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**Investigation of the real gas conversion method for a low-temperature methane compressor**

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**Abstract.** In this work, a study was made of methods for converting a real gas from a full-scale compressor to a model one for low-temperature pure methane using the equations of state of a real gas Benedict-Webb-Rubin and Peng-Robinson. In the course of the work, the features of recalculation methods were studied, a model of an air compressor was selected, corresponding in parameters to a model of a low-temperature methane compressor using the theory of similarity, using similarity criteria. Also, in this work, the features of the application of various equations of state were studied when describing the model of a low-temperature methane compressor, as well as the features that arise when this model is converted to an air model analogue. Data were obtained on the possibility of applying the proposed methods on real units, and the invariance of the method with respect to the used equations of state of a real gas for pure methane at temperatures from 150 to 300 K and a division of 0.2 MPa was proved. At the final stage of the work, comparative characteristics of two models of natural methane compressors were obtained, based on different equations of real gas, describing the medium and two models of model compressors using air as a working medium and being model analogs of the above units.

**Keywords:** Gas conversion equation of state, methane, estimation technique, similarity criteria, similarity theory, Peng-Robinson equation, Benedict-Webb-Rubin equation, real gas, compressor.

## 1 Introduction

The method of recalculation of real gas in this work means the method of recalculation of the parameters of a gas compressor for testing it in air based on the equations and laws of the similarity theory.

In general, the theory of similarity and similarity criteria in particular, in its original form, was developed as a theory that greatly simplifies the formulation and investigation of an experiment, generalizes experimental data and contributes to the development of design methods based on this theory. So, for example, using the similarity criteria in the experimental study of designed or operated compressors, you can achieve high resource savings and safety of the experiment in the following ways [1-4]:

1. Scaling the geometric parameters of the developed or operated compressor for conducting an experiment or testing on a smaller, more compact model;
2. Replacement of the working medium in the compressor during tests or experiments with a cheaper or inert one with a further reverse recalculation of the parameters for the desired medium;
3. Combination of points 1 and 2.

And if the first point 1, and as a consequence point 3, are not of great interest in the framework of this work, point 2 is key in further research. Considering in more detail the application of the similarity theory for carrying out physical experiments of gas compressors in air, the following positive factors can be noted [1-4]:

1. Saving the substance of the working medium of the gas compressor.

Replacing the working medium of the compressor with air during experimental studies of a model or full-size compressor allows you to save expensive substances on which the compressor will be used in the future at the place of its future operation, such as, for example, helium and other noble gases.

2. Simplification of the experimental setup working scheme.

In addition to saving matter, the economy of such experiments is achieved by simplifying the experimental setup, since for air, in contrast to various gases, there is no need for specific materials, for example, anti-corrosive and others, and special conditions to protect the working environment from the atmosphere and key equipment, such as oxygen from oil bearings.

3. Safety.

Also, a very important factor achieved in the study of gas equipment in the air is to ensure the safety of the environment and personnel from the unwanted effects of a number of toxic, poisonous, explosive or heavy gases that can harm the health or life of workers and service personnel, working and the environment, equipment, etc.

But despite all the above advantages of this method, there are a number of problems and conditions under which this theory has a high degree of accuracy. This phenomenon is caused not only by the imperfection of modern methods for describing the thermodynamics of complex systems and statistical errors of experiments, but also by the theory of similarity itself, namely, by many simplifications and assumptions. A number of assumptions include [3, 5]:

1. The processes considered by the similarity criteria are considered adiabatic, that is, processes without heat exchange with the environment;

2.

The similarity theory does not account for the various methods of compressor cooling;

3. The theory of similarity does not take into account the ingress of droplet moisture into the working environment of the compressor;

4. The similarity theory takes into account only stationary and quasi-stationary flows of the working medium;

5. Also, the similarity theory neglects the fact that the initial velocity and turbulence in the flow at the compressor inlet can have a significant effect on the flow of the working fluid inside the compressor;

This work is devoted to the study of the feasibility of applying the methods of the theory of similarity in relation to methane compressors at low temperatures.

## 2 Materials and methods

### 2.1 Similarity criteria

The equations of the similarity theory are based on the following principle [3]:

$$\varepsilon, \eta_i, N_i = f(Q, p_h, \gamma_h, k, v_h, D_2, n, \lambda, C_p). \quad (1)$$

In this equation, the thermal conductivity  $\lambda$  and isobaric heat capacity are used to take into account various internal thermal effects associated with friction, energy transformation, and uneven heat distribution in the flow.

Applying the theory of dimensions to equation 1, we obtain the following dependence [3]:

$$\varepsilon, \eta_i, N_i / (\gamma_h D_2^5 n^3) = f(\Pi_1, \Pi_2, \Pi_3, \Pi_4, k). \quad (2)$$

Using the similarity numbers in relation to equation 2, we obtain [3]:

$$\varepsilon, \eta_i, N_i / (\gamma_h D_2^2 u_2^3) = f(\varphi, M_u, \text{Re}_u, \text{Pr}, k). \quad (3)$$

It is important to note that the value of the Prandtl criterion  $\text{Pr}$  for most of the considered media is narrowly limited within the difference of no more than 30%. This, in turn, suggests that the influence of this coefficient is incomparably lower than the influence of other parameters. In addition, the Prandtl criterion value itself often does not have a significant effect on compressor operation. All this leads to the fact that this value can be excluded from the calculation. Thus, the above equation 3 will take the following form [3]:

$$\varepsilon, \eta_i, N_i / (\gamma_h D_2^2 u_2^3) = f(\varphi, M_u, \text{Re}_u, k). \quad (4)$$

Applying the above equation, you can solve three main problems of the similarity theory:

1. Simulation of full-scale tests of turbochargers

As mentioned in the introduction, this item allows you to save resources when carrying out various complex or laborious experiments, which significantly reduces the cost and simplifies the work with many experimental models.

2. Recalculation and simulation of machines operating in a non-air environment

Also, this equation is the basis for the technique of recalculating a real gas, which makes it possible to study the gas without resorting to expensive experiments on a full-scale model or computer simulation. [4] And although computer methods are often used in the design of new compressor equipment, they are often used only to adjust and refine the model compressor, in order to increase its efficiency [6, 7]. The data obtained from the similarity theory can serve as the basis for such a model.

3. Design of new compressor equipment based on the theory of similarity

This is a logical conclusion from points 1 and 2 of this list, because the design of new equipment is closely related to the creation of models, carrying out field experiments and using model data.

Observing the principles of similarity, namely  $M_u = idem$ ,  $Re_u = idem$  and  $k = idem$ , the following dependencies can be obtained for the model and full-scale compressors [3]:

$$u_2^X = u_2 \sqrt{R^X T_n^X / (RT_n)}; \quad (5)$$

$$I = u_2 \sqrt{R^X T_n^X / (RT_n)} p_n \mu_n^X / (p_n^X \mu_n), \quad (6)$$

where X denotes the parameters of the model compressor.

Thus, for air testing for a model compressor, the following relationships should be applied:

$$n^X = n \sqrt{R^X T_n^X / (RT_n)}; \quad (7)$$

$$p_n^X = p_n \sqrt{R^X T_n^X / (RT_n)} \mu_n^X / \mu_n. \quad (8)$$

At the same time, when designing a new compressor, it is necessary to ensure the equality of all 4 similarity criteria, and the scale factor takes the following form:

$$I^2 = \sqrt{RT_n / (R^X T_n^X)} Q^X / Q. \quad (9)$$

To create a new compressor using a similar technique, it is necessary to observe the equality of the factor I according to equations 6 and 9, which imposes certain restrictions on this theory.

However, despite all the above disadvantages and limitations, this method combines high simplicity and efficiency.

## 2.2 Similarity criteria Benedict-Webb-Rubin equation of state

In this paper, two equations for describing low-temperature methane are considered, and the Benedict-Webb-Rubin equation of state [8-11] and the Peng-Robinson equation of state [12-14].

In its standard form, the Benedict-Webb-Rubin equation looks like this [8]:

$$p = RT\rho + \left( B_0RT - A_0 - \frac{C_0}{T^2} \right) \rho^2 - (bRT - a) \rho^3 + a a \rho^6 + \frac{c \rho^3}{T^2} (1 + \gamma \rho^2) \exp(-\gamma \rho^2). \quad (10)$$

However, often, for practical calculations of various gases, various modifications of various equations are used. In this work, to describe the properties of pure methane, a modification of the Benedict-Webb-Rubin equation proposed by VNIIGaz (BWR) in the following form was used [15]:

$$Z^3 - Z^2 - Z \left( \frac{a_1}{\tau} - \frac{a_2}{\tau^2} - \frac{a_3}{\tau^4} \right) \pi - \left( \frac{a_4}{\tau^2} - \frac{a_5}{\tau^3} + \frac{a_6}{\tau^5} \right) \pi^2 = 0; \quad (11)$$

$$\frac{1}{Y} = 1 + \frac{1}{Z} \left[ Z - 1 + \left( a_4 - \frac{a_5}{\tau} + \frac{a_6}{\tau^3} \right) \cdot \frac{\pi^2}{\tau^2 Z^2} \right]; \quad (12)$$

$$X = \frac{Y}{Z} \left[ \left( \frac{a_2}{\tau} + \frac{3a_3}{\tau^3} \right) \cdot \frac{\pi}{Z\tau} + \left( \frac{a_5}{\tau} - \frac{3a_6}{\tau^3} \right) \cdot \frac{\pi^2}{Z^2 \tau^2} + Z \right] - 1; \quad (13)$$

$$\frac{\Delta C_p}{R} = \frac{Z(1+X)^2}{Y} + \frac{6a_3\pi}{Z\tau^4} - \frac{3a_6\pi^2}{Z^2\tau^5} - 1; \quad (14)$$

$$-\frac{\Delta i}{RT_{kp}} = \tau \left[ \left( \frac{a_2}{\tau} + \frac{3a_3}{\tau^3} \right) \cdot \frac{\pi}{Z\tau} + 0,5 \left( \frac{a_5}{\tau} - \frac{3a_6}{\tau^3} \right) \cdot \frac{\pi^2}{Z^2 \tau^2} + 1 - Z \right]; \quad (15)$$

This equation is suitable for describing natural gas with a high methane content at low pressure and medium temperature, however, when describing methane at low temperatures at low pressures, it has a relatively high degree of accuracy.

Thus, in the study of methane at temperatures from 150 to 300 K and pressures not exceeding 1 MPa, the modified BWR equation allows one to describe the thermodynamic processes of methane with a high accuracy, which confirms the coincidence of the curves of thermodynamic perimeters obtained by calculation with the experimental curves [8, 16-18].

## 2.3 Peng Robinson's equation of state

The Peng-Robinson equation is a modification of the Redlich-Kwong equation with a higher degree of accuracy.

In standard form, the Peng-Robinson equation of state for a real gas is as follows [12-14]:

$$p = \frac{R \cdot T}{v - b} - \frac{a}{v \cdot (v + b) + b \cdot (v - b)}. \quad (16)$$

This equation has a high degree of accuracy over a very wide range of temperatures and pressures.

Thus, in this work, using the Benedict-Webb-Rubin and Peng-Robinson equations, the thermodynamic properties of the gas under study, pure methane, were described for all the points under study. The use of two different equations made it possible to achieve a higher accuracy of calculations, as well as to study the invariance of methods for recalculating methane when using various equations of state for a real gas.

#### 2.4 Auxiliary calculation methods

To describe a model compressor, it is also necessary to apply auxiliary equations of the main characteristics of the unit [19-23].

To calculate the internal head of the compressor, use the equation:

$$h_i = \varphi_{u_2} (1 + \beta_l + \beta_{fr}) u_2^2. \quad (17)$$

To calculate the coefficient of theoretical pressure, we use the equation:

$$\varphi_{u_2} = 1 - \varphi_{r_2} \operatorname{ctg} \beta_{l_2} - \frac{\pi}{z_2} \sin \beta_{l_2}. \quad (18)$$

And to determine the loss factor, we use:

$$\beta_l + \beta_{fr} = \frac{0,12 + \frac{0,18}{\varphi_{u_2}}}{1000 b_2 \varphi_{r_2}}. \quad (4)$$

Based on the above dependencies and applying the laws of thermodynamics and methods for designing compressors on model units, it is possible to obtain a complete set of all key compressor parameters, of which  $\eta$  are important for this work. and the degree of pressure increase P.

### 3 Results

During the work, 4 compressor models were investigated:

- Model of a full-scale low temperature methane compressor using the BWR equation. Next - Me (BWR)
- Model of a full-scale low temperature methane compressor using the PR equation. Next - Me (PR)
- Model of a model air compressor using the BWR equation. Next - N (BWR)
- Model of a model air compressor using the PR equation. Next - N (PR)

When investigating the recalculation technique, a compressor model with fixed geometric parameters was designed. Each of the full-scale models was calculated based on the above geometry with the following fixed gas-dynamic parameters.

Compressor pressure ratio P = 1.3.

Compressor efficiency  $\eta = 0.77$ .

Based on the above parameters, the characteristics of full-scale compressors were obtained. At the next stage of work, using the similarity criteria, the characteristics of the model compressors were obtained.

Thus, consider the characteristics of the compressors below.

The dependences of the pressure increase  $P$ , the initial pressure  $p_n$ , the shaft rotation speed  $n$  and the internal compressor head were plotted for all four compressor models depending on the temperature of the test gas and are shown in Figures 1, 2, 3 and 4.

It is important to note that model compressors in air have an initial temperature of the working medium  $T_n = 300$  K, regardless of the compressor operating mode. And also, for the sake of assessing the accuracy of the methods, a graph of the dependence of the efficiency for all modes was built.

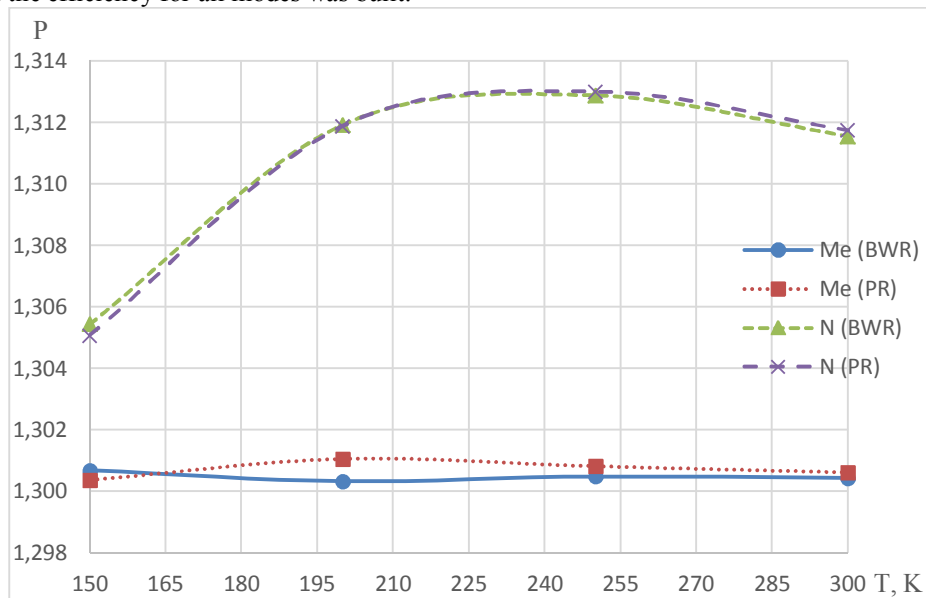


Fig. 1. Graph of the dependence of the degree of pressure increase P on the temperature of pure methane.

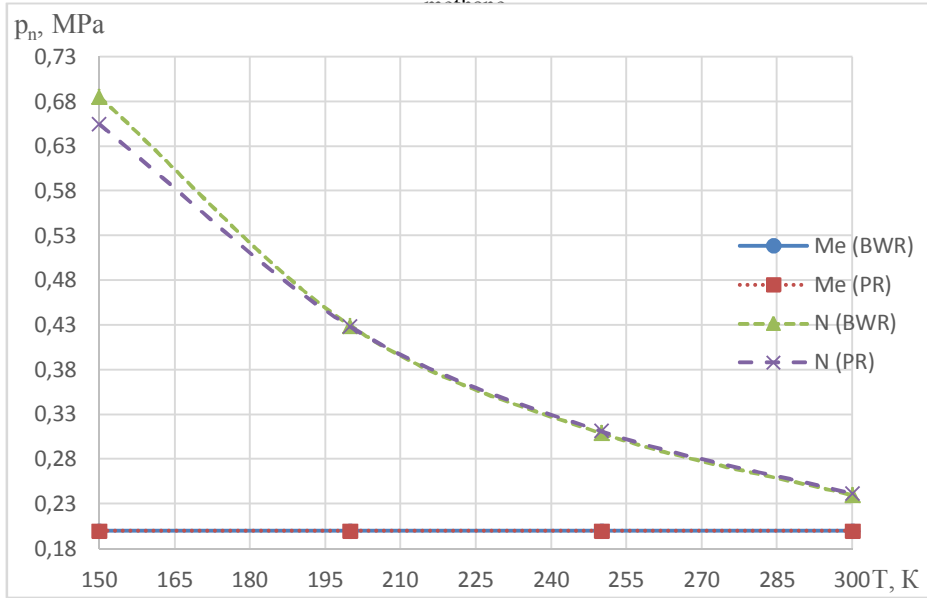


Fig. 2. Graph of initial pressure p<sub>n</sub> versus pure methane temperature.

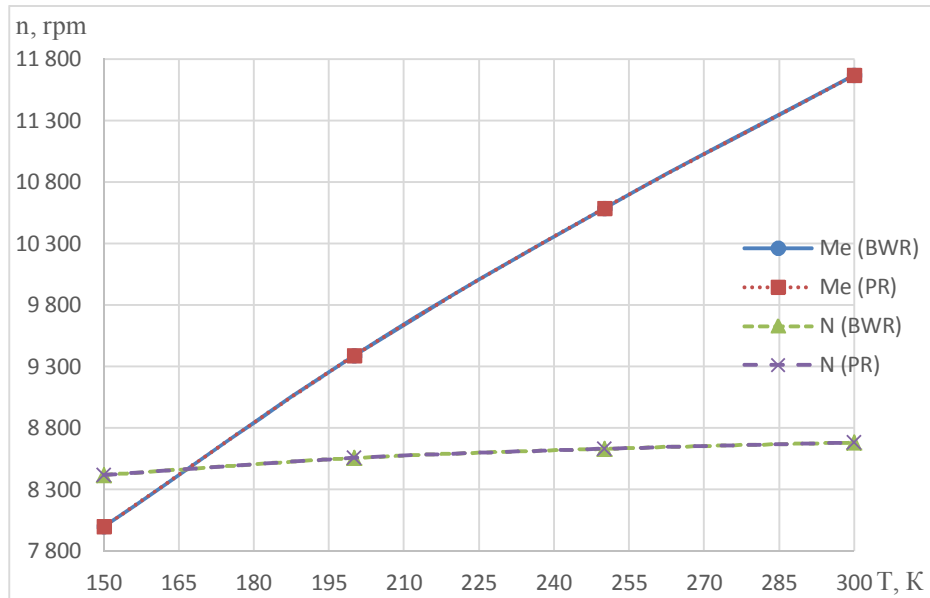


Fig. 3. A graph of the dependence of the shaft rotation speed n on the temperature of pure methane.



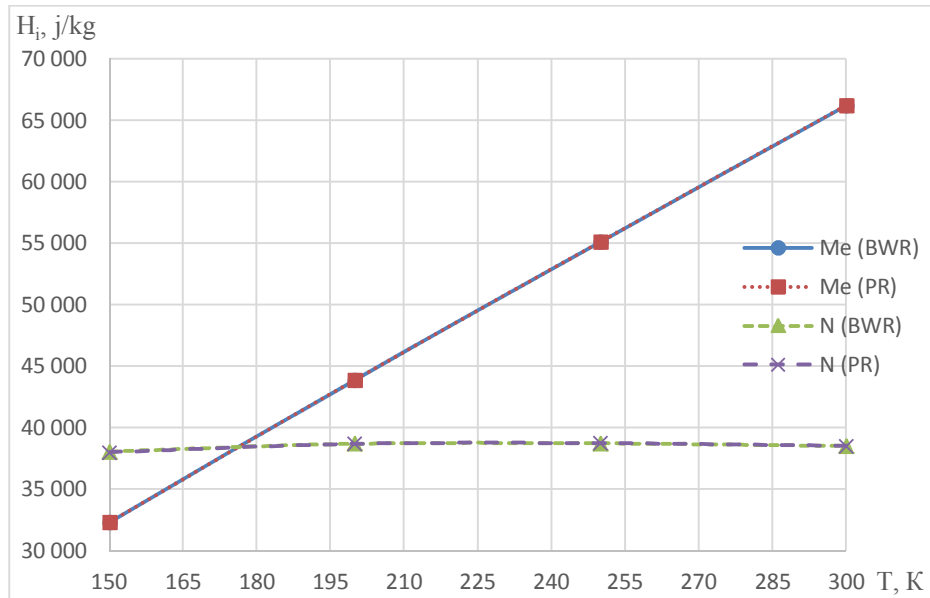


Fig. 4. Compressor internal head  $H_i$  versus pure methane temperature.

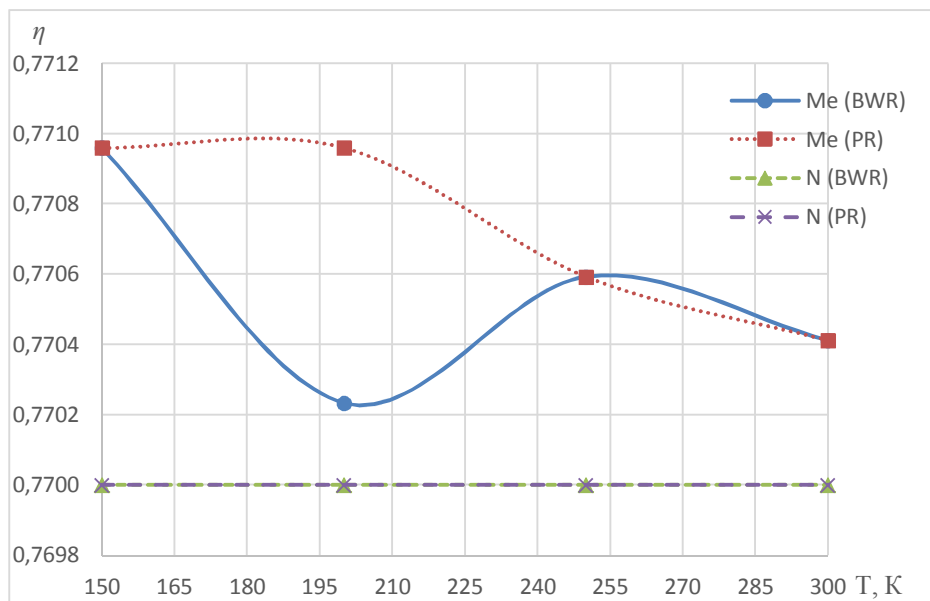


Fig. 5. Graph of compressor efficiency  $\eta$  versus pure methane temperature.

## 4 Discussion

As can be seen from the above graphs, the study showed some important factors and features of the methodology for converting real methane to air and the application of a similar methodology for the study and design of low-temperature methane compressors.

First, this technique is absolutely invariant from the way of describing the reality of a gas in the study of both a model and a full-scale compressor. This is evidenced by the almost perfect coincidence of the curves for two different equations, both on full-scale models and on model ones.

Secondly, this technique, despite many drawbacks and limitations, shows high accuracy for the results. This is evidenced by the practical complete coincidence of the key gas-dynamic parameters, on which the comparison was made - the efficiency and the degree of pressure increase. Thus, despite significant differences in the initial operating conditions of the compressor, up to the difference in working environments, thanks to this technique, it was possible to obtain an almost perfect match between model and full-scale compressors.

Third, the pressure curve, the pressure curve and the speed curve were obtained for all modes. The data indicate that for the study of methane at low pressure, it is necessary to supply air to the model compressor at high pressure; with an increase in the temperature of methane, the required initial pressure drops, but in contrast to this, the number of revolutions and the required drive power for the compressor increase. This is most likely due to the fact that for simulating a colder medium, it is necessary to use a denser and heavier medium, which is confirmed by the experimental data, and when simulating a lighter medium, the pressure required for its compression increases [24].

Oddly enough, but contrary to the theoretical assumption that the colder the simulated medium, the lower the accuracy of the model was incorrect and, as a result, the experimental picture turned out to be diametrically opposite - the gas recalculation technique works more accurately at low temperatures, as applied to pure methane.

## 5 Conclusion

In the course of the work, a technique was studied for recalculating real gas for a low-temperature methane compressor. Experimental data on 4 models of compressors were studied, 2 of which are full-scale methane units, 2 are air model units. The influence of the choice of the equation of state of a real gas for the description of such models is also studied.

As a result of the work, the effectiveness of such methods has been proved on the entire volume of experimental data, especially in the low-temperature region.

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