem 1).

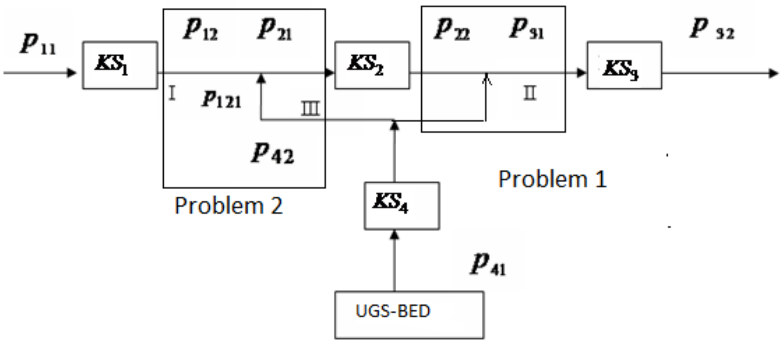

Figure 1. Diagram for calculation of the value of fuel gas for various kinds of connection of UGS to GM.

Using the distributions of gas pressure in technological objects included in the calculation scheme (Fig. 1), for the determination of the fuel gas value we obtain the formula

$$q = \theta_{31}Q_1\varepsilon_1^{\eta_1} + \theta_{32}Q_1\varepsilon_1^{\eta_2} +$$

$$+\theta_{33}(Q_1+Q_2)\left(\frac{p_{32}^2}{\varepsilon_1^2\varepsilon_2^2p_{11}^2 - \varepsilon_2^2\theta_{41}(T_1)Q_1^2 - \theta_{42}(T_2)Q^2}\right)^{\eta_3/2} + +\theta_{34}Q_2\left(\frac{\varepsilon_1^2\varepsilon_2^2p_{11}^2 - \varepsilon_2^2Q_1^2\theta_{41}(T_1)}{p_n^2 - AQ_2 - B_1Q_2^2}\right)^{\eta_4/2} - \theta .$$

Here

$$\theta = \theta_{31}Q_1 + \theta_{32}Q_1 + \theta_{33}(Q_1+Q_2) + \theta_{34}Q_2, \quad A = \frac{A_1}{k_{pl}} + \frac{A_2}{k_v}, \quad B_1 = \frac{B_{11}}{k_{pl}^{3/2}} + \frac{B_{22}}{k_v^{3/2}} + B_{33} + B_{44}, \quad A_1 = \frac{1}{h\pi}\mu p_s \ \ln\frac{R_k}{R_c},$$

$$A_2 = \frac{\mu p_s}{\pi h_x}\ \ln\frac{2R_ch}{2r_kl_kn_0h_x + \Theta(n_0)\left(r_1^2 - r_2^2\right)}, \quad B_{11} = 12\cdot10^{-5}\frac{\rho_0p_sd^2}{2\pi^2h^2m}\left(\frac{1}{R_c} - \frac{1}{R_k}\right),$$

$$B_{22} = \frac{\rho_0p_sd^2}{\pi^2h_xm}\left(\frac{1}{2r_kl_kn_0h_x + \Theta(n_0)\left(r_1^2 - r_2^2\right)} - \frac{1}{2R_ch}\right), \quad B_{33} = \lambda z\frac{RT}{D}\left(\frac{\rho_0}{S}\right)^2\frac{1-e^{-b}}{b}L_{sv},$$

$$B_{44} = \lambda_{sh}\, z_{sh} \frac{gRT}{D_{sh}} \left(\frac{\rho_0}{S_{sh}} \right)^2 L_{sh}\,,\ S = \frac{\pi D^2}{4}\,,\quad b = \frac{2gL_{sv}}{zRT}\,,\ \lambda = \left(\frac{Y + U + C^{1.5}}{1 + 76C} \right)^{0.2},\ U = \frac{k_{ш}}{D}\,,$$

$$Y = \frac{79}{\mathrm{Re}}\,,\ C = (2Y)^{10},\ \mathrm{Re} = \frac{D\,v\,p}{\mu_0\,RT} \frac{T + C}{273 + C} \left(\frac{273}{T} \right)^{3/2},\ z = \frac{1}{1 + fp_a},$$

where [2,4] k_{pl}, k_v are the coefficients of permeability of the bed and drilling zone, respectively; R_k is the radius of the surface of the well supply cylinder; R_c is the radius of the surface of the drilling zone cylinder; p_s, q_0, ρ_0 are the values of pressure, well yield and gas density under normal (standard) conditions; d is the diameter of grains of rock; h is the average seam thickness; h_x is the seam thickness in the zone of borehole; r_1, r_2 are radii of boring casing (inner) and collars (outer), respectively; r_k, l_k are the radius and the length of the perforation; n_0 is the density of perforation $f = \left(24 - 0.21 t^\circ C\right) \cdot 10^{-4}$, $p_a = p_a(x)$ is measured in the atmospheres, the index sh is related to trails, while sv is related to development boreholes of wells.

2. Now let gas from the underground storage comes into the main pipeline at arbitrary point between the first and the second compressor stations (Fig. 1, Problem 2). then

$$q = \theta_{31} Q_1 \varepsilon_1^{\eta_1} + \theta_{32} (Q_1 + Q_2) \varepsilon_2^{\eta_2} + \theta_{33} (Q_1 + Q_2) \varepsilon_3^{\eta_3} + \theta_{34} Q_2 \varepsilon_4^{\eta_4} - \theta_{v2}\,.$$

In the last equality

$$\theta_{v2} = \theta_{31} Q_1 + \theta_{32} (Q_1 + Q_2) + \theta_{33} (Q_1 + Q_2) + \theta_{34} Q_2\,.$$

For the given system we obtain the following formula for calculating fuel gas

$$q = \theta_{31} Q_1 \varepsilon_1^{\eta_1} + \theta_{32} (Q_1 + Q_2) \varepsilon_2^{\eta_2} +$$

$$+\theta_{33} (Q_1 + Q_2) \left(\frac{p_{32}^2}{\varepsilon_1^2 \varepsilon_2^2 p_{11}^2 - \varepsilon_2^2 \theta_{4121}(T_{121}) Q_1^2 - \varepsilon_2^2 \theta_{4122}(T_{122}) Q^2 - \theta_{422}(T_{22}) Q^2} \right)^{\eta_3/2} +$$

$$+\theta_{34} Q_2 \left(\frac{\varepsilon_1^2 p_{11}^2 - Q_1^2 \theta_{4121}(T_{121})}{p_n^2 - A Q_2 - B_1 Q_2^2} \right)^{\eta_4/2} - \theta_{v2}\,.$$

Process control parameters of the gas movement in the system of GM under study are the coefficients of gas compression at the first and second compressor stations, i.e. the total amount of fuel gas q is a function of the arguments ε_1 and ε_2 ($q = f(\varepsilon_1, \varepsilon_2)$). Obtained functional dependences of the fuel gas on ε_1 and on ε_2 allow us to find the global minimum with respect to these parameters and, therefore, to investigate the effect of kinds of connections of UGS to GM on total energy costs. Extrema points are found from the system of equations

$$\frac{\partial q}{\partial \varepsilon_1} = \frac{\partial f(\varepsilon_1, \varepsilon_2)}{\partial \varepsilon_1} = 0\,,\quad \frac{\partial q}{\partial \varepsilon_2} = \frac{\partial f(\varepsilon_1, \varepsilon_2)}{\partial \varepsilon_2} = 0\,.$$

For the obtained extrema points ε_{1m} and ε_{2m} we obtain the global minimum of the function $f(\varepsilon_1, \varepsilon_2)$ which determines the minimum value of fuel gas in the subsystem.

4. COMPUTATIONAL EXPERIMENT

Computational experimenthas been conducted for horizontally placed GM for the foolowing input data: pressure at the inlet and outlet of the system p_{11}=55 atm and p_{32}=65 atm respectively, the input volumetric gas consumption Q_1=900 m^3/s and volumetric gas consumption from the storage Q_2=180 m^3/s, the length of the pipeline L_1=90000 m and L_2=100000 m, Ø=1.338 m. Other parameters: p_n=50, A=1.02, B_1=0.008, ε_1=1.21, ε_2=1.22, η_{emy1}=0.84, η_{emy2}=0.85, η_{emy3}=0.85, η_{emy4}=0.82, k_1=1.31, k_2=1.32, k_3=1.3, k_4=1.31. The computational experiment was conducted to confirm the theoretical results obtained and the availability of the existence of a global extremum.

The compliance of the curves with different values of the coefficients of compression at the third and the fourth CS are presented in Table 1.

The results of calculations are presented in the form of graphs, where the x-axis represents the values of functions that correspond to:

» a is the total amount of fuel gas in the case of UGS connection to the inlet of the second CS;
» b is the total amount of fuel gas in the case of UGS connection to the outlet of the second CS.

Table 1.

No of curves	ε_1	ε_4
1	1.01	1.151
2	1.19	1.378
3	1.25	1.454
4	1.31	1.529
5	1.39	1.629

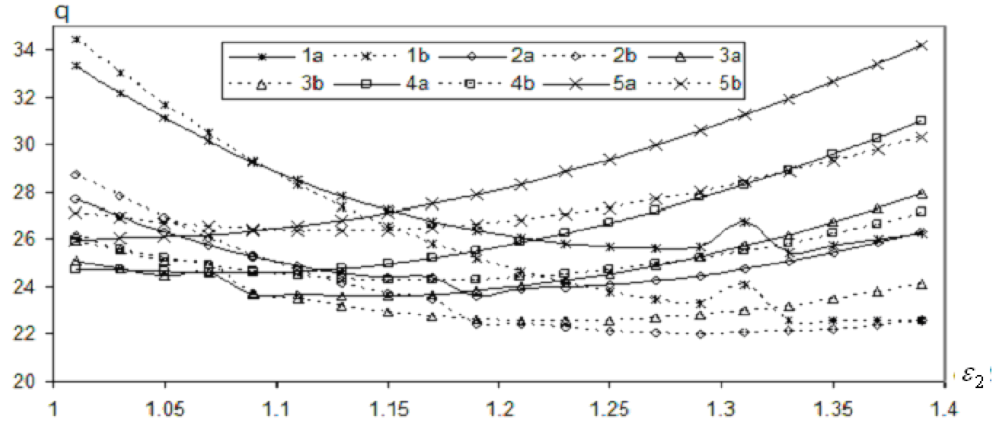

Figure 2. Dependence of the total fuel gas value q on the coefficient of compression ε_2 at CS_2 for various ways of connection of UGS to GM: to the inlet of CS_2 (with index a) and to the outlet (with index b).

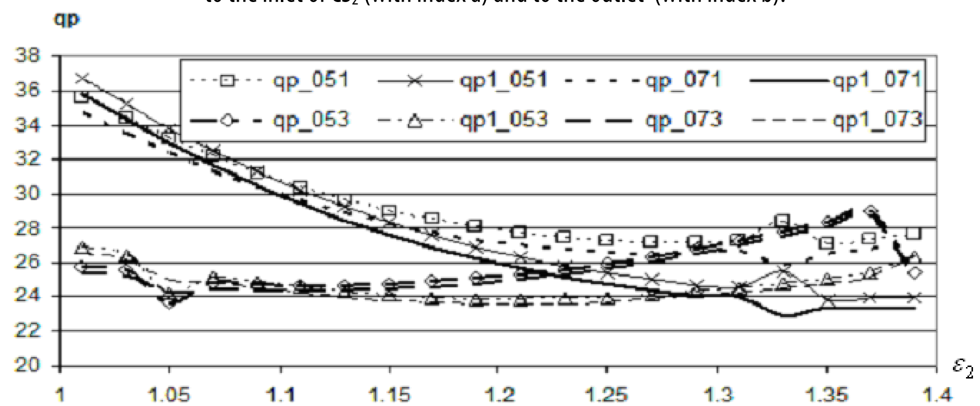

Figure 3. Dependence of the total fuel gas value on the coefficient of compression at CS_2 ε_2, when UGS is connected to MG in the middle between CS_1 and CS_2 (qp_05i) and at a distance of 63 km from KC_1 (qp_07i).

In Fig. 3, the last digit 1 in the notation of the curves corresponds to ε_1 =1,01, ε_4 =1,151, and the digit 3 to ε_1 =1,25, ε_4 =1,45.

5. CONCLUSIONS

In all the cases, there exist such corrrelations among the coefficients of compression at CS that the satisfaction of the given boundary conditions need a minimal amount of fuel gas for both kinds of UGS connection (Fig. 1).

In each case, there exist such values $\varepsilon_{i0}, i = 1,2,3,4,$ for which the amount of fuel gas does not depend on the connection of UGS (curves of total amount of fuel gas for various kinds of connections of UGS to GM have points of ntersection).

The place of joint between UGS and GM affects not only the value of total amount of fuel gas, but also the type of its dependence on the coefficients of compression at CS.

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