Systemic efficiency of re-equipment of gas transport objects with the environmental protection factor

V A Khrustalev1, V A Glukharev2, I A Rostuntsova1 and M V Novikova1

1Yuri Gagarin State Technical University, Saratov 410054, Polytechnical 77, Russia
2 Vavilov State Agrarian University, Saratov 410012, Theatrical sq. 1, Russia

E-mail: Rostunzeva@mail.ru

Abstract. The analysis of operation of gas-pumping units (GPUs) with various types of supercharger drives (gas turbine and electric drives) is presented. The assessment of overall system effect due to the conversion of a number of compressor stations (CSs) to combined supercharger drive is provided taking into account the concomitant environmental effect. For the successful development of the infrastructure of settlements of roadside consumers, the size of operations areas and environmentally-acceptable (in terms of emissions and noise) distances to the boundaries of the protection zone of CS of the main gas pipeline (MGP) are important. The method of determining the distance from the CS at which the air quality standard is observed is formalized and calculations of boundary distances for CS of MGP are carried out. The functional diagram for calculation of ecological factors during the modernization of CSs at the conversion to combined supercharger drive is made. The calculated characteristics of dispersion options for emissions from the CS with gas turbine drive are presented. Graphical dependences of the value $C_x/C_m$ on the distance to the point of maximum emission concentration in the surface air layer are obtained. The conversion of a number of CSs to combined drive is able to provide the following benefits: during the off-peak periods the electric power supply of the electric drive of GPU of the CS of MGP is carried out by additional load of nuclear power units; load of the electric drive at night is better because of the greater temperature difference between the exhaust gases of the gas turbine and the outside air, and at the same time, either smaller number of gases are evacuated through the mouth of the exhaust pipes (fragmentary conversion to the electric drive), or there is no flue gas emission at all (complete conversion to the electric drive); the project sanitary withdrawal of residential and agricultural land in the area of CS of MGP under the conditions of excess air pollution is reduced. At the high price of land near the right-of-way of CS of MGP this can result in additional tangible effect: more "close" abutting to the industrial site of the CS with combined drive (permitted by air quality standards), which causes less capital-intensive logistics solutions along the heating main.

1. Introduction

At the present time, the gas industry of Russia ensures the livelihoods of all sectors of the national economy and social sphere and determines the formation of the country's main financial and economic indicators. In addition, natural gas remains the most important fuel type and valuable raw material for the chemical industry. This is largely facilitated by the fact that more than 1/3 of the world's natural gas reserves are concentrated in Russia and unique production potential has been created. At the same time, specificity of the gas industry is the need to transport large volumes of gas over considerable distances from the Far North deposits to the European part of Russia and beyond. Intensive construction of gas pipelines in the Eastern regions of the country is underway. The technical-and-economic efficiency of
this process largely determines the price of gas from consumers making up to 52% of its cost today. The reserves and possibilities of significant reduction of this value, as shown by the studies [1], are available in the industry, but require systematic and balanced approach to the design and modernization of the equipment of compressor stations (CSs) and, in particular, gas pumping units (GPUs).

Herewith, priority tasks in the gas industry are:
- Reliable supply of energy;
- Maximum possible reduction of risks and prevention of crisis situations on main gas pipelines (MGPs);
- Reduction of unit costs for production and use of energy resources by reducing losses during extraction and transportation;
- Applications of energy-saving technologies and equipment.

2. Problem definition
According to [2], at present, GPUs with total capacity of 44.354 million kW are operated at CSs of MGPs, which includes GPUs with gas turbine compressor driver (GGPUs) – 38.39 million kW and with electric compressor driver (EGPUs) – 5.92 million kW. At the same time, CSs equipped with GGPUs are a major source of emissions of harmful substances.

Herewith, the following pollutants enter the atmosphere (per CS with total capacity of 23–24 MW), t/a:
- nitrogen oxides – 530–560, among them 70% – NO₂; 13% – NO;
- carbon oxides – 310–510;
- hydrocarbons (methane) – 60–85.

GPUs produced to date have exhaust pipes of low height (10-25 meters). This worsens the conditions for the dispersion of harmful impurities in the atmosphere and increases their negative impact on people and the environment, especially in the area of the roadside settlements of the operating staff and all residents of the settlements in general.

When assessing the overall systemic effect, including because of the change-over of a number of CSs to combined supercharger drive, it is necessary to study the concomitant environmental effect. For the successful development of the infrastructure of settlements of roadside consumers, the size of operations areas and environmentally-acceptable (in terms of emissions and noise) distances to the boundaries of the protection zone of CS of MGP are important.

3. Results
Economic assessment of damage caused by annual emissions of harmful substances into the atmosphere is determined by the well-known formula [3]:

\[ Y = \gamma \cdot \sigma \cdot f \cdot M, \ r/y, \]  

where \( \gamma \) – constant with the dimension of 2.4-9.6 rubles per conditional ton of emission; \( \sigma \) – dimensionless value of the relative risk of air pollution (for territories of industrial enterprises, industrial centers and settlements with population density which is low than 50 person per hectare \( \sigma = 4 \); for territories of resorts, sanatoriums, reserves, recreation areas and settlements with average population density of over 50 person per hectare \( \sigma = 8 \); for forest and farmland areas \( \sigma = 0.05-0.5 \)); \( f \) – correction for the character of dispersion of impurities in the atmosphere; \( M \) – reduced mass of annual emission of pollution from the source, conditional tons/year.

The value of correction \( f \) for gaseous impurities and solid particles (with collection coefficient of solid particles \( \gg 99% \)) is determined as follows:

\[ f = f_1 = \frac{100}{100 + \phi \cdot H} \cdot \frac{4}{1 + U}, \]  

where \( H \) – chimney height, meters; \( U \) – average annual value of the wind speed modulus at the level of the weather vane, meters per second (if the wind speed is unknown, it is assumed to be 3 meters per second); \( \phi \) – dimensionless correction for the rise of emission plume in the atmosphere.

\[ \phi = 1 + \Delta T/75, \]
where $\Delta T$ – average annual difference in temperature at the mouth of chimney stack and in the environment.

If the value of correction $f$ for different types of impurities (gases and solid particles) emitted by a single source is different, the total damage is equal to the sum of damages related to each type of impurities, i.e.:

$$ Y = \gamma \cdot 6 \cdot (f_1 \cdot M_1 + f_2 \cdot M_2 + f_3 \cdot M_3) \quad (4) $$

The value of $M$ is determined by the formula

$$ M = \sum A_i \cdot m_i, \quad (5) $$

where $m_i$ – mass of annual emission of the $i$-th type impurity into the atmosphere, tons per year; $A_i$ – index of aggressiveness of the impurity of the $i$-th type (carbonic oxide – 1; sulphurous anhydride-49, nitrogen oxides – 41.1; carbon black without impurities – 41.5; benz (a) pyrene – 12.6·105; solid particles in the combustion of gas and fuel oil – 200; vanadic oxide – 1225; coal and peat ash-60-80).

The amount of emissions depends on the type of GPU and its mode of operation. If maximum one-time number of emissions $M_{mss}$ is unknown, it can be determined by the formula:

$$ M_{mss} = V_g \cdot q \cdot 10^{-3}, \quad (6) $$

where $V_g$ – volume of smoke fumes emitted from the pipe at the flue gas temperature, m$^3$/second; $q$ – concentration of harmful substances in smoke fumes, milligrams per nanometer$^3$ (for nitrogen oxides we take 220 mg / nm$^3$, for carbonic oxide - 200-500 mg / nm$^3$).

The total amount of harmful emissions $M_{year}$ (tons per year) depends on the mode of operation of GPU and is determined by the expression

$$ M_{year} = z_{rp} \cdot M_{mss} \cdot \tau_p \cdot 10^{-6}, \quad (7) $$

where $\tau_p$ – operating time of GPU during the year (hours per year) (determined in the technological part of the project of newly constructed or reconstructed CS of MGP); $z_{rp}$ – number of exhaust pipes of one unit.

Calculation of the standard fee rate for harmful emissions is carried out according to the expression

$$ \Pi = \frac{Y}{\sum m_i} \quad (8) $$

In Table. 1 data for environmental impact assessment per unit GPU-C-6.3 are presented.

**Table 1.** Basic data and characteristics for assessing the environmental impact on the environment and residents of settlements of a unit GPU-C-6.3.

| Indicator name | Notation | Dimension | Value |
|----------------|----------|-----------|-------|
| Power in station conditions | $N_e$ | MW | 6.3 |
| Effective efficiency under station conditions | $\eta_e$ | % | 24.0 |
| Fuel gas consumption | $q_{tr}$ | m$^3$/h | 2829 |
| $G_{tr}$ | kg/s | 0.524 |
| Temperature of the combustion products at the inlet to the turbine | $T_1$ | $^\circ$K | 1033 |
| Air temperature at the inlet to the combustion chamber | $T_5$ | $^\circ$K | 508 |
| Temperature of the combustion products behind the turbine (at the slice of the exhaust manifold of the turbine) | $T_2$ | $^\circ$K | 688 |
| Temperature of the combustion products at the exhaust of the gas turbine installation (at the slice of the pipe) | $T_2'$ | $^\circ$K | 688 |
| Flow of cyclic air | $G_3$ | Kg/s | 47.0 |
| Indicator name                                                                 | Notation | Dimension | Value |
|------------------------------------------------------------------------------|----------|-----------|-------|
| Consumption of combustion products (at the slice of the exhaust manifold of the turbine) | $G_2$    | Kg/s      | 47.5  |
| Degree of air pressure increase in the compressor                            | $E_K$   | -         | 5.7   |
| Air excess factor                                                            | $\alpha_u$ | -     | 5.22  |
| Oxygen content in dry combustion products                                     | $O_2$   | %         | 17.3  |
| Carbon dioxide in dry combustion products                                     | $CO_2$  | %         | 2.08  |
| Concentration of nitrogen oxides in dry combustion products (in terms of nitrogen dioxide) | $C_{NOX}$ | mg /nm³ | 100   |
| Concentration of nitrogen dioxide in dry combustion products                 | $C_{NO_2}$ | mg /nm³ | 5     |
| Reduced concentration of nitrogen oxides (at conditional concentration of 15% in dry combustion products) | $C_{15}^{NOX}$ | mg /nm³ | 163   |
| Emission capacity of nitrogen oxides, including nitrogen dioxide             | $M_{NOX}$ | g/s      | 3.56  |
| Specific emission of nitrogen oxides (emission index) per unit of fuel gas   | $m_{NOX}$ | g/m³     | 4.53  |
| Specific emission of nitrogen oxides per unit of work                         | $m_{NNOX}$ | g /kW·h | 2.04  |
| Concentration of carbon oxide in dry combustion products                     | $C_{CO}$ | mg /nm³  | 150   |
| Reduced concentration of carbon oxides (at conditional oxygen concentration of 15% in dry combustion products) | $C_{15}^{CO}$ | mg /nm³ | 245   |
| Carbon oxide emission power                                                   | $M_{CO}$ | g/s      | 5.35  |
| Specific emission of carbon oxide (emission index) per unit of fuel gas       | $m_{CO}$ | g /m³    | 6.8   |
| Specific emission of carbon oxide per unit of work                           | $m_{NCO}$ | g /kW·h | 3.1   |
| Height of the exhaust pipe (stack)                                           | $H$     | m        | 23.5  |
| Diameter (dimensions) of the exhaust pipe (stack)                            | $D$     | m        | 2.5   |
| Sectional area of the exhaust pipes (stack)                                  | $S$     | m²       | 4.9   |
| Velocity of the combustion products at the slice of the exhaust pipe (stack)  | $V$     | m/s      | 19.1  |

3.1. The calculation of the boundary distance from the compressor stations of main gas pipelines (CS of MGP), which complies with the normative air quality indicators. For newly designed CSs and during reconstructing existing ones, it is necessary to justify conservatively the distance at which air quality is observed (in terms of total pollution and noise) (as the settlement is removed from their source - CS of MGP). For this purpose, a preliminary analysis of the results of calculations for the field of concentrations of pollutants varying with the distance from the CS of MGP and the noise field in the residential area is required [5, 16].
This is necessary for the location of the residential settlement at an acceptable distance during the implementation of the expansion project or new construction of CS of MGP or due to additional protection measures in the case of existing settlements in connection with the development of their own infrastructure.

It should be taken into account that the prevented damage is distributed unevenly in the chronology of the year, but in strict accordance with the changing configuration of failures of the current schedules in a particular unified energy system. At the same time, the priority task is always the implementation of the almost constant schedule of gas transportation during the year.

The equipment with drives of different types is represented by the example of OAO “Gazprom Transgaz” in Table. 2, which shows the complete absence of combined supercharger drives at the CS of MGP. Meanwhile, according to some data, such solutions are increasingly used in a number of CSs of MGPs, for example in Germany.

| Operated units                                      | Total number | Share by number | % of total capacity |
|-----------------------------------------------------|--------------|-----------------|---------------------|
| Electric drive                                      | 64           | 29              | 31.43               |
| Gas engine compressors (GEC)                        | 13           | 6               | 0.86                |
| Gas turbine drive (stationary gas turbine plant)    | 85           | 39              | 43.21               |
| Aircraft drive (transport gas turbine plant)        | 57           | 26              | 24.5                |

In conditions of Russia, an important condition for the comparative efficiency of using a combined drive is the "displacement" of fuel natural gas from the needs of the gas transportation system, as a more valuable export resource. The ratio of the values in the conventional equivalents of uranium load and natural gas at domestic Russian prices for natural gas (2015 indicators) is 0.25-0.28, and at export prices for natural gas for Europe, this figure drops to 0.05 ÷ 0.07.

The second most important condition for the efficiency of the combined drive is associated with the possible increase in capacity factor of the NPP. Filling of load failures in the schedule of specific NPP units during off-peak periods (night hours of working days, weekends, holidays) also leads to an increase in the efficiency of all the output of these units by the units being loaded. In addition, it is possible (with differentiated tariffs for basic, peak and "failed" electricity) - reducing the cost of gas pumping.

Thirdly, it is necessary to take into account the ecological component. In the current state of the air basin of the European part of Russia, it is necessary to single out zones of large cities with an already exceeding background concentration exceeding the maximum allowable concentration (MAC) for the main industrial pollutants: oxides of nitrogen (NO\(_X\)) , sulfur oxides (SO\(_X\)), carbon monoxide (CO) and etc., as well as areas where the average annual background is close enough to the MPC, which leaves small quotas for emissions of the CS of MGP. As is known, in the areas of even long-range scattering of the radionuclide radionuclides and their mixing with local emissions of other industrial, including thermal power plants, combined effects with a "synergetic" character are possible. One of the most probable causes is the secondary precipitation of radionuclides of nuclear power plants on industrial aerosols (particles of outside, for example, industrial emissions).

The transfer of a part of the CS of MGP to a combined drive, among other effects, is capable of providing the following environmental benefits:

- When switching to an electric drive with operation during \(\tau_{\text{np}}\) hours per year with a conditional average electric power \(N_e\) without air pollution, it is assumed that during off-peak periods the power supply of the electric drive CS of MGP is carried out by additional loading of nuclear power plants;
At night, the conditions for dispersion are, on average, better because of the greater temperature difference between the outgoing gases of the GTU and the outside air; in addition, during this period, either a smaller number of gases are evacuated through the mouth of the exhaust pipes (a partial transition to an electric drive), or there is no emission of flue gases at all (a complete transition to an electric drive);

- The project sanitary exclusion of residential and agricultural lands in the area of the CS of MGP under the conditions of excess air pollution is reduced. At high prices for land near the right-of-way of the CS of MGP, this can give an additional tangible effect;
- More "close" junction (permissible according to air quality standards) to the compressor station with combined drive (but within the sanitary norms) stipulates less capital-intensive logistics solutions for the heating main, auxiliary power lines from the compressor station to the roadside villages: roads, communication lines and so on;
- Negative effect of noise, which is manifested more strongly in the cool night time, can also be limited, but it is not excluded by the transition of GPU to electric drive (noises of superchargers, etc.).

To assess the environmental factor when justifying the most effective composition of compressor plant equipment at CS MGP a flowchart has been developed (Figure 1).

![Figure 1](image_url)

**Figure 1.** Functional diagram of accounting for environmental factors during the modernization of CSs of MGPs by change-over to combined supercharger drive.

The maximum value of ground level concentration of the harmful substance $C_m$ (milligrams per meter$^3$) during the emission of air-gas mixture from a single point source with circular mouth is achieved under unfavorable meteorological conditions at distance $X_m$ (meters) from the source and is determined by the formula [4]:
\[ C_m = \frac{A \cdot F \cdot m \cdot h}{H^2 \cdot \sqrt{V_g \cdot \Delta T}}. \]  

(9)

where \( A \) – is coefficient that characterizes the conditions for vertical and horizontal dispersion of harmful substances in the atmospheric air (stratification coefficient); \( F \) – for the European part of the Russian Federation, the value \( A \) is equal to 120; \( M \) is maximum one-time amount of the harmful substance emitted into the atmosphere, grams per second; \( H \) – pipe height, meters; \( \Delta T \) – difference between the temperature of the flue gases emitted and the average air temperature, °C (when determining the value of \( \Delta T \) it is necessary to take the temperature of the ambient air equal to the average maximum air temperature of the hottest month of the year); \( V_g \) – volume of smoke fumes emitted from the pipe at flue gas temperature, meters³ per second; \( F \) – dimensionless coefficient that takes into account the sedimentation rate of harmful substances in the atmosphere, for gaseous substances and fine-dispersed aerosols we take \( F=1 \); \( n \) – coefficient depending on the parameter \( V_m \) (the functional relationship is established further); \( m, f \) – dimensionless coefficients that take into account the conditions for release of the gas-air mixture from the mouth of the emission source.

\[ m = \frac{1}{0.67 + 0.1\sqrt{f} + 0.34 \sqrt[3]{f}}; \]  

(10)

\[ f = \frac{1000 W^2 \cdot D_s}{H^2 \cdot \Delta T}; \]  

(11)

\[ W_o = \frac{4 \cdot V_g}{\pi \cdot D^2}; \]  

(12)

where \( D \) – diameter of the mouth of the pipe, meters; \( W_o \) – gas outlet velocity from the mouth of the pipe, meters per second. During the calculation of \( W_o \) in the conditions of utilization of part of the heat of the exhaust gas, for example, from \( 410 \) °C to \( 180 \) °C, calculation of changes in the volume of gases is carried out according to the formula:

\[ V_g(180) = V_g(410) \cdot \frac{180 + 273}{410 + 273} = 64.7 \, \text{m}^3/\text{s}. \]

When determining \( \Delta T \), the temperature of the hottest month of the year was taken (for Saratov’s condition) \( t_{air} = 26.7 \) °C.

When only gas turbine drive is used and \( H = 10 \div 25 \) meters without utilization of the exhaust gases of gas turbine plant: \( \Delta T = 410 \div 26.7 \approx 383 \) °C. Thermodynamically, the option with the presence of utilization is more effective (we take \( t_{utiliz} = 180 \) °C): \( \Delta T = t_{utiliz} - 26.7 = 180 - 26.7 \approx 153 \) °C. The temperature difference of the gases to be used in the heat exchanger is \( \Delta t_{utiliz} = 410 - 180 = 230 \) °C. This makes it difficult to create and place expensive batteries using a solid-state battery (SSB). Therefore, in the calculations we take \( V_g = 102.8 \, \text{m}^3/\text{c} \) for \( t_{ex} = 410 \) °C and \( V_g = 64.7 \, \text{m}^3/\text{c} \) for \( t_g = 180 \) °C. Such a decision can also be justified by the relatively short operating time of the SSB.

For 4 units in operation with conditional "round" mouth of the pipe, rectangular and circular cross-section of the mouth is equivalent:

\[ \pi \cdot \left(\frac{D_g}{2}\right)^2 = A \cdot B = 3.15 \cdot 2.67 = 8.41; \]

so \( D_g = 3.27 \).

Further, the values of \( m, f \) are determined. The value of \( f \) is determined for different conditions:

- basic – without utilization of heat of the exhaust gases: \( \Delta T = 383 \) °C; \( V_g = 102.8 \, \text{m}^3/\text{s} \) – for three different pipe heights: 10, 20, 25 meters;
- if there is a utilization of heat of outgoing gases: \( \Delta T = 153 \) °C; \( V_g = 64.7 \, \text{m}^3/\text{s} \) – at the same pipe heights. Calculation at this stage was carried out for a single compressor shop of the compressor station equipped with six units GPU-C-6.3 (4 working, 2 in reserve or repair, scheduled maintenance).

For the basic version, in dependence the height of the exhaust stack of GPU we get from using formulas (10), (11) the following values \( m, f, \) presented in table. 3a:
Using the formula of continuity of flow we recalculate the gas velocity at the mouth of the exhaust pipe \( W_{\text{util}} \) for the option with the utilization of heat of the exhaust gases, \( W_0 = 19.1 \text{ m/s} \).

\[
W_{\text{util}} = W_0 \cdot \frac{V_g}{V_{g,\text{utiliz.}}} = 19.1 \cdot \frac{64.7}{102.8} = 12.02 \text{ m/s}.
\]

Calculated values for \( m, f \) for GPU with the utilization of heat of the exhaust gases is given in Table 3b.

### Table 3b. Calculated values for \( m, f \) for GPU with utilization.

| H, meters | \( f \) | \( m \) |
|-----------|--------|--------|
| 10        | 30.8   | 0.436  |
| 20        | 7.69   | 0.618  |

Calculation of the maximum value of the ground level concentration of the harmful substance \( C_m \) (formula (9) requires taking into account the coefficient \( n \) and maximum one-time emissions of harmful substances \( M \). For example, in the case of GPU with gas turbine drive these are values determined by regulations or technical conditions [1]: \( M_{NO_x} = 2.2 \text{ g/s}; M_{CO} = 8.2 \text{ g/s} \). For calculated example of considered compressor section with four operating GPU as the only source of emissions: \( M_{NO_x} = 4 \cdot 2.2 = 8.8 \text{ g/s}; M_{CO} = 4 \cdot 8.2 = 32.8 \text{ g/s} \).

Coefficient \( n \) is determined depending on the parameter \( V_m \) as follows, for example, for assessment the base case (without utilization), \( \Delta T = 283^\circ \text{C}; V_g = 102.8 \text{ m}^3/\text{s}; H = 10; 20; 25 \text{ m} \):

\[
V_m = 0.65 \cdot \frac{\sqrt{V_g \Delta T}}{H}.
\]

### Table 4. Calculated values of parameter \( V_m \).

| \( H, \text{m} \) | 10    | 20   | 25    |
|-----------------|-------|------|-------|
| \( V_m, \text{m}^3/\text{s} \) | 10.26 | 8.15 | 7.56  |

According to the method [4], it is necessary to consider that if:
\( V_m < 0.5 \); then \( n = 4.4 \ V_m; \)
\( V_m \geq 2 \); then \( n = 1; \)
\( 0.5 \leq V_m < 2 \); \( n = 0.532 V_m^2 - 2.13 V_m + 3.13 \).

For example, to estimate the basic case we find the value \( V_m \) for different height of the exhaust pipe of GPU and reduce them to Table 4.

The calculated values of all characteristics for emission dispersion options (without and with the utilization of heat of the exhaust gases) are presented in Table 5. In Table 5 (line 9) the value of \( C_m \) calculated by the formula (9) and the dimensionless parameters \( X_m = d \cdot H \) and \( d = X_m/H \) (lines 10, 11 of Table 5) determined by the formulas of the Methodology [4] are marked. Then for relative values \( C_x/C_m = S \) and \( X/X_m \) by the formulas (17), (18) the dependence \( S = f(X/X_m) \) is calculated. In Table 5 calculations are made for five accepted values in the higher or lower side relative to the unit. When the electric drive is switched on average by \( \tau_p \) per day the calculated emissions are corrected by
multiplying by the correction – by the share of day when the gas turbine drive operates, i.e. by the
expression \((1 - \frac{\tau_{edo}}{24})\), where \(\tau_{edo}\) - is the average operation time of the electric drive per day. The
results obtained for the "base" emission values (only the gas turbine drive) and the correction factors to
their values are presented for various \(\tau_{edo}\) below in Table 5.

Corrections for \(\tau_{edo} = 6; 12; 18; 24\) respectively, in options 1; 2; 3; 4 (Figure 2) are equal to 1.0;
0.75; 0.5; 0.25.

For roadside areas where atmospheric air is already polluted with harmful substances emitted by
other enterprises, background concentrations of harmful substances must be taken into account. Then
the condition of compliance with the air quality standard (from Table 5) will look like:
\[
C_m + C_b \leq MAC,
\]
where MAC is maximum permissible concentrations, \(C_b\) is background concentration of harmful
substance emitted by other sources, mg/ m³ (is adopted according to the State Hydrometeorological
Service or is specified in the design for specific areas).

### Table 5. Calculated characteristics of the options of dispersion of emissions by typical CS of MGP
with gas turbine drive.

| Name of quantity                                      | Characteristic                  | The basic version (without utilization of heat of the exhaust gases) | Variant with utilization of the exhaust gases |
|--------------------------------------------------------|---------------------------------|-----------------------------------------------------------------|-----------------------------------------------|
| Chimney height                                         | H, m                            | 10 20 25                                                         | 10 20 25                                      |
| Average annual value of temperature difference at the   | \(\Delta T, ^\circ C\)           | 383 383 383                                                     | 153 153 153                                   |
| mouth of the pipe and in the environment               |                                 |                                                                |                                               |
| Volume of smoke fumes emitted from the pipe at \(t\)   | \(V_g, m^3/s\)                  | 102.8 102.8 102.8                                              | 64.7 64.7 64.7                                |
| Parameter defined by formula (13)                      | \(V_m\)                         | 10.26 8.15 7.356                                               | 6.48 5.14 4.77                               |
| Dimensionless coefficient that takes into account the   | \(F\)                           | 31.12 7.78 4.97                                                | 30.88 7.69 4.92                               |
| conditions of the gas-air mixture outlet from the mouth| \(D_e = 3.27\)                  |                                                                |                                               |
| Gas outlet velocity from the mouth of the pipe         | \(W_o\)                         | 19.1 19.1 19.1                                                 | 12.0 12.0 12.0                                |
| Dimensionless coefficient that takes into account the   | \(m\)                           | 0.435 0.616 0.678                                              | 0.436 0.618 0.696                             |
| conditions of the gas-air mixture outlet from the mouth| \(n\)                           | 1.0 1.0 1.0                                                   | 1.0 1.0 1.0                                   |
| (determined depending on \(V_m\))                     | Maximum one-time concentration  | \(C_m, mg/m^3\)                                               | 0.007 0.0041 0.0029                           |
| (formula (9))                                         | \(d\)                           | 23.35 20.5 19.72                                              | 18.72 17.86 15.74                             |
| Dimensionless coefficient Distance from the pipe, where| \(X_m = d \cdot H\)             | 233.5 41.0 493                                                | 187.2 374.4 393.5                             |
| the maximum ground level concentration is reached      |                                  |                                                                |                                               |
Table 6. To the calculation of the function $S = f\left(\frac{X}{X_m}\right)$ (in relative units) (option 1 – only gas turbine drive), $\tau_{eda} = 0$ hours.

| $\frac{X}{X_m}$ | 0.5 | 1.0 | 2.0 | 4.0 | 8.0 | 10.0 |
|-----------------|-----|-----|-----|-----|-----|------|
| $S = \frac{C_x}{C_m}$ | 0.75 | 1.0 | 0.74 | 0.37 | 0.12 | 0.073 |

Figure 2. Dependences (in relative units) of the value $C_x / C_m$ on the distance to the point of maximum concentration of emissions in the surface air layer.

For CS of MGP, where four GPUs are simultaneously operating, it is necessary to calculate the value $C_m$ from the maximum (according to the project) number of simultaneously operating sources. Given that the units are located close to each other and have the same (or slightly different) height of the exhaust pipe, with a certain degree of error they can be taken as a single point source of emission [4]. Then the maximum one-time concentration of harmful substance from several aggregates will be equal to

$$ C = C_m \cdot z = 4 \cdot C_m, $$

where $C_m$ – maximum one-time concentration from one source, calculated by formula (7), mg/ m$^3$; $z$ – maximum (according to the project) number of simultaneously operating sources (and exhaust pipes) of harmful emissions.

The value $4 \cdot C_m$, thus, determines the total emissions from the CS of MGP, consisting of four continuously unit GPU-C-6.3– for nitrogen oxides – 42.2 = 8.8 g/s; for carbon oxides – 48.2 = 32.8 g/s.

3.2. Determination of the distance from the CS, which complies with the air quality standard

For newly designed CS, it is necessary to find the distance at which the air quality standard will be observed. When expanding or reconstructing existing CSs, it is necessary to carry out verification calculations to determine the concentration of pollutants in the residential area. If the air quality standard is not met in the residential area, measures are developed to reduce the amount of harmful emissions from the CS. Equipping the GPU on the CS of MGP with combined drive (gas turbine and electric) with increase in the number of operating hours of the electric drive is also have a positive impact on the environmental situation in the air.
Obviously, the environmental advantage of combined drive is the absence of harmful emissions during the operation of electric drive. If initially this method of operation of the CS of MGP in the failed periods leads to additional load on only nuclear power units, then emissions will be absent not only locally – in the area of the CS of MGP, but in general in the power system as a whole.

The average daily factor of reduction of intensity of emissions at the site of CS of MGP and in the area with combined drive is \((1 - \frac{τ_{elo}}{24})\).

In unfavorable weather conditions, the maximum ground level concentration is achieved along the axis of the flame in the direction of the wind at distance \(X_m\) (meters) from the pipe, which, if inequality \(f < 100\) is used (option adopted in table 4), is determined by expression

\[
X_m = d \cdot H \cdot \frac{5-F}{4} = d \cdot H .
\]  

In formula (12) \(F\) is a dimensionless coefficient (for gaseous impurities \(F = 1\)); \(H\) is pipe height, meters; the value of \(f\) is estimated earlier (shown in Table 4); \(d\) is dimensionless parameter which is found by the formulas:

\[
d = 2.48 \cdot (1 + 0.28 \cdot \sqrt[3]{f}) \text{ при } V_m \leq 0.5;
\]

\[
d = 4.95 \cdot (1 + 0.28 \cdot \sqrt[3]{f}) \text{ при } 0.5 < V_m \leq 2;
\]

\[
d = 7 \cdot \sqrt{V_m} \cdot (1 + 0.28 \cdot \sqrt[3]{f}) \text{ при } V_m \geq 2.
\]  

From row 4 of table 5 it follows that the third variant of the formula (16) should be applied for the calculation of \(d\) in this example (table 5, line 10).

The ground level concentrations of harmful substances \(C_x\) in the atmosphere along the flame axis at different distances from the pipe (emission source) \(x\) are calculated as fraction of \(C_m\) according to the formula:

\[
C_x = C_m \cdot S ,
\]

where \(C_m\) is maximum one-time concentration of harmful substance determined by the expression (9), milligrams per meter\(^3\); \(S\) is a dimensionless coefficient. The value of \(S\) is calculated and the plot of function \(S = \frac{C_x}{C_m} = S = f(X/X_m)\) is constructed (Fig. 2), taking into account that

\[
\text{when } \frac{X}{X_m} \leq 1; \quad S = 3 \cdot \left(\frac{X}{X_m}\right)^4 - \frac{8}{3} \cdot \left(\frac{X}{X_m}\right)^3 + 6 \cdot \left(\frac{X}{X_m}\right)^2 ;
\]

\[
\text{when } 1 < \frac{X}{X_m} \leq 8; \quad S = \left[0.13 \cdot \left(\frac{X}{X_m}\right)^4 + 1\right];
\]

\[
\text{when } \frac{X}{X_m} > 8; \quad S = \frac{X}{X_m} .
\]  

For newly designed CSs, it is necessary to find the minimum allowable distance at which residential settlement of gas workers can be located. That is, it is necessary to determine the distance at which the boundary condition \(C_m + C_{all} \leq C_{MAC}\) begins to be satisfied. To do this, we set a number of distances \(x\), for which the coefficient \(S\) is calculated. Then, using the expression (17), we find ground level concentrations of harmful substances and make a comparison with maximum permissible concentrations by the ratio \(C_m \leq C_{MAC}\) (for \(C_{dac} = 0\)) (if the development of the site is planned on territory free from industrial enterprises).

When determining the distance to the boundaries of settlement from the line of MGP it is necessary to use absolute values of emissions from individual CSs of MGP and to find this distance as really admissible only by the descending branch of the curve (Figure 2). As can be seen from the nature of the family of curves, the more electric drive is used during the day, the more situation is environmentally friendly, which makes it possible to have logistical advantages. However, this factor is considered as system-auxiliary.
During the reconstruction or expansion of the CS, when the ratio (14) in the residential area is not met, it is necessary to develop and apply measures to reduce the amount of harmful emissions. In addition, organizational and technical measures are implemented, which include limiting the capacity of the CS during periods of unfavorable weather conditions, switching to more environmentally friendly equipment, prohibiting scheduled repairs of equipment accompanied by the exhaust of significant amount of gas into the atmosphere, and other similar activities.

Technological measures include the following:
– conversion of GPU to microflame fuel combustion;
– water injection into the combustion zone;
– increasing the amount of air in the combustion zone;

During the conversion of GPU to microflame fuel combustion of gas concentration of nitrogen oxides decreases by 30–50% of the initial level. The amount of nitrogen oxides is reduced due to the maximum temperature in the combustion zone and more even distribution of the temperature field. The investments are approximately 3–10% of the cost of GPU.

The supply of water to the combustion zone reduces the amount of nitrogen oxides emitted by 10–30% depending on the amount of water supplied. The disadvantage of this method is increase in fuel consumption (by 0.8–2.5%) and the need for chemical treatment of water supplied to the combustion zone in view of the possibility of salt deposition on the GPU blade when using untreated water.

With increase in the amount of air in the combustion zone, the concentration of nitrogen oxides decreases by 5–10% due to the cooling of the combustion zone by additional amount of air. However, the possibilities of this method are limited by the capacity of the compressor unit of GPU.

The most developed methods of purification of exhaust gases include catalytic and non-catalytic reduction of nitrogen oxides by ammonia. The concentration of nitrogen oxides decreases by 80–95% of the initial level. The disadvantages of this method are significant investments (from 10 to 30% of the cost of GPU), large ammonia consumption of 90.2–90.3 kg of ammonia per 1 kg of nitrogen oxides, the complexity of transportation and storing of large quantities of ammonia, which is explosive and harmful substance, the possibility of ammonia entering the atmosphere with flue gases of GPU during its overdose or deterioration of the quality of the catalytic nozzle.

4. Conclusions
1. The basic characteristics for assessing the ecological impact on the environment of GPU of type GPU-C-6.3 are determined;
2. The calculation of the boundary distance from CS of MGP, which complies with the normative parameters of air quality, is made;
3. The block diagram of the account of ecological factors at modernization CS MGP by transfer on the combined drive of superchargers is developed;
4. Calculated characteristics of variants of dispersion of emissions of a typical compressor station with a gas turbine drive;
5. Dependences (in relative units) of the value of Cx / Cm on the distance to the point of maximum concentration of emissions in the surface air layer;
6. The technique for determining the distance from the CS, which complies with the air quality standard;
7. For the wider use of gas-pumping unit with electric drive (EGPA) at the compressor station, it is necessary to implement a whole range of measures, primarily related to the provision of uninterrupted power supply for compressor stations. The choice of the type of GPU drive should be based on a systematic and detailed analysis of technical and economic and other factors in the construction of new and reconstruction of old compressor stations.

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