UDC 681.518.22 DOI:

The usage of statistical analysis methods for controlling the operational stability of Gas Treatment Facility

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Abstract

The paper considers the solutions to the scientific and practical task of improving the accuracy and reliability of natural gas consumption by conducting a statistical analysis of the results of gas pressure measurements in the pipeline, obtained from three pressure sensors during 12 hours. The importance of this task is underlined by the fact that the confidence interval for RMS errors is usually very wide. Testing of the hypothesis of the instability absence in the process of measuring gas pressure is carried out using a single factor dispersion analysis (the equation of the median values), a linear regression analysis (no influence of time on the value of the indicator for each voter) and a covariance analysis (no difference in the functional influence of the time on the number of an indicator). Three series of the measurement results of X control indicator (gas pressure in the pipeline) have been used. The analysis has confirmed the hypothesis that there are no disruptions to the stability of the gas pressure measurement process, which makes the pressure sensors metrologically reliable. It has been proved that the scientific and applied problems of increasing the reliability of objects control and diagnostics with stochastic parameters and improving their metrological reliability are relevant and important for the development of the theory and practice of non-destructive control and functional diagnostics of objects.

Keywords: gas equipment; metrological reliability; statistical evaluation.

Received: 21.12.2020 Edited: 25.01.2021 Approved for publication: 29.01.2021

Introduction

Improving the efficiency of natural gas use is its accurate and reliable accounting, which is also necessary when making calculations between suppliers and consumers. Given the fact that the task of metrological control of gas metering complexes is quite relevant, there is a correct and accurate accounting of gas consumption supplied to the general gas pipeline. The automated computing complex collects data using the measuring equipment that the Gas Treatment Facility (GTF) is equipped with.

The dispersion analysis is based on a number of assumptions about a random value and the parameters that form the error of the experiment [1–3]: the mathematical expectation of each residual random variable is zero, i.e. there is no systematic component; the residual random variables are relative independent (this requirement means that the sum dispersion of all residual random variables is equal to the sum of the dispersions of these variables) all residual random variables have the same mean variation (this is an assumption about the dispersion homogeneity) each residual random variable is distributed according to a normal law (this assumption is usually not fulfilled, but even significant variations do not have a noticeable effect on the analysis procedure). In contrast to dispersion and regression analysis, covariance analysis aims to investigate the nature of the relationship between a dependent response value and a set of quantitative and qualitative independent predictor variables and to construct a regression model, i.e., it is a kind of regression and variance analysis synthesis [2]. Only the combined use of the three types of analysis makes it possible to draw an objective conclusion about the metrological reliability of measuring equipment (in our case these are gas pressure sensors).

Analysis of recent research and publications

The analysis methods for the stability of technological processes can be divided into two groups: methods of statistical evaluation of control indicators – used to test random deviations of indicators, their compliance with acceptable values; methods of parametric testing of random deviations, to check the dispersion stability of measured values over time. The practical tasks of these methods are the following: the calculation of control and warning limits; the evaluation of the minimum number of measurements, which makes it possible to draw the conclusions about the accuracy disruptions in technological processes [1]. The stability testing of the parameters is reduced to the stability testing of average values of control indicators [2]. Mathematical models of testing are based on the parametric models of dispersion, regression and covariance analyses (multidimensional statistical analysis) [3]. It is worth noting the usage of the regression analysis in the planning of scientific experiments in the tasks of many parametric identification of dynamic objects in medical practice [4] and the evaluation task of measurement accuracy for a linear frequency-modulated continuous radiolocation monitoring of the radar shift [5]. The improvement of metrological reliability of measuring instruments is considered in the publication [6]. The author has justified the criteria of the signal differences and ratios for calculating dynamic error indicators for stationary and non-stationary processes. In the paper [7] the approaches to ensuring high metrological stability of measurements by increasing the metrological integrity of the production measuring systems are suggested. The problems of metrological reliability of gas equipment are directly discussed in [8–9].

The main text

The aim of the study is to test the hypothesis that there are no disruptions to the stability of the measurement process by using three series of measurement results of the X control indicator (gas pressure in the pipeline) obtained from three pressure sensors during 12 hours (i = 1, 2, ... 12 hours) with the help of the following: a single-factor dispersion analysis (the equality of the average values); a linear regression analysis (no effect of time on the value of the indicator for each card); a covariance analysis (no differences in the functional impact of time on the X control indicator). The confirmation of hypotheses will help to conclude about the metrological reliability of measuring instruments, particularly the pressure sensors. The main task of metrological control at Gas Treatment Facility (GTF) is to correctly and accurately record the flow of gas supplied to the general gas pipeline. The main measuring instruments for calculating gas consumption at the Gas Treatment Facility are the following: an angular method of pressure difference selection by means of a narrower; a differential pressure sensor; a temperature sensor and an autonomous computing complex forming a measuring section (Fig. 1).

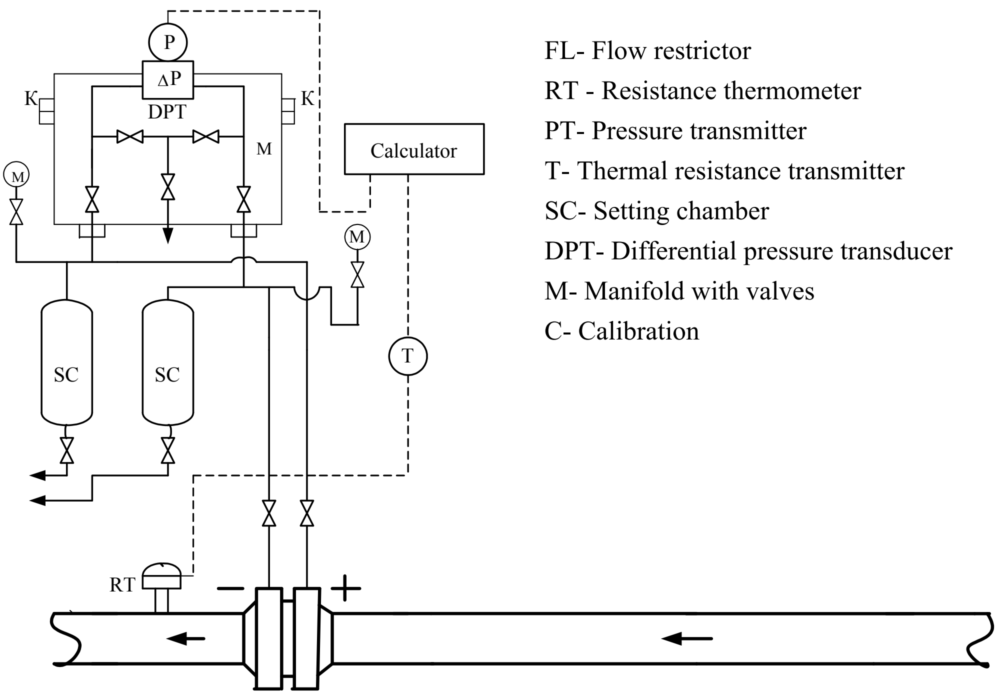
An autonomous computing complex collects data using measuring instruments. Data on the gas composition obtained in the chemical and analytical laboratory is entered into the compotator remotely by the dispatcher. The method of dispersion analysis consists in checking by F criterion of H_0 null hypothesis about the equality of factor and residual dispersion [3].

We choose that X is a control indicator, in the course of value measuring of which obtained samples F_j. Let $\bar{X}$ is the average value of all the results of the observation N, and $\bar{X}_i$ is the average value of j-th sample. We propose the hypothesis: H_0: $H_0 : \bar{X}_1 = \bar{X}_2 = \ldots = \bar{X}_k = \bar{X}$ (the process has no disruptions), then the following is true:

$$X_{ji} = \bar{X} + \gamma_j + e_{ji}, \tag{1}$$

where γ_j – a deviation caused by a factor; e_{ji} – a random deviation in the j-th group, for the i-th observation.

The model (1) is divided into two options: a) α parametric; b) α, P random. The model (1) is a qualitative one-factor model for dispersion analysis. If there is a systematic shift in the mean value of the monitored indicator, a quantitative model of dispersion analysis is used to detect this shift



FL- Flow restrictor
RT - Resistance thermometer
PT- Pressure transmitter
T- Thermal resistance transmitter
SC- Setting chamber
DPT- Differential pressure transducer
M- Manifold with valves
C- Calibration

Fig. 1. Measuring section

$$x_i = b_0 + b_i t_i + e_i. \quad (2)$$

If in the model (2) coefficients b_0, b_1 are random values, the measurement result of indicator x is

$$x_{ij} = (b_0 + \Delta b_j) + (b_0 + \Delta b_j) \cdot t_{ij} + e_{ij}. \quad (3)$$

The model (3) identifies disruptions in accuracy and stability. The results of the dispersion analysis are summarized in Table 1.

$$F = \frac{\bar{S}_1}{\bar{S}_2},$$

where F is a random value with F-distribution.

The data obtained from the pressure sensors are shown in Table 2. We give the desired reliability of the conclusion – we set the level of significance $\alpha = 0.05$ ($P = 0.95$). The mean value on the results of three samples: $\bar{X} = 3531.5$ Pa.

We determine the total, factor and residual sum of deviation squares from the average. The total sum of the squares of deviation of the observed values from the total average:

$$S_G = \sum_{j=1}^{p} \sum_{i=1}^{q} (X_{ij} - \bar{X})^2,$$

$S_G = 161.25$ kg/m³.

The factor sum of the group average deviations from the total average characterizing the variation between groups

$$S_F = q \sum_{j=1}^{p} (\bar{X}_{gr\,j} - \bar{X})^2,$$

$S_F = 20.42$ kg/m³.

The residual sum of the deviation squares of the observed values of a group from its group average characterizing the variation within groups.

$$S_R = \sum_{i=1}^{q} (X_{i1} - \bar{X}_{gr1})^2 + \sum_{i=1}^{q} (X_{i2} - \bar{X}_{gr2})^2 + \ldots + \sum_{i=1}^{q} (X_{iN} - \bar{X}_{grN})^2,$$

$S_R = 140.83$ kg/m³.

By dividing the squares sums by the corresponding number of degrees of freedom, we obtain total, factor and residual dispersions:

$$S_G^2 = \frac{S_G}{k \cdot N - 1}, \quad S_F^2 = \frac{S_F}{k - 1}, \quad S_R = \frac{S_R}{k \cdot (N - 1)}$$

$$S_G^2 = \frac{S_G}{12 \cdot 3 - 1}, \quad S_F^2 = \frac{S_F}{12 - 1}, \quad S_R^2 = \frac{S_R}{12 \cdot (3 - 1)}.$$

$S_G^2 = 4.607$ kg/m³; $S_F^2 = 1.856$ kg/m³; $S_R^2 = 5.868$ kg/m³.

If the H_0 hypothesis [1, 2] is true, then all these dispersions are unbiased evaluations of the general dispersion. We can show that the null hypothesis test is reduced to a comparison of the factor and residual dispersion by the Fisher – Snedecor criterion [2].

1. Let us suppose that hypothesis H_0 is correct. Then the factor and residual dispersion are unbiased evaluations of the unknown general dispersion and therefore differ only slightly. Therefore, the result of the Fisher – Snedecor criterion (F) will prove that the null

Table 1

The Dispersion Analysis Results

The impact source	The number of degrees of freedom	The squares sum of deviations	The average deviation square (dispersion)
γ_i	$W_1 = k - 1$	$S_1 = \sum_{j=1}^{K} n_j \left(\bar{X}_j - \bar{X}\right)^2$	$\bar{S}_1 = \frac{S_1}{W_1}$
e_{ji}	$W_2 = N - k$	$S_2 = \sum_{j=1}^{K} \sum_{i=1}^{n_j} \left(X_{ji} - \bar{X}_j\right)^2$	$\bar{S}_2 = \frac{S_2}{W_2}$
$(\gamma_i + e_{ji})$	$W = N - 1$	$S = \sum_{j=1}^{K} \sum_{i=1}^{n_j} \left(X_{ji} - \bar{X}\right)^2$	$\bar{S} = \frac{S}{W} = D_X$

Table 2

The Output data

	i, h	1	2	3	4	5	6	7	8	9	10	11	12	$\bar{X}_{gr\,j}$
The output signal values of P, kg / m³	F_1 Sample	6534	6534	6533	6531	6531	6529	6533	6530	6530	6533	6530	6531	6531.583
	F_2 Sample	6534	6535	6533	6529	6530	6530	6533	6530	6530	6533	6530	6531	6531.5
	F_3 Sample	6535	6535	6533	6529	6529	6528	6533	6532	6531	6533	6530	6529	6531.417

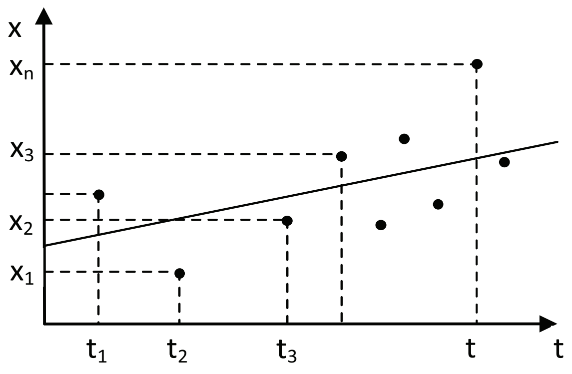


Fig. 2. Sampling of the n-pair observations

hypothesis is accepted. Thus, if the hypothesis about the equality of mathematical expectations of general sets is correct, the hypothesis about the equality of factor and residual dispersions is also correct (3).

2. If the null hypothesis is incorrect, then as the variance between the mathematical expectations increases, the factor variance increases and the ratio $F_L = \frac{S_F^2}{S_R^2}$ increases together with it. Therefore, as a result, F_L will be larger than F_C and the hypothesis of equality of dispersion will be rejected. Thus, if the hypothesis of equality of mathematical expectations of general sets is false, the hypothesis of equality of factor and residual dispersion is also false [3]: F_L = 0.316, F_C= 3.32. Since $F_C > F_L$, the hypothesis of equality of mathematical expectations of general sets is confirmed, and consequently, the hypothesis of equality of factor and residual dispersion is also confirmed. Suppose that X is a control indicator for which a sample of n-pair observations $\{X_i, t_i\}$ is obtained (Fig. 2) [2].

$$X = (X_1,\ t_1),\ (X_2,\ t_2),.....(X_n,\ t_n),$$

where X_i is the measured value of the indicator; t_i is the time moment of the observation.

The obtained time row can be approximated by a linear function $\hat{X}_i = a + b \cdot t_i$ – a linear regression model. For a stable technical process, the angular coefficient $b=0$, thus for an unstable technical process, – $b \neq 0$. The initial conditions: the law of the distribution of the X_i values relative to the $\hat{X}_i$ line is normal. The measurement result $x_i = \hat{X}_i + e_i$ (the residual e_i is a random component of the regression model) [2].

$$X_i = \hat{X}_i + e_i \tag{4}$$

$$X_i = a + b \cdot t_i + e_i,$$

where X_i is the full observation model of the X indicator.

To calculate the coefficients a, b we use the method of the least squares method (LSM). We find the sum of squares of deviation of X_i values from the $\hat{X}_i$ regression.

$$L = \sum_{i=1}^{n}\left[X_i - (a + b \cdot t_i)\right]^2 = \sum_{i=1}^{n}(X_i - a - b \cdot t_i)^2 = \min.$$

$$\left.\begin{cases} \frac{\partial L}{\partial a} = 2\sum_{i=1}^{n}(X_i - a - b \cdot t_i)\cdot(-1) = 0 \left| \sum_{i=1}^{n} X_i - n \cdot a - b\sum_{i=1}^{n} t_i = 0 \right. \\ \frac{\partial L}{\partial a} = 2\sum_{i=1}^{n}(X_i - a - b \cdot t_i)\cdot(-t_i) = 0 \left| \sum_{i=1}^{n} X_i \cdot t_i - a\sum_{i=1}^{n} t_i - b\sum_{i=1}^{n} t_i^2 = 0 \right. \end{cases}\right\}, \tag{5}$$

where (6) is a system of normal equations [2].

$$a = \frac{1}{n}\sum_{i=1}^{n} X_i - b\left(\frac{1}{n}\sum_{i=1}^{n} t_i\right) = \bar{X} - b \cdot \bar{t}, \tag{6}$$

$$b = \frac{\frac{1}{n}\sum_{i=1}^{n} X_i \cdot t_i - \left(\frac{1}{n}\sum_{i=1}^{n} X_i\right)\cdot\left(\frac{1}{n}\sum_{i=1}^{n} t_i\right)}{\frac{1}{n}\sum_{i=1}^{n} X_i^2 - \frac{1}{n}\sum_{i=1}^{n} t_i^2} = \frac{\mathrm{cov}(X,t)}{D_x}, \tag{7}$$

where cov is the second order bonding moment [2]

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i, \qquad \bar{t} = \frac{1}{n}\sum_{i=1}^{n} t_i.$$

The standard residual deviation is determined by the formulas:

$$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X - \bar{X})^2}. \tag{8}$$

$$\sigma_t = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(t - \bar{t})^2}. \tag{9}$$

The pair correlation coefficient:

$$R^2 = \frac{\mathrm{cov}^2(Xt)}{D_x D_t}, \tag{10}$$

where $D_x = \sqrt{\sigma_x}$, $D_t = \sqrt{\sigma_t}$, $\mathrm{cov}^2(Xt)$ is the covariance between X and t.

$$F = \frac{R^2}{1 - R^2}(n-2). \tag{11}$$

Now from the Table of F-distributions we choose F_C, equal to $F_C = F_{1,(n-2),\alpha}$. If $F < F_C$, then the hypothesis of the process stability is confirmed [2].

Using the data from the Table 2, let us consider F_1 sample. The standard residual deviations are determined according to formulas (8) and (9). After the calculations we have obtained the following results: σ_x=1.72982, σ_t=3.60555.

The direct regression is described by the following equation: $\bar{X} = a + b\bar{t}$. The values of a and b are determined by formulas (6) and (7), respectively. After the calculations, the following results have been obtained: a=-2.31266, b=6546.616.

In order to test the hypothesis that there are no disturbances in the stability of the technological control using a regression analysis model, it is necessary to calculate R^2 pair correlation coefficient. We calculate it by the formula (10). The following results are obtained: D_x=2.992277889, D_t=13, R^2=-0.07819272.

In order to disprove or confirm the hypothesis of a disturbance in the stability of the technological process using a regression analysis model, it is necessary to calculate F_p coefficient according to the formula (11): F_p=-0.84825458.

Table 3

The result of the covariance analysis

The impact source on x_i	The sum of deviation squares	The number of degrees of freedom	The average square
B_0	$S_0 = \omega_0 + B_0^2 = 429.0719$	$\nu_0 = 1$	$\bar{S}_0 = \frac{S_0}{1} = S_0$
(AB)	$S_{AB} = S - S_0 - S_R = -1003.31$	$\nu_{AB} = 2k - 2 = 4$	$\bar{S}_{AB} = \frac{S_{AB}}{\nu_{AB}} = 35.25$
The random residual	$S_R = \sum_{j=1}^{k}\sum_{i=1}^{n_j}(x_{iji} - A_j - B_j \cdot t_{ji})^2 = 715.2355$	$\nu_R = N - 2k = 6$	$\bar{S}_R = \frac{S_R}{\nu_R} = 119.2$
Total	$S = \sum_{j=1}^{k}\sum_{i=1}^{n_j}(x_{ji} - \bar{x})^2 = 141$	$\nu = N - 1 = 11$	–

It is necessary to compare F_p estimated coefficient with F_C that is chosen from the Table of 5% of the F-distribution points [2]:

$$F_c = F_{1,(n-2),\alpha} = F_{1,10,0.05}.$$

F_c is equal to 2.97. Hence $F_p < F_C$ then the hypothesis of the stability of the process is confirmed, the F_1 sample is accepted. Using the above formulas, a similar calculation is performed for the F_2 and F_3 samples. The standard residual deviations for the F_2 sample are following: $\sigma_x = 1.9884$, $\sigma_t = 3.6056$.

The coefficients needed for the construction of the direct regression we determine from the formulas (6) and (7) accordingly: $a = -0.2447$, $b = 6533.0909$. The R^2 coefficient of the pair correlation we determine from the formula (10): $R^2 = -0.05674648$. The F_p coefficient from the formula (11): $F_p = -0.60160372$. F_C is equal to 2.97 [2]. Hence $F_p < F_C$ then the hypothesis of the stability of the process is confirmed, the F_2 sample is accepted. The standard residual deviations for the F_3 sample are following: $\sigma_x = 2.4571$, $\sigma_t = 3.6056$. The coefficients needed for the construction of the direct a and b regressions are following: $a = -0.3042$, $b = 6533.3939$.

The coefficient of the pair correlation R^2 we determine from the formula (10): $R^2 = -0.04618531$. The F_p coefficient from the formula (11): $F_p = -0.48421682$. F_C is equal to 2.97 [2]. Since $F_p < F_C$ then the hypothesis of the stability of the process is confirmed, the F_3 sample is accepted. The covariance patterns of instability are based on the dispersion analysis of the linear dispersion coefficients [2]:

$$\hat{x}_{k_i} = A_k + B_k \cdot t_i,\ i = \overline{1, n_k};$$

$$\hat{x}_{ji} = A_j + B_j \cdot t_i,\ i = \overline{1, n_j};$$

$$\sum_{j=1}^{k} n_j = N.$$

The total regression is of the form:

$$\hat{x}_i = A + B \cdot t_i,\ i = \overline{1, N}. \quad (12)$$

We can analyze at least three regressions. The results of the covariance analysis are summarized in Table 3.

Hypothesis tests [2]:

1. $F_0 = \frac{\bar{S}_0}{\bar{S}_R} = 3.59$, from the Table of 5% of the F-distribution points [2] we choose F_C, equal to $F_C = F_{1,(N-2k),\alpha} = F_{1,6,0.05} = 4.49$. Hence $F_0 < F_C$, then this indicates that the process is stable.

2. $F_1 = \frac{\bar{S}_{AB}}{\bar{S}_R} = 0.296$. In that case, we choose F_C, equal to $F_{2(k-1),(N-2k),\alpha}$. We choose F_C from the Table of 5% of the F-distribution points [2]: $F_C = F_{4,6,0.05} = 4.28$ [2]. Hence $F_1 < F_C$, then this indicates the absence of noise.

Conclusions

We have carried out the test of the hypothesis that there are no disturbances in the stability of the gas pressure measurement process at the Gas Treatment Facility (GTF) using a single factor dispersion analysis (equality of mean values), a linear regression analysis (no influence of time on the value of the indicator for each sample), a covariance analysis (no difference in the functional influence of the time on the number of X indicator) in the paper. Three series of the measurement results of the X control indicator (gas pressure in the pipeline) obtained from three pressure sensors for 12 hours ($i = 1, 2, \ldots 12$ hours) have been used. The analysis has confirmed the hypothesis that there are no disruptions to the stability of the gas pressure measurement process, which makes the pressure sensors metrologically reliable. This conclusion is based on the fact that during measurements at Gas Treatment Facility, assuming that deviations follow a normal distribution law, the confidence interval

$\overset{o}{\Delta}_{\partial} = \pm 2\sigma_{\overset{o}{\Delta}} = \pm 7$ kg/m^3 ($P = 0.95$) is used. As a result, to confirm that the maximum allowable flow instability is not exceeded, the measurements should be taken more frequently (at least every half an hour) to determine accurately the distribution law of the measurement results and the limits of the confidence interval.

Використання методів статистичного аналізу для контролю стабільності роботи установки комплексної підготовки газу

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Анотація

Розглянуто вирішення науково-практичної задачі підвищення точності та достовірності обліку природного газу шляхом проведення статистичного аналізу результатів вимірювань тиску газу у трубопроводі, отриманих із трьох давачів тиску впродовж 12 годин. Правильний і точний облік витрат газу є актуальним завданням метрологічного контролю. Важливість цього завдання підкреслюється тим, що довірчий інтервал для середньоквадратичних помилок виявляється зазвичай вельми широким. Перевірка гіпотези про відсутність порушення стабільності процесу вимірювання тиску газу проводиться за допомогою однофакторного дисперсійного аналізу (рівності середніх значень), лінійного регресійного аналізу (відсутність впливу часу на величину показника за кожною вибіркою), коваріаційного аналізу (відсутність розходжень у функціональному впливі часу на величину показника). Спільне використання трьох видів аналізу дає змогу зробити висновок про метрологічну надійність засобів вимірювальної техніки. Використано три серії результатів вимірювань показника контролю X (тиск газу у трубопроводі). Аналіз підтвердив гіпотезу про відсутність порушень стабільності процесу вимірювання тиску газу, що дає змогу визнати давачі тиску метрологічно надійними. Доведено, що наукова й прикладна проблеми підвищення вірогідності контролю й діагностики об'єктів зі стохастичними параметрами, підвищення їх метрологічної надійності є актуальними й мають важливе значення для розвитку теорії й практики неруйнівного контролю, а також функціональної діагностики об'єктів. Рекомендовано, що для підтвердження неперевищення максимально допустимої нестабільності потоку вимірювання потрібно проводити частіше (як мінімум кожні пів години), щоб мати змогу точно визначити закон розподілу результатів вимірювань та границі довірчого інтервалу.

Ключові слова: газове устаткування; метрологічна надійність; статистичне оцінювання.

Использование методов статистического анализа для контроля стабильности работы установки комплексной подготовки газа

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Аннотация

Рассмотрены решения научно-практической задачи повышения точности и достоверности учета природного газа путем проведения статистического анализа результатов измерений давления газа в трубопроводе, полученных из трех датчиков давления в течение 12 часов. Проверка гипотезы об отсутствии нарушения стабильности процесса измерения давления газа производится с помощью однофакторного дисперсионного анализа (равенства средних значений), линейного регрессионного анализа (отсутствие влияния времени на величину показателя по каждой выборке), ковариационного анализа (отсутствие различий в функциональном воздействии времени на величину показателя). Использованы три серии результатов измерений показателя контроля *X* (давление газа в трубопроводе). Анализ подтвердил гипотезу об отсутствии нарушений стабильности процесса измерения давления газа, что позволяет признать датчики давления метрологически надежными. Доказано, что проблемы повышения достоверности контроля и диагностики объектов со стохастическими параметрами, повышения их метрологической надежности актуальны и имеют важное значение для развития теории и практики неразрушающего контроля, а также функциональной диагностики объектов.

Ключевые слова: газовое оборудование; метрологическая надежность; статистическое оценивание.

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