Development and Research of a Regression Model for Assessing the Efficiency of Gas Compressor Units Operating Modes

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Abstract. This article addresses the issue of improving the energy efficiency of gas transportation equipment in main gas pipelines. To ensure the operation of gas compressor units (GCUs), transported gas is used, and as a result, compressor stations (CSs) consume a significant amount of fuel gas for their own needs. Therefore, increasing the length of main gas pipelines requires a high degree of fuel gas utilization efficiency. The article demonstrates the principles of using GCUs for gas transportation and the operating modes of GCUs. An analysis of methods for assessing the efficiency of GCU operation is conducted. To obtain a forecast of GCU operating modes, a mathematical model for evaluating the efficiency of GCU operating modes is proposed based on real statistical data of equipment operating mode parameters during industrial operation of GCUs in main gas pipelines. The regression model for GCU operating efficiency obtained from calculating the dependency of fuel gas consumption on pressure drop and transported gas flow inadequately reflected the GCU operating mode. To improve accuracy, a regression model for assessing the efficiency of GCU operating modes is developed based on quadratic dependencies on pressure drop, transported gas flow, and gas temperature at the inlet, satisfying the dispatcher control of GCU efficiency.

1 Introduction

The main method of providing natural gas to the industry, energy sector, and population of the Russian Federation is pipeline transportation. Due to the depletion of gas reserves in operating fields, new wells are being drilled and new fields are being developed, which are located further north and east. This leads to an increase in the length of pipelines and, consequently, an increase in the cost of energy resources in the country. The increase in production volume and the development of new fields require new equipment, modernization, and replacement of existing equipment. In the process of reconstructing the gas extraction industry, there is a pressing need to improve the energy efficiency of gas transportation equipment.

As a result of the increase in the length of main gas pipelines, the number of gas compressor units (GCUs), and the power of compressor stations, there is a constant increase

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in the requirements for accurate accounting of production resources and the economic efficiency of the installed power equipment at the compressor station (CS).

The main arguments for using GCUs at compressor stations are their high energy intensity, autonomy without the need for additional energy supply, and long service life.

To ensure the operation of gas compressor units (GCUs), transported gas is used, and as a result, compressor stations (CSs) consume a significant amount of fuel gas for their own needs. Thus, reducing own energy consumption is a relevant task in the process of natural gas transportation.

To solve the task of improving the energy efficiency of gas compressor units, it is necessary to have new tools and methods for measuring energy consumption and calculating energy efficiency indicators of GCU operation [4].

Modern mathematical, algorithmic, and software solutions allow for the development of new models for assessing the parameters of operating GCU units.

This work is dedicated to the development and research of a model for assessing the efficiency of GCU operating modes.

2 Materials and methods

The aim of this article is to develop and investigate a regression model for assessing the efficiency of operating modes of gas compressor units (GCUs) using statistical data from the industrial operation of GCUs on main gas pipelines.

To achieve this goal, the following tasks need to be addressed:

1. Demonstrate the principles of GCU application for gas transportation and GCU operating modes.
2. Conduct an analysis of methods for assessing the efficiency of GCU operation.
3. Develop a regression model for assessing the efficiency of GCU operating modes.

Currently, compressor stations use gas turbine installations of various types and designs, including stationary, transportable, aviation, imported, with and without waste gas heat regeneration. These installations, along with centrifugal compressors, are referred to as gas compressor units with gas turbine drive (GCUs), which represent the dominant type of drive for gas pipelines, accounting for over 80% of the total installed power on gas pipelines [3].

The main advantages of using GCUs at compressor stations are their compact size, allowing for modular design and simplifying installation and maintenance procedures. The average power of gas turbine-driven compressor units ranges from 4 to 25 MW.

In recent years, the oil and gas industry has been undergoing a phase of modernization and replacement of technical equipment that was put into operation in the 20th century. Gas compressor units are grouped into compressor workshops, and compressor workshops form compressor stations.

In the current conditions, any measures that can reduce natural gas losses are relevant and a priority for PAO Gazprom. For instance, a 1% increase in the efficiency of gas compressor units reduces fuel gas consumption by 1.4 billion cubic meters per year [2].

One of the most important tasks in the use of gas turbine drive in gas pipelines is to ensure the most economical operating modes of GCUs when transporting a specified amount of gas, which is always associated with fuel gas savings at the station. Transitioning between operating modes and stopping compressors should be performed by regulating the smoothness of the transient process.

Currently, approximately 86% of the GCU fleet consists of units with gas turbine drive (GTD). The average thermal efficiency of gas turbine units is around 28-30%, according to Russia's energy strategy. Additionally, approximately 10% of the natural gas being transported by GTD-driven GCUs is consumed for their own needs [1].

Therefore, among the indicators of energy efficiency for gas compressor units, the most

important ones are the thermal efficiency and specific fuel gas consumption.

The effective thermal efficiency of the gas turbine unit is used as a criterion for assessing the efficiency of GCU operation, according to the methodology described in STO Gazprom 2-3.5-113-2007 "Methodology for Assessing the Energy Efficiency of Gas Transmission Facilities and Systems."

The evaluation of fuel energy resource consumption efficiency for GCUs is carried out based on energy efficiency indicators.

As shown above, the efficiency of gas turbine units reaches 30-39.4%. Additionally, around 10% of the transported natural gas is consumed for their own needs.

Therefore, the development of methods aimed at improving the energy efficiency of GCU operation is of great relevance. To obtain a reliable real-time assessment of the gas transmission system and predict the operating mode of GCUs, a regression mathematical model for evaluating the efficiency of GCU operating modes is being developed.

3 Results

Currently, in the gas industry, significant attention is being paid to the problems of optimal management of the gas transmission system and the reliable assessment and prediction of gas transportation modes during operational control, taking into account the actual technical condition of the equipment [5]. To obtain a reliable real-time assessment of the gas transmission system, a statistical method is used. To predict the operating mode of GCUs, the authors propose a mathematical model for assessing the efficiency of GCU operating modes based on statistical data of technological parameters during the industrial operation of GCUs on main gas pipelines - Northern LPUMG, KC-1.

Experimental samples of values of certain технological parameters of GCUs are compiled into an Excel spreadsheet, a fragment of which is shown in Figure 1.

	A	B	C	D	E	F	G	H	I	J
1	КС Соковка. КЦ-1	Р входа [кг/см	Р выхода [кг/см	Q перекачки (час) [тыс.м	ГПА в работе [ш	ГПА в резерве [ш	ГПА в ремонте [ш	Схемы работы ГПА	Кол-во потокс	№ схем
2	01.01.2014 0:00	51,9	71,6	3239,6	4	3	1	2X2	2	2
3	01.01.2014 2:00	52,5	71,6	3205,5	4	3	1	2X2	2	2
4	01.01.2014 4:00	52,9	71,8	3200,1	4	3	1	2X2	2	2
5	01.01.2014 6:00	53,4	72,1	3210,7	4	3	1	2X2	2	2
6	01.01.2014 8:00	53,6	72,4	3214,3	4	3	1	2X2	2	2
7	01.01.2014 10:00	53,8	72,7	3220,5	4	3	1	2X2	2	2
8	01.01.2014 12:00	54,2	73,2	3280,8	4	3	1	2X2	2	2
9	01.01.2014 14:00	54,3	73,2	3269	4	3	1	2X2	2	2
10	01.01.2014 16:00	54,5	73,5	3265,1	4	3	1	2X2	2	2
11	01.01.2014 18:00	54,7	73,7	3270,4	4	3	1	2X2	2	2
12	01.01.2014 20:00	55,1	73,5	3251,5	4	3	1	2X2	2	2
13	01.01.2014 22:00	55,1	73,5	3238,1	4	3	1	2X2	2	2
14	02.01.2014 0:00	55,1	73,6	3235,2	4	3	1	2X2	2	2
15	02.01.2014 2:00	55,2	73,6	3231,4	4	3	1	2X2	2	2
16	02.01.2014 4:00	55,2	73,6	3234	4	3	1	2X2	2	2
17	02.01.2014 6:00	55,2	73,6	3233,9	4	3	1	2X2	2	2
18	02.01.2014 8:00	55,3	73,6	3233,5	4	3	1	2X2	2	2
19	02.01.2014 10:00	55,2	73,6	3231,5	4	3	1	2X2	2	2
20	02.01.2014 12:00	55,2	73,6	3247,3	4	3	1	2X2	2	2

Лист1

Fig. 1. Samples of technological parameters of GCUs in the compressor shop of Northern LPUMG, KC-1.

The data samples were obtained from a station where GCUs with GTD were used during the period from 01.01.2014 0:00:00 to 31.12.2016 22:00:00. The following technological parameters are used for the development of the statistical model: inlet and outlet pressure of the compressor station measured in kg/cm², volume of the transferred gas measured in thousand m³, information on the number of GCUs in operation, in reserve, and under maintenance. Data on the operating scheme of the GCUs in the compressor shop are also provided, indicating the mode in which the compressor units operated. The objective of the modelling task is to minimize the fuel gas consumption. The development of a regression model will allow determining the efficiency of GCU operating modes with the minimum fuel

gas consumption. The sequence of statistical analysis is as follows: the GCU operating mode is determined based on known parameters:

- pressure differential, Pin, Pout;
- gas flow rate through the compressor. To simplify the model development, the average statistical data will be grouped on a daily basis.

We will calculate the average inlet and outlet pressure of the GCU for a day using the program provided below (MATLAB m-file).

```
Pin = SevernoeKC1(:,1);
Pout = SevernoeKC1(:,2);

Na = length(Pin)/12;
for i = 1:Na
    i1=1+(i-1)*12;
    i2=12+(i-1)*12;
    Pinday(i,1)=mean(Pin(i1:i2));
end

Nb = length(Pout)/12;
for i = 1:Nb
    i1=1+(i-1)*12;
    i2=12+(i-1)*12;
    Poutday(i,1)=mean(Pout(i1:i2));
end
```

The algorithm takes two arguments, Pin and Pout, which are arrays of gas pressure values at the inlet and outlet of the compressor station, respectively. These pressure values are recorded at a two-hour interval. The algorithm calculates the average daily values of the inlet and outlet pressures and stores them in the arrays Pinday and Poutday. The mean function is used to calculate the average daily pressures.

Given the samples of average daily technological parameters for the Gas Compressor Plant (GPA) of Severnoye LPUMG, KC-1, let's represent the relationship between fuel gas consumption and pressure differential, as well as the flow rate of transported gas, in the following form:

$$\mathrm{Q_{tg}} = f(\Delta P, Q_g) \tag{1}$$

where $\Delta \mathrm{P}$ – pressure differential;
Qg – daily values of transported gas;
Qtg – daily values of fuel gas;

MATLAB code that implements the dependence described in equation (1) as a three-dimensional graph:

```
ΔP = SevernoeKC1day(:,2)-SevernoeKC1day(:,1);
Qg = SevernoeKC1day(:,3)./SevernoeKC1day(:,5);
Qtg = SevernoeKC1day(:,4)./SevernoeKC1day(:,5);
i=ΔP >20;
ΔP (i)=[];
Qg (i)=[];
```

```
Qtg (i)=[];

figure('Color',[1 1 1])
plot3(deltaP,Qg,Qtg,'.','MarkerSize',15)
grid on
title('Dependence of fuel consumption on differential pressure
and gas consumption','FontSize',14)
xlabel('ΔP, kg/cm^2','FontSize',12,'FontWeight','bold')
ylabel('Qg, r.m^3','FontSize',12,'FontWeight','bold')
zlabel('Qtg, r.m^3','FontSize',12,'FontWeight','bold')
```

The input parameters of this algorithm are as follows: ΔP – pressure differential, which is the difference between the outlet and inlet pressures., Q_g – daily values of transported gas divided by the number of streams, Q_{tg} – daily values of fuel gas divided by the number of streams.

The regression model obtained for the efficiency of the gas compressor unit (GPU) based on the calculation data is inadequate. This problem may have arisen due to the lack of two-hour data on fuel gas, which led to the use of averaged input and output pressure data.

To address this issue, we will additionally perform data filtering to exclude data points where the pressure significantly varied during the day. By using the standard deviation (std()) method, we can assess the dispersion of the dataset:

$$\sigma_{\text{std}} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \mu)^2}{n}}, \qquad (2)$$

where σ – standard deviation, x_i – individual value of a sample, μ – arithmetic mean of a sample, n – sample size.

Calculation of the standard deviation in MATLAB:

```
ΔP = SevernoeKC1(:,2)-SevernoeKC1(:,1)
Nd = length(deltaP)/12;
for i = 1:Nd
    i1=1+(i-1)*12;
    i2=12+(i-1)*12;
    deltaPStd(i,1)=std(deltaP(i1:i2));
end
figure('Color',[1 1 1])
hist(deltaPStd)
grid on
title('Histogram of the standard deviations of pressure
changes ','FontSize',14)
xlabel('Value of the standard
deviation','FontSize',12,'FontWeight','bold')
ylabel('Frequency','FontSize',12,'FontWeight','bold)
```

To perform a qualitative analysis of the data, let's construct a histogram with 50 bins (Figure2).

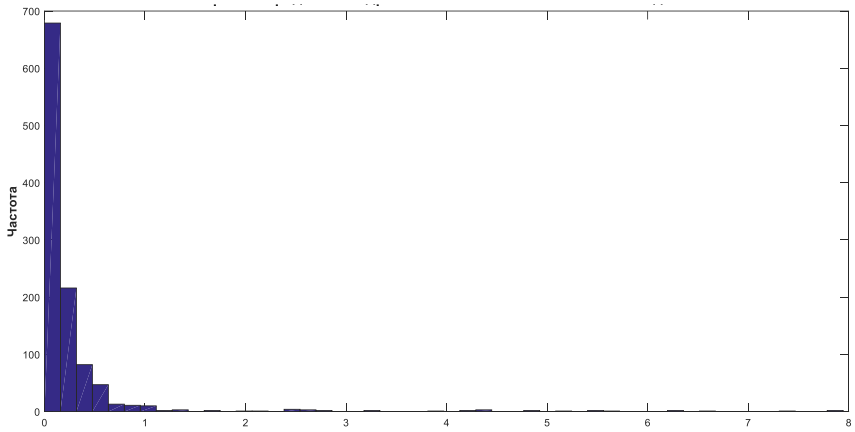

Fig.2. Histogram of the standard deviation of pressure changes, Severnoye LPUMG, KC-1. Source: "Compiled by the authors".

Based on the histogram (Figure 2) and the obtained values of the standard deviation of pressure changes, we filter out 50% of the original data, specifically those values σ_{std} that are greater than 0.1.

As a result, we obtain the following surface (Figure3).

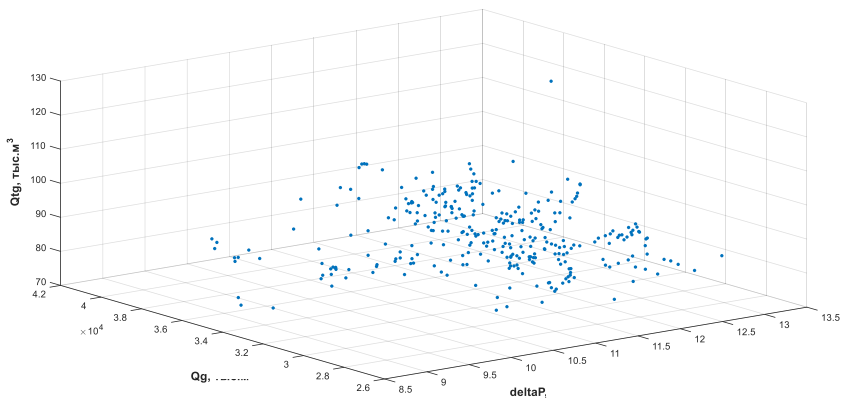

Fig. 3. Graph showing the relationship between fuel gas consumption, pressure differential, and transported gas flow rate, Severynoe LPUMG, KC-1. Source: "Compiled by the authors".

To improve the accuracy of the model, we will perform an approximation for our point cloud.

The calculation of regression coefficients can be done for the matrix C, composed of feature columns, using the formula for pseudo-inverse:

$$\mathrm{C} = [\Delta \mathrm{P}^2 \; Q_g^2 \; Q_g \cdot \Delta P \;\; \Delta P \, Q_g \;\; ones(size(Q_g))]$$
$$d = (C' \cdot C) \backslash (C' \cdot Q_{tg})$$

where d is the vector of regression coefficients.

Polynomial dependencies of the input variables were used as features, and a formal approach was used to form the feature matrix.

$$(x_1 + x_2 + \cdots + x_n)^0 + (x_1 + x_2 + \cdots + x_n)^1 + (x_1 + x_2 + \cdots + x_n)^2 + \cdots =$$
$$= 1 + x_1 + x_2 + \cdots + x_n^2 + 2x_1x_2 + 2x_1x_3 + \cdots + 2x_1x_n + x_2^2 + 2x_2x_3 + \cdots$$

On Fig. 4, the graph of the original data and the graph of the model response are presented.

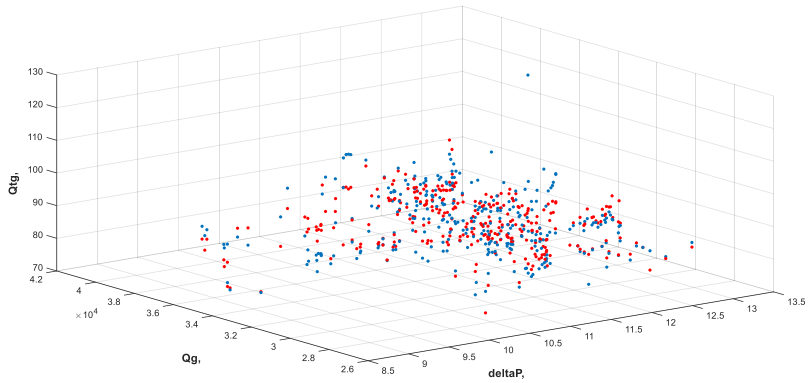

Fig. 4. Graphs of the functional dependence of fuel gas consumption on pressure differential and transported gas flow rate, Severnoye LPUMG, KC-1. Source: "Compiled by the authors."

To finally confirm whether this filtering worked, let's calculate the mean absolute error (MAE).

$$\text{MAE} = \frac{\sum_{i=1}^{n} | y_i - x_i |}{n} = \frac{\sum_{i=1}^{n} | e_i |}{n}, \qquad (3)$$

where $|e_i| = |y_i - x_i|$ – the absolute value of the i-th error,

y_i – the output data from the model;

x_i – the real data.

Below is a fragment of a program (MATLAB m-file) that calculates the mean absolute error:

```
MAE1 = sum(abs((C*d)-Qtg1))/length (Qtg1)

MAE = sum(abs((A*b)-Qtg))/length (Qtg)
```

Finally, we obtain approximately the same values. The mean absolute error of the unfiltered data (MAE) is 3.9516, while the mean absolute error of the filtered data (MAE1) is 3.9322.

On the graph, a scattered cloud of points is obtained, to improve the convergence of the model, we introduce an additional a priori factor. In our case, the third parameter will be the pressure at the inlet. Let's build a chart of the dependence of the fuel gas flow rate on the pressure drop, gas flow rate, and gas pressure at the inlet using the program implemented in a MATLAB m-file and presented in Fig. 5.

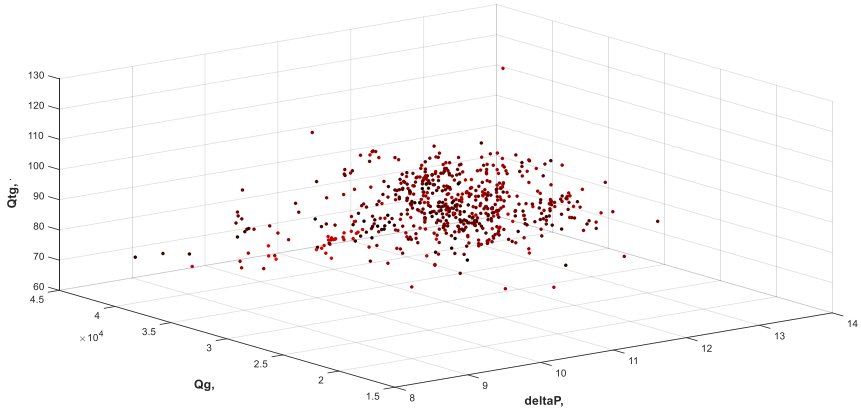

Fig. 5. Dependence of fuel gas consumption on pressure drop, transported gas flow rate and gas pressure at the inlet, Northern LPU gas station, KC-1, Source: Compiled by the authors.

The pressure at the inlet is shown in color: from the lowest (black) to the highest (red). The cloud has become denser, but it can be seen that there is no dependence trend on the inlet pressure since there is no gradient distribution from black to red. The MAE was 3.5155, which slightly improves the model without considering pressure by 10.6% and confirms the conclusion obtained from visual analysis. Therefore, we can try to see if there is dependency on another parameter, for example, the gas temperature at the inlet. Let's plot the graph of the dependence of fuel gas consumption on pressure drop, gas flow rate,
and gas temperature at the inlet (Fig.6):

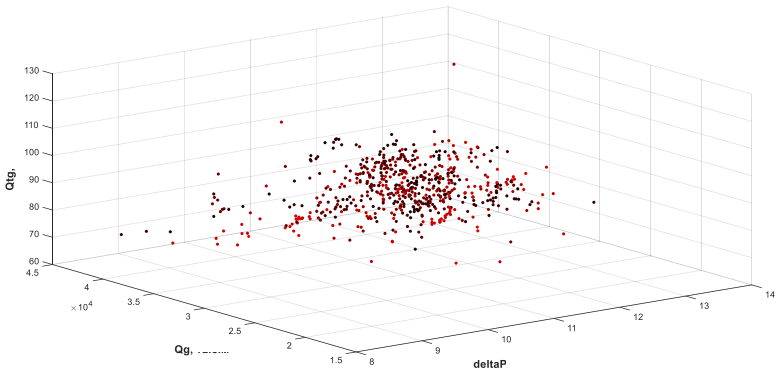

Fig. 6. Dependence of fuel gas consumption on pressure drop, transported gas flow rate, and gas temperature at the inlet, Northern LPU gas station, KC-1, Source: Compiled by the authors.

The temperature at the inlet is shown in color: from the lowest (black) to the highest (red). It can be seen that the dependence of fuel gas consumption on the inlet temperature is also weak, since there is no gradient distribution from black to red. The number of situations is 611. The MAE was 3.4316, which also insignificantly improves the result relative to the model without considering temperature by 12.7% and confirms the conclusion obtained from visual analysis. It is possible that due to the design features of the KC, it is necessary to differentiate the efficiency of the KC operation with different numbers of operating GPA. To test this hypothesis, only those situations where two GPAs were operated were selected, and a regression model was obtained with a 10% reduction in the number of situations. The coefficients of the regression model with temperature were recalculated based on this data,

and the average absolute error MAE was calculated for them. The result was 2.8127, which is 18% better compared to the previous model.

We obtain the following regression coefficients:

$$h = \begin{vmatrix} 1833.6 & -228.6 & -0.1 & -31.9 \\ 18.6 & 0 & -7.3 & 0 \\ 0 & 3.2 & -0.49 & 0 \\ 0.3 & 0 & 0 & 0 \\ 0 & -0.06 & 0 & 0 \end{vmatrix}$$

The resulting regression model is in the form of a third-order polynomial:

$$\mathrm{Q}_{\mathrm{tg}}(\Delta P, Q_g, T) = -0.49\Delta P^3 - 0.06T^3 + 0.3\Delta P^2 \cdot T + 18.6\Delta P^2 + 3.2T^2 - \\ - 7.3\Delta P \cdot T - 228.6\Delta P - 0.1Q_g - 31.9T + 1833.6$$

Thus, the regression model constructed on the quadratic dependence of fuel gas flow rate on pressure drop and transported gas flow rate has an absolute error within 3.9516. The model that takes into account the dependence of fuel gas flow rate on pressure drop, transported gas flow rate, and gas temperature at the inlet has an absolute error of 2.8127, which is 18% better than the initial model, indicating that the dispatch control for the efficiency of gas pumping units is satisfied.

Therefore, it can be concluded that to increase the accuracy of the model, it is necessary to consider the number of working gas pumping unit aggregates at the station.

4 Discussion

The modern gas pumping unit (GPU) fund consists of gas turbine-driven (GTP) units by approximately 86%. The useful coefficient of the gas transport unit (GTU) averages 28-30% today [1]. Additionally, around 10% of the natural gas pumped by GPU with GTP is consumed for its own needs [5].

As the length of trunk gas pipelines and the power of compressor stations increase, the requirements for improving the energy efficiency of gas transportation equipment, the accuracy of accounting for production resources, and the economic efficiency of installed power equipment at the compressor station (CS) are constantly growing.

An extensive study of the performance of modern electric-driven gas pumping units [1] has been conducted, but there is not enough research to assess the efficiency of gas pumping units with gas turbine drive.

The authors propose developing a regression model based on statistical data on the operational use of GPU trunk gas pipelines to evaluate the effectiveness of gas pumping unit operating modes.

Thus, by adjusting the technological parameters of GPU operation, the most efficient operating mode of gas pumping units with gas turbine drive in terms of fuel consumption can be determined using the developed model..

5 Conclusion

The increasing length of trunk gas pipelines and the number of GPU and power of compressor

stations continually increase the demand for accurate accounting of production resources and economic efficiency of the installed power equipment at the compressor station (CS).

Therefore, among the indicators of the energy efficiency of gas pumping units, the most important ones are the useful coefficient and specific fuel gas consumption. To obtain a reliable real-time assessment of the gas transportation system and a forecast of a GPU operating mode, the authors developed a regression mathematical model for evaluating the efficiency of GPU operating modes.

Thus, the regression model built using statistical data from the industrial operation of GPU trunk gas pipelines enables the determination of fuel gas consumption in real time. This, in turn, by regulating the technological parameters of GPU operation, allows the determination of the most efficient operating mode of gas pumping units with gas turbine drive in terms of fuel consumption savings using the developed model.

In the future study of this issue, to increase the accuracy of the model, it is necessary to conduct research within the framework of a factorial experiment on the significant parameters of GPU.

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