Improving the Energy Efficiency of a Gas Compression System at a Compressor Station

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Abstract. For natural gas pumping via main gas line gas compressor units are used. During the gas compressor units’ operation, there are natural gas consumption as a fuel and for technological needs. To prevent the escape of gas from the internal cavity of the centrifugal compressor N-370-18-1 into machine room, the design considers a hydraulic seal "oil-gas". The feature of centrifugal compressor with hydraulic seal "oil-gas" is the discharge of gas from the degassing chamber through a candle into the atmosphere. Rational use of wasted gas make it possible to gain a benefit by saving raw and reducing environmental charges. The gas discharged into the atmosphere is proposed to be used in the fuel gas system of the unit. This requires to bring gas parameters in particular pressure and temperature, to the required ones. The kinetic energy of the low-pressure (passive) gas directed from the gas separator to the candle can be increased by direct contact (mixing) with the high-pressure (active gas) flow in the gas-jet ejector. The complexity of the mathematical description of all processes occurring in ejectors with a three-dimensional flow, and the high cost of conducting experiments with gases other than air, make it cost-effective to use CFD (Computational fluid dynamics) modeling methods to study the processes of gas flow in ejectors. The article presents the gas flow modeling results of the gas flow in an ejector by the ANSYS Fluent software package.

1. Introduction

Taking action to reduce greenhouse gases is one of the top-priority energy efficiency and energy-saving policies of Gazprom PJSC and Russia as a whole up to 2030. In 2019, the greenhouse gases emitted by Gazprom amounted to 117.09 mln tons of CO₂ equivalent, with 29% of those coming from pipeline transportation of natural gas [1, 2]. Reducing the amounts of natural gas consumed for in-house and process needs, as well as the losses during pipeline transportation, are among the key aspects of energy saving and they were reviewed in several works [3-5,6,7].

Centrifugal compressors (CFC) in gas compressor units feature hydraulic oil-gas packing involving the discharge of the gas from the degassing chamber via the flare and into the atmosphere.

1.1. Objective

The reduction of greenhouse gas emissions from operating compressor stations as exemplified by a GTK-10M «Rekon» gas compressor unit.
1.2. Problem
This article deals with analyzing and rationalizing the technical solution that can capture the gas from the degassing chamber of the CFC oil packing system and use it for the in-house needs of GCU with the jet ejector. The work [8] provides an assessment of gas losses through the flares of four GTK-10M «Rekon» GCUs, which amounted to 162.1 thousand m³/year (taking into account the total running time for the CS units, which is 15.4 thousand hours/year).

Following the economic assessment performed for the reduction of degassing chamber emissions [9], we calculated the funds lost through the emissions of natural gas into the environment from the degassing chamber of a GTK-10M Rekon CFC for one of the CS (Table 1). The total fund lost for 4 units operating at a CS amounted to 56.447 thousand dollars/year (at the exchange rate of 1 USD = 92 RUB). As of January 1, 2017, Gazprom operated 384 GTK-10M «Rekon» GCUs.

The total greenhouse gas emissions in carbohydrate equivalent were determined taking into account the potential global warming [10]. The reduction of funds lost due to the emissions of greenhouse gases was calculated for the price of 13 euro per 1 ton of the carbohydrate equivalent and the exchange rate of 1 EUR = 92 RUB [11].

The fees within (equal or below) the permissible values for the emissions of (Fpe) were calculated using the following formula [12]:

\[ F_{pe} = \sum_{i=1}^{n} M_{pei} \cdot Hri \cdot K_{pe} \cdot K_{pe} \]  

where \( M_{pei} \) – is the amount of pollutant emissions in tons; 
\( Hri \) – is the rate of fees for pollutant emissions into the atmosphere from stationary sources. For methane, it is 1.42 dollars/t; 
\( K_{pe}, K_{pe} \) – are the additional rate of fee factors equal to 2 and 1 respectively; 
\( n \) – is the number of pollutants.

The assessment of the economic profit obtained through increasing energy efficiency due to the rational use of fuel and energy resources is performed depending on the price for natural gas. In our calculations, we used the price for 1000 m³ of gas as the funds necessary to cover the in-house needs of Gazprom, which was 59.2 dollars as of January 1, 2020.

| Title | GCU number  |
|-------|-------------|
|       | 1           | 2             | 3             | 4             |
| Gas losses through degassing chamber flare, m³/h | 14.13 | 12.15 | 11.59 | 5.93 |
| Gas losses through degassing chamber flare, m³/year | 36370.6 | 43181.1 | 56848.9 | 25718.4 |
| GCU hours of service, h/year | 2574 | 3554 | 4905 | 4337 |
| Greenhouse gas emission fees, thousand dollars/year | 10.434 | 12.395 | 16.316 | 7.368 |
| Lost gas cost, thousand dollars/year | 2.158 | 2.553 | 3.355 | 1.526 |
| Fees for permissible pollutant emissions, thousands of dollars/year | 0.079 | 0.092 | 0.118 | 0.053 |
| Aggregate monetary losses, thousands of dollars/year | 12.674 | 15.039 | 19.789 | 8.947 |
| Aggregate monetary losses for 4 units in operation, thousands of dollars/year | 56.447 |
1.3. The description of the proposed system

The gas discharged into the atmosphere shall be used as the fuel for the unit [13,14,15]. To do this, it is necessary to restrict the parameters of gas, pressure and temperature in particular, to the required levels.

The kinetic energy of low pressure (passive) gas transferred from the gas separator to the flare can be increased through the direct contact (mixing) with a flow of high-pressure (active) gas in the gas jet ejector [16].

Active gas can be off-taken at the CFC 370-18-1 inlet or outlet with a pressure of 5.4-7.4 MPa respectively. The flow of the off-taken gas will depend on the compression rate in the jet ejector, which depends on the geometry of the device.

To clean the collected gas of the oil particles, we suggest installing a dehydration filter, as well as a pressure regulator at the fuel collector inlet to maintain constant pressure.

The cost assessment for the application of an ejection unit depends on the costs of purchasing the equipment, such as the jet ejector, gas pipe, pressure regulator, pressure meter, filter, and shutoff valves.

Since the compressor station (CS) is equipped with 8 gas compressor units, each of the centrifugal compressors shall be fitted with this set of devices.

Table 2 shows the capital investment required to purchase the basic equipment required to capture the gases discharged into the atmosphere. The equipment was selected following the results of the calculations of the jet ejector dimensions and geometry.

![Diagram of the ejection unit layout](image)

**Figure 1.** Ejection unit layout (M – pressure meters; PR – pressure regulator; 1-4 – valves; 5 – jet ejector, 6 – filter).

To calculate the payback period of the ejection unit, we took into account the costs associated with the installation and commissioning works (14.2% of the gas equipment price).

| Process equipment                | Number (pcs) | Price per 1 unit (dollars) | Total price (dollars) |
|----------------------------------|--------------|---------------------------|----------------------|
| Jet ejector                      | 8            | 7368.4                    | 7368.4               |
| Gas pipe, 32×3 mm                | 16 (12 m each)| 842.1                     | 842.1                |
| Gas pipe, 25×2.8 mm              | 8 (12 m each)| 421.1                     | 421.1                |
| Pressure regulator RD-25-64      | 8            | 29368.4                   | 29368.4              |
| Pressure meter                   | 16           | 315.8                     | 315.8                |
| MS filter                        | 8            | 368.4                     | 368.4                |
| Ball valve (DU 25 11B27P)        | 8            | 42.1                      | 42.1                 |
| Ball valve (DU 32 11B27P)        | 16           | 160.0                     | 160.0                |
| Total, dollars                   | 38886.3      |                           |                      |
The results of the calculations showed that if ejection units are installed at CFCs of all CS units, the payback period will be 5 years.

Thus, the use of the ejection unit to feed gas into the fuel collector within the control system of a centrifugal compressor is economically feasible.

To visualize the movement of gas in jet ejectors and assess the parameters of mixed gas flow at the ejection unit outlet depending on the active gas offtake point, as well as the CS operating modes, we performed a simulation in the ANSYS Fluent software.

We selected the ANSYS hardware and software suite as the simulation environment as it can solve the problems of computational fluid dynamics using the finite element method. To analyze the possible operating modes for gas jet ejectors with helical bevel mixing chamber, we used the Fluid Flow (Fluent) package that employs the finite volume mesh (numeric values in cell centers).

As a result, we received finite-volume equations that ensure the preservation of flow values, which is compulsory for the accurate solution of fluid dynamics problems.

2. Methodology
Firstly, we determined the basic dimensions and geometry of the jet ejector, and the further calculations were carried out in the ANSYS. The complete calculation cycle for the jet ejector in the ANSYS includes the following: creating (or importing) the geometry, mesh generation, solver adjustment, solving, and result analysis.

To simplify the calculations, we used a 2D model, the geometry was broken down into orthogonal quadrilaterals cells, to get a total of 216347 elements and 218357 nodes (Figure 2).

The flow in the jet ejector was classified as a steady turbulent flow of the compressed perfect gas (methane). To solve non-linear equations, we used a bound implicit solver based on the pressure.

\[
\begin{align*}
\frac{\partial (p h_{tot})}{\partial t} - \frac{\partial p}{\partial t} + V \cdot (\rho V h_{tot}) &= V \cdot (\rho V T) + V \cdot (\rho \tau) + \rho \cdot S_{M} + S_{E} \\
h_{tot} &= h_{stat} + \frac{V^2}{2} \\
h_{stat} &= h_{stat}(T, p)
\end{align*}
\]  

Figure 2. The flow passage of the jet ejector created in the DesignModeler with the mesh.

Since flow temperature fluctuates, we used the energy conservation equation:

\[
\begin{align*}
\frac{\partial (p h_{tot})}{\partial t} - \frac{\partial p}{\partial t} + V \cdot (\rho V h_{tot}) &= V \cdot (\rho V T) + V \cdot (\rho \tau) + \rho \cdot S_{M} + S_{E} \\
h_{tot} &= h_{stat} + \frac{V^2}{2} \\
h_{stat} &= h_{stat}(T, p)
\end{align*}
\]  

where  
\( p \) – is the pressure;  
\( \rho \) – is the density;  
\( V \) – is the speed;  
\( T \) – is the temperature;  
\( t \) – is the time;
\( h_{\text{tot}} \) is the total enthalpy;
\( h_{\text{stat}} \) is the static enthalpy;
\( S_M \) is the source term for the impulse;
\( S_E \) is the source term for the energy;
\( \lambda \) is the thermal conductivity factor;
\( \mathcal{V} \) is the Hamilton operator (nabla);

\(-\) denotes a vector variable.

Turbulence was simulated using a model that –, that ensured a compromise between the calculation accuracy and its duration and computational mesh requirements.

Works [17-19] show that the selected model gives the least error when calculating similar flows.

Variables are determined directly from different transfer equations for turbulent kinetic energy and the turbulence disintegration rate:

The equation for \( k \):
\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho U_j k)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_k - \rho \varepsilon + P_{kb} \tag{5}
\]

The equation for \( \varepsilon \):
\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho U_j \varepsilon)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon}{k} \left( C_{\mu} P_k - C_{\varepsilon} \rho \varepsilon + C_{\mu} P_{kb} \right) \tag{6}
\]

The equation for turbulent viscosity:
\[
\mu_t = C_{\mu} \rho \frac{k^2}{\varepsilon} \tag{7}
\]

where
\( k \) – is the turbulent kinetic energy determined as the scattering of velocity oscillations.
\( \varepsilon \) – is the turbulent vortical scattering (the normal scattering for velocity oscillations);
\( \mu \) – is the volume viscosity factor;
\( C_{\mu}, C_{\varepsilon}, \sigma_k, \sigma_\varepsilon \) – are the empirical constants;
\( P_k, P_{kb}, P_{\varepsilon} \) – are the elements bound to the gravity effect on the turbulence.

During the calculations, the following parameters were used as boundary conditions:
- the pressure at the active gas nozzle inlet – or pressure-inlet (we tried different total pressure and temperature value);
- the flow inlet velocity at the passive gas inlet – or velocity-inlet (we defined the total temperature and various passive gas velocities);
- the pressure at the jet ejector outlet – or pressure-outlet (the static pressure at the ejector outlet, assumed to be constant);
- we assumed that the wall was stationary, hydrodynamically smooth (without rugosities), and adiabatic so that the flow would not slip along it.

The temperature and pressure of the ejected gas were assumed to be constant and equal to 288 K and 0.2 MPa respectively.

To fill the computational model with primary values and initial conditions, we performed the hybrid initialization of the solution.

We were searching for the solution until at some iteration all of the residual errors were below the default value (0.001) the solution did not converge.

3. Results
For the improved representation, the results of the analysis were visualized in Figures 3-5 as colored distribution outlines of the following parameters: total pressure, temperature, and turbulence intensity.
Figure 3. The distribution of the total pressure in the ejector flow passage.

The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in table 2 should be used.

Based on the simulation, we can claim that the ejection takes place as a result of the spread of the inducing jet, the drop in its pressure, and the created suction at the mixing chamber inlet.

The rapid narrowing of the active gas flow section results in the increased flow velocity, which is then reduced in the mixing chamber and the diffuser.

Figure 4. The distribution of the temperature in the ejector flow passage.

The temperature of the gas in the ejector basically does not change.

The results of the numerical calculation of the basic parameters for the ejector in question were compared with the results obtained by other researchers [20].

Figure 5. The distribution of the turbulence intensity in the ejector flow passage.
The distribution of the column charts varies depending on the active gas offtake point (before or after the compression), which can be linked to the technical specifications of the CFC.

The results of the calculations obtained during the simulation are presented in Figure 6.

The results of the simulation demonstrate that the parameters at the ejection unit outlet comply with the required parameters at the GTU fuel gas system inlet (1.4 MPa) irrespective of the seasonality and the active gas offtake points.

![Figure 6. The pressure at the ejector outlet according to the results of gas ejector simulation in the ANSYS based on the actual data from CS, with active gas offtake at the CS (outlet (P1) and the CS inlet (P2)).](image)

The pressure regulator installed after the ejection unit allows for maintaining a constant pressure at the outlet, so the off-take point for active gas (before or after the CFC) was selected depending on the simplicity of installation.

4. Conclusions

We analyzed the reduction of processing losses of gas after the degassing chamber of a centrifugal compressor. The economic effect of the collection of the gas discharged into the atmosphere for the entire set of GTK-10M «Rekon» GCUs at Gazprom will amount to 56.447 thousand dollars/year. The payback period of the ejection units, if they are fitted to all of the compressor station GCUs, is less than 5 years.

The construction and calculation of the mathematical model of the ejector in the ANSYS Fluent software resulted in pressure and temperature values for the outlet. The gas pressure varies between $2.043 - 2.145$ MPa (with the active gas off-take at the CS inlet) and $2.203 - 2.330$ MPa (with the active gas off-take at the CS outlet), which complies with the requirements for the GTU fuel gas system inlet.

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