GEOECOLOGICAL RISK MANAGEMENT BY OPTIMIZING THE COMPRESSOR PLANT OPERATION AT THE NATURAL GAS MAIN PIPELINES

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The approaches for optimizing the ecological risk management in the impact areas of compressor stations of natural gas main pipelines are considered based on the minimization of energy consumption. The relevant mathematical models for the given optimization task are suggested. As a pilot project the main pipeline “Central Asia – Center” is selected aimed the increasing gas transport and reconstruction. The emission optimization calculation and critical loads for emitted pollutants on the impacted ecosystems are carried out. The economical speculations are suggested to include the preventive ecological damage.

Due to the works carried out under Gazprom’s “Gas transportation” program in 2005 the economy of fuel-energy resources amounted to 2720,5 mln m3 of natural gas, 385,1 mln KWh of electric power and 260,1 thou heat energy. Nevertheless, gas emissions into the atmosphere at gas-turbine units (GTU) or gas-processing plants (GPP) of Gazprom’s gas transmission system are currently estimated at: nitric oxide – 140 thou t/y, carbon monoxide – 210 thou t/y and carbonic dioxide – 81.5 mln t/y. An average weighted concentration of pollutants is as follows: nitric oxide – around 180 mg/m^3 and carbon monoxide – 250 mg/m^3 [1]. It is clear that the emissions of such pollutants are accompanied by environmental impact and geoecological risks.

Geoecological risk management when operating compressor stations as elements of the gas transmission system assumes the development of programs on control and reduction of pollutant emissions. The main trends for reducing NO_x, CO, CH_4 and CO_2 emissions include:

- Development and introduction of new types of low-emission GTU;
- Upgrading of GPP combustion chambers;
- Investigation of operation factor influence;
- Investigation of the processes of emission dispersal and transformation;
- Monitoring of emissions and the atmosphere condition;
- Development of catalytic combustion chambers (NO_x emission is less than 10 mg/m^3).

In recent years Gazprom has accomplished a complex of investigations on reducing pollutant emissions during compressor station operation. On average this research has resulted in 1.8-fold reduction of harmful emission volumes. The greatest success in the reduction of pollutant emissions has been reached thanks to upgrading around 670 gas-turbine units having the highest emission (GTK-10, GT-750-6), with NOx emission having been reduced to 160 thou t/y. By 2007, a level of NOx emissions at compressor stations of the Russian gas transmission system is planned to decrease by 4.5 times as compared with 1992.

The introduction of new low-emission technologies at gas transmission systems is the most important tool of geoecological risk management, especially in regions where the environmental impact has reached its critical level.

In the foreseeable future the problem of CO_2 emission reduction will be solved by increasing GTU efficiency, as well as by optimizing process parameters of the gas transmission system. CO emission will be reduced in the same way. Methane losses as a main component of natural gas take place firstly as a result of leakage and accidents.

Therefore, the reduction of the most harmful gases in the process of gas transportation (NOx, CO and sulfur, the latter in the presence of H_2S in natural gas (the Astrakhan and Orenburg gas fields)) and the decrease in environmental impact and thus in geoecological risks take place under power inputs decrease.

Let us consider mathematical models and algorithms allowing minimization of power inputs on a gas pipeline section with several compressor stations under the condition of their full loading.

The basic procedure of calculation of compressor operating conditions is the use of its compression ratio characteristic $\varepsilon(Q,\tilde{n})$, polytropic efficiency $\eta_{pol}(Q,\tilde{n})$ and internal effective power $N_i(Q,\tilde{n})$, which establish empiric dependence between the above parameters of the compressor, its volumetric capacity and shaft speed.

In accordance with the ONTP 51-1-85 (the All-Union norms of process engineering) [2], the use of polynomials of the third power approximating characteristics of volumetric reduced to rated output is regulated for these purposes:

Compression ratio:

$$\varepsilon = a_\varepsilon + b_\varepsilon \cdot q_{re} + c_\varepsilon \cdot q_{re}^2 + d_\varepsilon \cdot q_{re}^3 \tag{1}$$

Polytropic efficiency:

$$\eta_{pol} = a_\eta + b_\eta \cdot q_{re} + c_\eta \cdot q_{re}^2 + d_\eta \cdot q_{re}^3 \tag{2}$$

Relative internal power

$$N_{re} = a_N + b_N \cdot q_{re} + c_N \cdot q_{re}^2 + d_N \cdot q_{re}^3 \qquad (3)$$

where: a, b, c, d - coefficients of approximation of appropriate reduced characteristic, and q$_{re}$- volumetric reduced rate:

$$q_{re} = Q_{vol} \frac{1}{\tilde{n}} \qquad (4)$$

where: Q_{vol} - volumetric reduced rate at compressor input $[m^3/\min]$ or $[m^3/\sec]$; $\tilde{n}$ - relative revolution; $(\tilde{n} = \frac{n}{n_n})$

$$q_{rc} = q_{rc}^0 \left(0,75 \cdot \frac{N}{N_n} + 0,25 \cdot \sqrt{\frac{T_{air}}{T_{nair}} \cdot \frac{p_{air}}{p_{nair}}} \right) \cdot K_{rc} \cdot K_{\widehat{n}} \qquad (5)$$

where: $q_{rc}^0 = \frac{3,6 \cdot N_n}{\eta_n \cdot H_{aux}^*}$ - rated consumption of fuel gas $[ths.m^3/hr]$; N_n - rated power $[kW]$; η_n - GTU nominal efficiency; H_{aux}^* - nominal specific volumetric low heat value (taken as 34500 kJ$/m^3$); T_{air} - specified temperature of atmospheric air $[{}^0K]$; T_{nair} - nominal air temperature $[{}^0K]$; p_{nair}- design pressure of air $[mP]$; p_{nair} - nominal pressure of air $[mP]$; K_{rc} - operating efficiency; $K_{\widehat{n}}$ is usually considered in K_{rc}.

Fuel gas consumption for a design period is calculated with the following formula [3-5]:

$$Q_{rc}^{\tau} = q_{rc} \cdot \tau \cdot 10^{-3} \qquad (6)$$

where τ - time of design period.

Initial data for this subsystem will be characteristics that are necessary for calculating active elements (compressor stations) and passive elements (linear pipeline portions).

For one-valuedness of problem definition it is necessary also to set boundary conditions. For a chain-type corridor these conditions are input gas pressure and consumption.

The problem includes the formation of optimal management (operating conditions of all the compressor stations of the subsystem) to minimize expenses on gas pumping, i.e. minimization of a total gas cost consumed by gas-turbine units and electric power consumed by motor-driven units.

Let us consider a schematic design diagram of a gas main illustrated in Fig. 1.

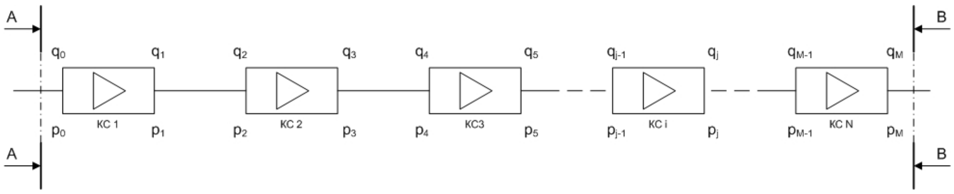

*Figure 1. S*chematic design diagram of *gas pipeline*

The boundary conditions of the illustrated gas pipeline are p_0, p_M, q_0. Additive target function for the considered diagram is as follows:

$$\begin{aligned}&\Phi = \varphi_1\left(p_0,\vec{u}_1\right)+\varphi_2\left(p_1,\vec{u}_2\right)+\ldots\\&\ldots+\varphi_i\left(p_{j-1},\vec{u}_i\right)+\ldots+\varphi_N\left(p_{M-1},\vec{u}_N\right)\end{aligned} \tag{7}$$

Command vector $\vec{u}_i$ и CS input condition p_{j-1} unambiguously define a final condition p_j. And vice versa, conditions p_{j-1} and p_j allow to find the command vector $\vec{u}_i$, though not necessarily unambiguously. Assume that for fixed p_{j-1} and p_j we can find such a command vector $\vec{u}_i$, at which the target function could be minimal

$$g_i\left(p_{j-1},p_j\right)=\min_{p_j=p_j\left(p_{j-1},\vec{u}_i\right),\vec{u}_i}\varphi_i\left(p_{j-1},\vec{u}_i\right) \tag{8}$$

Minimization is carried out by those values of $\vec{u}_i$ which lead to value p_j

Function $g_j\left(p_{j-1},p_j\right)$ are expenses at an j-element of the system given that pressure before it equals p_{j-1}, and after it equals p_j.

For a passive element, due to the absence of command for each p_{j-1}, there is only one legitimate value p_j, with corresponding value of function g_j equaling zero.

For an active element when either $p_{j-1}=p_j$ and $g_i\left(p_{j-1},p_j\right)=0$, $q_j=q_{j-1}$ (station is shut down), or if the pair p_{j-1} and p_j is technologically possible ($p_{j-1}<p_j$) and the appropriate limits are hold, then the function g_i, $i=1..N$ is calculated as follows:

- For gas-turbine CS (C_g - cost thou m^3 of gas)

$$g_i\left(p_{j-1},p_j\right)=C_g q_{m.г.}\left(p_{j-1},p_j,q_{j-1}\right),q_j = \\ q_{j-1}-q_{m.г.}\left(p_{j-1},p_j,q_{j-1}\right) \tag{9}$$

- For motor-driven CS (C_e - cost KW*h)

$$g_i\left(p_{j-1},p_j\right)=C_e E\left(p_{j-1},p_j,q_{j-1}\right),q_j=q_{j-1} \tag{10}$$

Let us denote $p_j-p_{j-1}=\Delta p_j$, change in pressure at j-element, then the following condition should be hold

$$\sum_{j=1}^{M}\Delta p_j = p_M - p_0 \tag{11}$$

The problem is reduced to finding such a distribution $p_1,p_2,...,p_{M-1}$, which satisfy the equation (6) и minimize the function

$$R(p_1,...,p_{M-1})=g_1(p_0,p_1)+g_N(p_{M-1},p_M) \tag{12}$$

The principle of optimality can be directly applied to multi-step process. Let us take the sequence of functions $f_i(p_j)\,(i=1,...,N)$. The function f_i is the total costs at the first j-steps given that the trajectory $p_0,p_1,...,p_j$ is optimal.

It is naturally consider that $f_0(p_0)=0$, then

$$f_1(p_1)=g_1(p_0,p_1) \tag{13}$$

For the function $f_i\ (i>1)$ we have recurrence relation

$$f_i(p_j)=\min_{p_{j-1}}[f_{i-1}(p_{j-1})+g_i(p_{j-1},p_j)]\ \ (i=1...\mathrm{N}) \tag{14}$$

Minimization is carried out by the values p_{j-1} at which the transition from the condition p_{j-1} into the condition p_j is possible. A change range p_j varies from step to step $p_j\in[p_*,p^*]$, where p^* and p_* is a maximum and minimum value of p respectively. Values p^* and p_* will be defined by an appropriate set of relations.

Assume $g_j(p_{j-1},p_j)=\infty$, when, because of technical limits, it is impossible to transit from the condition p_{j-1} into the condition p_j.

Numerical solution results in discretization in the region of phase coordinates p_j. Interval $[p_*,p^*]$ is divided with a scale in such a way that the function

$f_i(p_j)$ values at points of grid p_j^l give reasonably sufficient representation on the behavior f_i along the whole interval $[p_*, p^*]$.

Thus, a general form of the equation, on the basis of which one can build iterative process, can be written as follows:

$$f_i(p_j^l) = \min_{\varsigma}[f_{i-1}(p_{j-1}^{\varsigma}) + g_i(p_{j-1}^{\varsigma}, p_j^l)] \qquad (15)$$

1420-dia and 963-km length gas pipeline consisting of 3 lines and 9 compressor stations is cited as an example of realization of this algorithm, Fig. 2

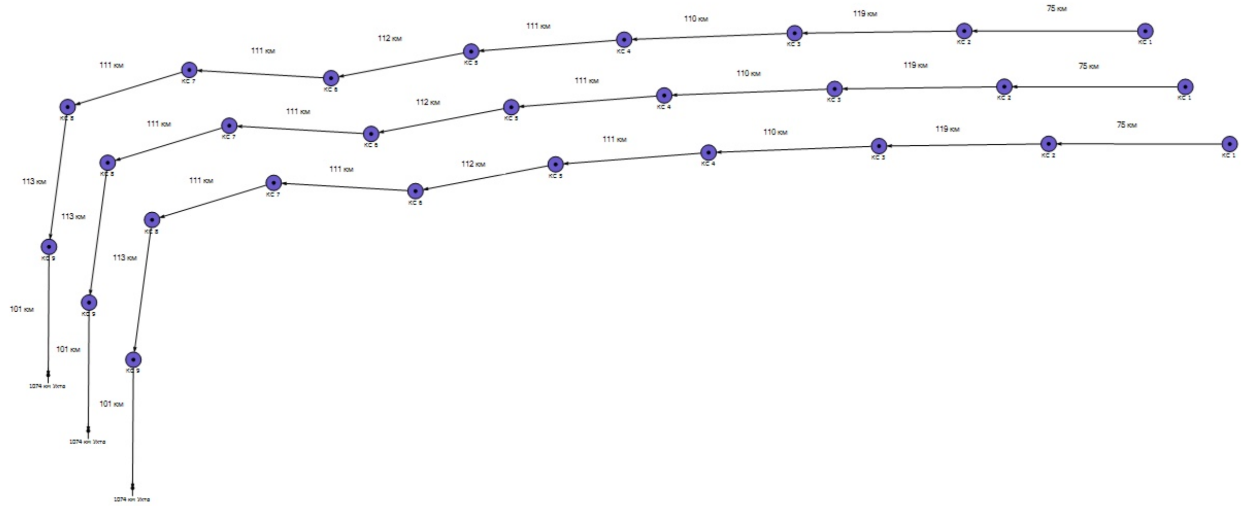

Figure2. Diagram of gas transmission system section

The results of optimization are given in Table 1.

Thus the analysis of the results obtained show their adequacy and the algorithms developed can be used for practical application in order to determine pollutant emissions at gas pipeline compressor stations. In this case CS operating conditions under calculation allow optimization of volumes of natural gas burned at gas processing plants at a given gas pipeline throughput capacity. It should be noted that a ratio between fuel gas consumption and transported volumes of gas characterizes the CS efficiency (when CS operates under the existing operating conditions, this averaged ration is estimated at 33m^3/mln m^3·km).

Table 1

An example of optimized algorithm realization

CS name	**CS-1**	**CS -2**	**CS -3**	**CS -4**	**CS -5**	**CS -6**	**CS -7**	**CS -8**	**CS -9**
Number of CS shops	3	3	3	3	3	3	3	3	3
Max number of GPP	15	12	10	12	12	12	12	12	10
GPP number under load	15	10	10	12	11	12	11	11	10
GPP number under load in each shop	/5/5/5/	/4/4/2/	/3/3/4/	/4/4/4/	/4/4/3/	/4/4/4/	/4/4/3/	/4/4/3/	/3/3/4/
Compression ratio	1,48	1,30	1,58	1,61	1,60	1,63	1,59	1,58	1,54
CS output pressure,MPa	11,52	11,80	11,80	11,80	11,74	11,80	11,80	11,80	11,46
CS input pressure,MPa	7,98	9,32	7,68	7,56	7,56	7,47	7,65	7,69	7,64
Gas flow rate at CS input, mln. M^3/d	554,1	552,3	551,1	549,1	546,7	544,5	542,1	539,8	537,6
CS output gas temperature, ^{0}C	12	-2	12	12	12	12	12	12	12
CS input gas temperature, ^{0}C	-2	4	-19	-5	-5	-5	-4	-4	-4
Max available power of GPP MW	264,0	211,2	275,0	330,0	330,0	330,0	330,0	330,0	275,0
Available power of active GPP MW	264,0	176,0	275,0	330,0	302,5	330,0	302,5	302,5	275,0
coupling power of rotary pump, MW	262,6	172,4	267,4	306,9	301,7	313,6	295,4	290,7	274,2
coefficient of utilization	0,99	0,98	0,97	0,93	1,00	0,95	0,98	0,96	1,00
Fuel gas consumption Mln m^3/d	1,79	1,18	2,03	2,35	2,27	2,39	2,24	2,21	2,07

The estimation of geoecological risks carried out during reconstruction and development of the Central Asia-Center gas transmission system (CAC GTS) is taken as a practical realization of the approach suggested. Due to expected increase in gas supply through the CAC GTS (from 45 to 80 bcm), the volumes of nitrogen in oxide composition were calculated along with the estimation of possible geoecological risks from emissions harmful pollutants containing in natural gas. During the calculation it was assumed that nitrogen concentration in natural gas transported through the CAC GTS amounts to, on average, 2.5% (nitrogen density under standard conditions were taken from reference data). The optimization was based on the above algorithms and the available data on the current and perspective gas supply by Central Asia gas pipelines for the period between 2005 and 2010. As a preliminary, calculations were performed by a pessimistic scenario that was based on the assumption of keeping specific volumes of NOx emissions at the existing level.

The calculation results NOx emission volumes for each compressor station of the CAC GTS are illustrated in Table 2.

Table 2

Comparison of NOx emission volumes at compressor stations of the CAC GTS

Name of pipeline section	CS number	Emission volumes (tons) before GTS extension	Emission volumes (tons) after GTS extension
Gazli - Khiva	2	825	2060
Belek - Beineu	4	205	1030
Shatlyk - Khiva	3	3610	5155
Khiva - Beineu	5	4435	7220
Beineu – Al. Gai	6	4640	8250

As it was mentioned above, the calculation data were given without consideration of up-to-date technologies directed for reducing emissions of pollutants during gas pipeline operation including those exhausted with combustion products of compressor stations. For comparison, the calculations of NOx emission volumes are given with allowance made for the possibility of their 1.8-fold reduction at the expense of introduction of up-to-date commercial gas processing plants and optimization of operating conditions of all the compressor stations (optimistic scenario).

The calculation results for the CAC GTS are given in Table 3.

Table 3

Comparison of NOx emission volumes at CS of the CAC GTS (optimistic scenario)

Name of pipeline section	CS number	Emission volumes (tons) before GTS extension	Emission volumes (tons) after GTS extension
Gazli - Khiva	2	825	1145
Belek - Beineu	4	205	570
Shatlyk - Khiva	3	3610	2865
Khiva - Beineu	5	4435	4110
Beineu – Al. Gai	6	4640	4585

As it was mentioned above, the optimization of geoecological risk management during operating compressor stations on gas mains is related with the decrease in emissions of pollutants forming in the process of natural gas burning. These pollutants after photochemical and physico-chemical conversions in the atmosphere can enter into surface and water ecosystems of a CS zone defining background and impact effect on different components of these ecosystems. An allowable level of these impacts can be calculated based on the methodology of critical loads [6]. The increase in calculated values of critical loads (CL) can result in geoecological risks.

Pilot calculations of geoecological risk values for natural ecosystems within the Central Asia-Center gas transmission system (the CAC GTS) were performed on the basis of literature and cartographic data. GIS-project consisting of several layers of subject information (soil, soil-forming rocks, type of land usage, precipitation, temperature, nitrogen fall-out, etc.) and attributive table of parameters that are needed for calculating CL values and their exceeding was prepared in ArcView program package. Spatial distribution of the CL data obtained for nutritional nitrogen (CL N_{nut}) designed to preserve biodiversity and maximum nitrogen CL (CL N_{max}) designed to prevent ecosystem acidification within the territory under consideration is illustrated in Fig. 3.

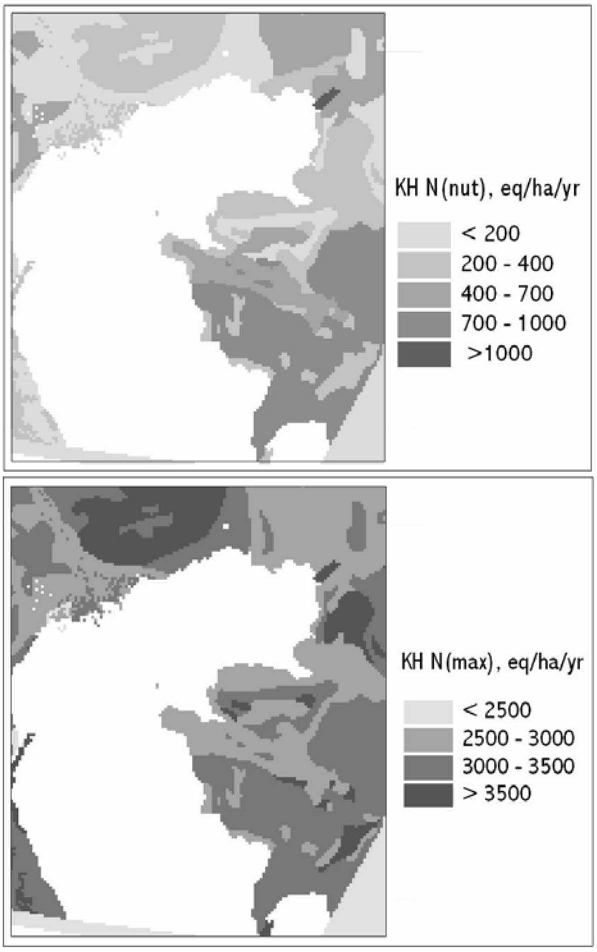

Figure 3. Distribution of nutritional nitrogen critical load values (left)
and maximum nitrogen (right) in the CAC GTS zone of emission impact

Nutritional nitrogen CL values vary from 125 to 1400 eq./ha per year that corresponds allowable entry from 1.5-2 to 18-20 kg N/ha per year. CL maximum values were obtained for highly productive meadow communities actively used for pastures on meadow-brown semi-desert soils and minimum values were obtained for strongly rare communities of solonetz complexes. The majority of the territory is characterized with ecosystems with CL level of 300-450 eq./ha or 4-6.5 kg N/ha per year.

Calculated *values of loads of maximum nitrogen* are sufficiently higher (from 2450 to 3500 and higher eq./ha per year). This results from high potential of ecosystems of arid zone concerning neutralization of acid constituent of nitrogen fall-out. By the results of pilot estimations for the most part of the territory under consideration an allowable level of the total nitrogen load may come to 2600-3100 eq./ha per year or 35-40 kg N/ha per year.

The current level of NOx fall-out within the territory concerned is estimated at 0.5-2.5 kg N/ha per year that corresponds the values of background regions. These levels are lower of calculated CL values. Spatial distribution of the atmospheric migration of NOx tends to decrease from the west to the east testifying its transboundary transport. As a result of design increase in gas volumes transported through the CAC GTS, a level of nitrogen load will increase, according to preliminary estimate, up to 1-4 kg N/ha per year. The data analysis shows that the *exceeding* of calculated CL *values* by nutrient nitrogen is possible for separate ecosystems of solonetz complexes, which are characterized by low parameters of nitrogen carry-over with vegetative biomass and nitrogen accumulation in soil organic matter. The exceeding of maximum critical load of nitrogen in the CAC GTS development scenarios under consideration has not been discovered.

In the presence of CL exceeding one need to reduce pollutant emission both at the expense of application of technological operations, and total reduction of power inputs. Since these processes are expensive, it is necessary to estimate a value of prevented ecological damage (PED) in order to calculate the efficiency of these processes.

For aggregative PED calculation for bioresources of ecosystems (soil, flora and fauna) during CS operation on the basis of normative method the following formula can be used [7]:

$$У^{б}_{прс} = \sum_{i=1}^{N} N^{p}_{i} \text{ x } К_{p} \text{ x } H, \qquad (16)$$

where:

$У^{б}_{прс}$ – a money value of prevented bioresources damage thanks to minimization of power inputs and corresponding reduction of pollutant emission during CS operation for a reporting period of time, thou. ruble/yr;

N^{p}_{i} – a total number of bioresources types (complex from types from 1 to N), which can be lost due to inertial impact, pcs;

H – a bioresoirces damage tariff (an average value of the tariff sum for each type of the analyzed complex of types in the territory concerned), ruble.

Prevented ecosystems damage in a zone of CS effect will be calculated as the difference between a value of predicted ecological damage caused without environmental measures (inertial scenario) and residual ecological damage after realization of these environmental measures.

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