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DEVELOPMENT OF A METHOD FOR STUDYING GAS IMBALANCE IN THE SECTION OF THE MAIN GAS PIPELINE OF KAZAKHSTAN

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The existing models, methods, and technologies for managing the gas transmission system of the Republic of Kazakhstan have significantly become outdated. Therefore, during the operation of the gas transmission system, the phenomenon of a gas imbalance occurs. The presence of an imbalance leads to unjustifiably high technical and economic losses, as well as disagreements and disputes between consumers and suppliers of gas in the gas transmission system.

To eliminate this problem, the task was set to analyse the features of the AS for data collection, gas metering, and detection of an imbalance and its development, taking into account the identified features of the AS method for determining a gas imbalance and identifying the causes of its occurrence. It was proposed to consider a section of the main gas pipeline as a set of gas supply and consumption systems. A two-sided F-test was used as a general indicator of a gas imbalance at the site and for each element of the gas supply and consumption systems. It was shown that a comparison of the variances of samples for individual elements and for the area as a whole identified such reasons for a gas imbalance as measurement errors and changes in the operating modes. The developed method for determining a gas imbalance and identifying the causes of its occurrence makes it possible to assess quantitatively and qualitatively the gas imbalance at the section of the main gas pipeline and to determine the most significant cause of this imbalance.

The developed method was tested while analysing the metering data on gas transportation in the section of the main gas pipeline 'Bukhara Gas-Bearing Region-Tashkent-Bishkek-Almaty' for two calendar months. We analysed the data on the equality of the variances of the gas supply and consumption systems in this section, as well as the equality of the variances of the samples describing the operation of individual elements of these systems for two months. Solution options were proposed, which made it possible to formulate a conclusion about a change in the value of the gas imbalance and the main reason for this change

Keywords: gas imbalance, automated system, gas metering function, hypothesis of equality of dispersions, Fisher criterion, cause of imbalance

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1. Introduction

One of the main features of the gas transportation and distribution system operating in the Republic of Kazakhstan is the unification of all main gas pipelines into a single gas transmission system (GTS). Currently, the GTS of Kazakhstan consists of about twenty main gas pipelines in a multi-threaded design with reverse sections. In addition, the GTS of Kazakhstan includes sections connecting this system with the GTS of neighbouring countries and distribution networks.

The GTS of Kazakhstan is managed by the national company KazTransGas during the transportation and supply of gas to the domestic market [1]. One of the most important problems that this company has to solve is the problem of gas metering during transportation through the main gas pipelines and distribution to consumers. This problem is a very important task of the economy of gas production and gas transmission companies [2, 3].

To solve this problem, the control system of the GTS of Kazakhstan provides for the division of the system into

separate sections, the operational management of which is carried out from control centres. Operational management decisions made in control centres are based on the following data coming from production facilities [4, 5]:

– technical data of the main gas pipelines, compressor stations (CS), gas distribution stations (GDS), metering units (MU), and gas metering systems (GMS);

– technological data (pressure, temperature and other parameters of technological equipment of the main gas pipelines); and

– analytical data, which include, in particular, the gradual tendency of changes in pressure, temperature, gas volume, values of physicochemical parameters (PChPs) of the gas; the tendency of changes in the technical condition of the equipment on objects of the main gas pipeline, etc.

In this case, the control system of the GTS during the transportation and distribution of gas is entrusted with the work to ensure the efficiency and reliability of data received by control centres [6].

However, the current management system of Kazakhstan's GTS, including the processes of gas transportation and distribution within the country, is largely outdated. In particular, during the design of the major part of the main gas pipelines of Kazakhstan, built in the 1960s, there were no systems for automating the collection of measured data for control centres. The introduction of new automated data collection and control systems (SCADA) is carried out gradually and currently fails to cover all GTS facilities in Kazakhstan.

One of the consequences of the obsolescence of the control system of the GTS of Kazakhstan and the low pace of its modernisation is the presence of a gas imbalance. An imbalance is understood as inequality of volumes of supplied and consumed gas [7, 8]. The reasons for such inequality can be measurement errors (accidental and non-random), technological losses, unauthorised gas extraction, emergencies, changes in gas pumping regimes, gas metering in the population, closing volumes when meters and correctors are removed (repair, inspection), gas metering complexity due to overflows in the distribution networks [8–10]. The existence of an imbalance in the GTS leads to unreasonably high technical and economic losses, disagreements and disputes between consumers and gas suppliers. If the imbalance is negative, the gas supplier incurs significant losses. If the imbalance is positive, the supplier will have unjustified profits and consumers losses. Therefore, conducting research to determine the presence of an imbalance and localise its causes is relevant from a theoretical and practical point of view.

2. Literature review and problem statement

Currently, the phenomenon of a gas imbalance in general is formally represented as the difference between the volumes of supplied and consumed gas, expressed by a formula of the form [7, 8]:

$$V_{imbal}=(V_{cons}+V_{resid}+V_{loss})-V_{supply}, \qquad (1)$$

where V_{cons} is the volume of gas consumed, V_{resid} is the volume of residual gas in the pipe, V_{loss} is the volume of gas technological losses (inevitable losses) and own needs in the transportation and distribution of gas, and V_{supply} is the volume of gas supplied.

However, formula (1) helps to describe formally only the presence of a gas imbalance, not the causes of its occurrence. Therefore, many modern studies are aimed at developing and improving models and methods for determining a gas imbalance as a consequence of individual causes. Such studies focus on statistical models and methods. Thus, in [8] it was stated that the largest contribution to the total amount of an imbalance is made by both consumers and suppliers of gas whose meters have the largest measurement error. Therefore, in [8] considerable attention was paid to the mathematical description of a gas imbalance by analysing the values of the absolute and relative errors of the equipment of the gas metering units. In addition, in [8] it was proposed to determine the presence of a gas imbalance by comparative analysis of the variances of the absolute errors of the gas supplier and consumers. However, the tests were based on the hypothesis of even distribution of both supplied and consumed gas. In this case, [8] did not provide sufficient evidence for the validity of this hypothesis.

In [12], two methods were proposed for estimating the degree of the imbalance in the volumes of gas supplied and consumed. The first method was suggested to be used in conditions when all the errors of gas metering are known to both the supplier and consumers. The second method was proposed to be used in conditions when the collection of detailed information on all means of gas metering is not possible. This method involves estimating the mean value of a gas imbalance and its standard deviation, after which the error of the mean value of the gas imbalance is calculated. The degree of the imbalance is considered random in this method if the value of the estimate of the mean value of the imbalance does not exceed the value of the error of the mean value [12]. However, this method only allows testing the hypothesis of accidental occurrence of a gas imbalance without identifying the causes of its occurrence. The issue of assessing the admissibility of the identified gas imbalance from the point of view of efficient operation of the GTS also remains unresolved.

In [13] the application of methods of statistical control of processes in the management of unaccounted gas in the GTS was considered. The efficiency of applying such methods for detection of significant malfunctions was proven for the measuring equipment, in particular gas meters. However, research in [13] noted that the application of such methods in large segments of the GTS is seriously hampered due to the size and complexity of the system. In addition, the accuracy of the methods is negatively affected by the lack of redundancy in the monitoring data of such segments and the presence of errors specific to each particular segment of the GTS. Therefore, the application of statistical control methods for the management of large segments of the GTS was recommended in [13] only if a multilevel system of metering and control of gas transportation is designed, covering both the main gas pipelines and individual consumers.

In [14], an analysis of the causes of a gas imbalance was performed. It was shown that in addition to the known causes – measurement errors and seasonal changes in the volume of gas transported – an imbalance can occur due to the influence of ambient temperatures. The significance of the studied factors causing a gas imbalance was determined by testing the relevant hypotheses. To estimate the degree of the gas imbalance, it was proposed in [14] to use the simplest statistical estimates based on the comparison of real measurement errors with the expected ones.

Another area of research on ways to solve problems related to a gas imbalance in the GTS is focused on the development and improvement of analytical (deterministic) models. Such models are the result of long-term scientific and technical work and do not depend on the presence or absence of data sets that require processing by statistical methods. Thus, the monograph [15] was devoted to the study of technological losses of natural gas during transportation through gas pipelines. Models and methods of calculating technological losses of gas at transportation by the main gas pipelines, in external gas pipelines and the equipment and in internal gas pipelines were considered. However, in [15] the issues of determining the gas imbalance caused by unauthorised gas extraction, emergencies, changes in gas pumping regimes, and other similar reasons remain unresolved.

In [16] the issues of monitoring and controlling a gas imbalance in distributed gas networks were considered. To determine the gas imbalance, a model based on data matching techniques was proposed. However, the application of this model is possible only after the installation of the same gas meters at all nodes of the network and the collection of data on gas consumption.

Closely related to the considered areas of research are scientific and applied works on the creation and development of information systems and technologies that allow automating the solution of problems of determining a gas imbalance and identifying the causes of its occurrence. Thus, in [17] it was stated that it is almost impossible to reduce the imbalance in gas metering to zero, but it is extremely important to minimise it within a certain degree of reliability. To this end, in [17] it was proposed to introduce a single multilevel metering system in a complex and branched complex of gas transportation and distribution – from the field to the consumer. Such a system is based on the assumption that the causes of a gas imbalance are errors in measuring the volume of the gas, the lack of reliable gas metering, and various gas losses. In [17] the basic principles of construction were considered and the main stages of introduction of similar system of the account were offered. However, the metering system proposed in [17] was focused on the operation of mostly closed regional GTSs, the interaction of which with other GTSs is extremely low. Therefore, issues related to the manifestation of a gas imbalance in the main gas pipelines were not considered in that paper.

In [18] the scientific and applied aspects of the construction of information technologies of automated dispatch control as important elements of the GTS control system were considered. As a mathematical support for such technologies, it was proposed to use models and methods of data mining and synergy analysis as well as various modelling technologies. However, the problem of applying these models and methods to solve problems related to the detection and analysis of gas imbalance at control points in [18] was not considered separately. In addition, the application of data mining methods requires significant costs for the creation and maintenance of additional computing systems with high performance and a large amount of memory in addition to existing computer systems for operational management.

The possibility and expediency of using Big Data methods to solve gas transportation problems were reported in [19]. However, this approach to automating the solution of gas transportation problems makes the GTS control system more vulnerable. In particular, the lower links of the GTS control system, implemented as SCADA systems, are becoming vulnerable. Thus, in [20] it was noted that SCADA systems with a traditional architecture become particularly vulnerable in grid systems and systems with an architecture based on the Internet of Things. As any vulnerability of SCADA systems during gas metering is dangerous and can lead to serious financial consequences, effective security strategies need to be developed. These issues have not yet been resolved, as they require additional research to address vulnerabilities in SCADA systems.

The results of the literature review about solving the problems of detecting and analysing a gas imbalance in a GTS allow making the following conclusions:

a) currently, the main models and methods used to address the gas imbalance are statistical models and methods;

b) the existing statistical models and methods are focused on estimating the basic parameters of the gas transportation process (average and dispersion) and practically do not make it possible to test hypotheses about the causes of a gas imbalance;

c) the existing analytical models allow describing only individual GTS nodes;

d) the efficiency and accuracy of applying statistical models largely depends on the features of automated systems for collecting and processing information in the GTS;

e) the use of modern information technologies for data collection and processing of data mining and Big Data is largely hampered by the high cost of their implementation and maintenance, as well as the increasing vulnerability of SCADA systems as the lower links of current data collection.

These findings determine the need for research to develop special methods for estimating a gas imbalance and analysing the causes of its occurrence in the GTS. At the same time, it is necessary to take into account the peculiarities of the GTS control system of Kazakhstan, which, as shown above, is largely obsolete and is undergoing a long-term reconstruction. Therefore, the most promising for solving the problem of detection and analysis of a gas imbalance in the GTS of the Republic of Kazakhstan should be research in the field of creating methods of statistical analysis of gas imbalances, helping to draw conclusions based on samples of small metering data.

3. The aim and objectives of the study

The aim of the study is to develop a method for determining a gas imbalance and identifying the causes of its occurrence. The method to be developed should determine the absolute and relative degrees of the gas imbalance and offer the user options for addressing the causes of the imbalance. This makes it possible to formalise the implementation of the study in the operational management of the GTS of Kazakhstan and its individual sections and to apply the proposed method in the form of elements of the designed automated system (AS) of data collection, gas metering, and imbalance detection.

To achieve this aim, the following tasks were set:

– to analyse the features of the designed AS of data collection, gas metering, and imbalance detection to define the peculiarities of presenting initial data of the developed method;

– to formalise representations of sections of the main gas pipeline to formulate the purpose of managing gas transportation at the site; and

– to check the possibility of formally determining the degree of the gas imbalance and deciding on the cause of

its occurrence on the basis of the results of metering for gas transportation at Bukhara Gas-Bearing Region-Tashkent-Bishkek-Almaty.

4. Analysis of the peculiarities of presenting gas metering data in the automated system of data collection, gas metering, and imbalance detection

4. 1. Description of the automated system of data collection, gas metering, and imbalance detection

The system of data acquisition, gas metering, and imbalance detection is one of the results of the gradual modernisation of the GTS control system of Kazakhstan. The AS is designed and put into operation alternately. This allows taking into account the results of implementing and performing the tasks of the previous queues during the creation of each subsequent queue of tasks in the AS.

The AS is developed and implemented as a system with the client-server architecture. The Angular web development platform [21], the JavaScript programming language, the Angular 2 application development framework and the Bootstrap 4 library were used to create the client part of the AS. The PHP programming language, MySQL database and the web interface for administration were used to create the server part of the AS for the DBMS PhpMyAdmin [22].

Currently, the AS offers users the possibility to automatically perform the following functional tasks and functions shown in Fig. 1.

The functional task “Data Entry” is solved by employees who are directly responsible for the relevant production facilities. In this functional task, the specified functions are “Events”, “Physicochemical Properties (PChPs) of Gas”, and “Gas Balance”.

The results of solving the functional task “Data Output” are intended for all stakeholders (users of information) in accordance with the existing hierarchy of access to information. In this functional task, the specified functions are “Event Log”, “Mode Sheets”, and “PChP Log”.

The “Event Log” function allows displaying data on all production events at the main gas pipeline facilities, including switching of crane units of the linear part and on the territory of compressor stations, start and stop of gas pumping units, disconnection and activation of gas pipeline sections, and measurement events. This function was one of the first to be implemented, as previously the “Event Log” document was kept on paper separately for each level of the GTS and transmitted between levels by telephone. At the same time, the processing and analysis of the document data took much time.

The “Mode Sheets” function allow displaying data on such technological parameters of gas as pressure, temperature, and volume in the form of separate sheets for each main gas pipeline. An example of an interface with the results of this function is shown in Fig. 1.

The data on this interface are automatically updated as information becomes available. This feature also allows viewing archive data for any day.

The ‘PChPs of Gas’ function allows displaying data on the physicochemical structure of the transported gas. An example of the interface of this function is shown in Fig. 2.

It should be noted that before the development of this function, the results of gas analysis obtained in chemical laboratories were transmitted to the dispatching services either in a paper version with the signatures of the performers, or in the form of a scanned copy of the paper version. The introduction of this function has reduced the time of processing the data from a few days to 10–15 minutes.

The functional task, denoted as “Appendix”, includes the functions “Gas Balance and Metering” and “Calculators”.

The ‘Gas Balance and Metering’ function is one of the main functions of the AS data collection, gas metering, and imbalance detection. During the performance of this function, the calculation of the gas balance is carried out, taking into account the division of the pipeline into sections from the current crane node to the next crane node. An example of the interface “Selection of the Pipeline Section” of the function “Gas Balance and Metering” is shown in Fig. 3.

REFERENCE of gas flow through the main gas pipeline							Trend
NAME	Parameter	1:00	2:00	-	23:00	24:00	
Shymkent	T, atm	24	22	-	28	23	
MU «328 km»	Pinput	30,3	30,3	-	30,5	30,3	
	Poutput	30,1	30,1	-	30,1	30,1	
	Tinput	24	24	-	24	24	
	Toutput	24	24	-	24	24	
	Qhours	115	114	-	140	140	
MU «283 km»	Pinput	25,9	25,9	-	26	26	
	Poutput	25	25		25,2	25,1	
	Tinput	29	29	-	30	29	
	Toutput	29	29		30	29	
	Qhours	217	215	-	215	215	

Fig. 1. An example of the interface with the results of the ‘Mode Sheets’ function

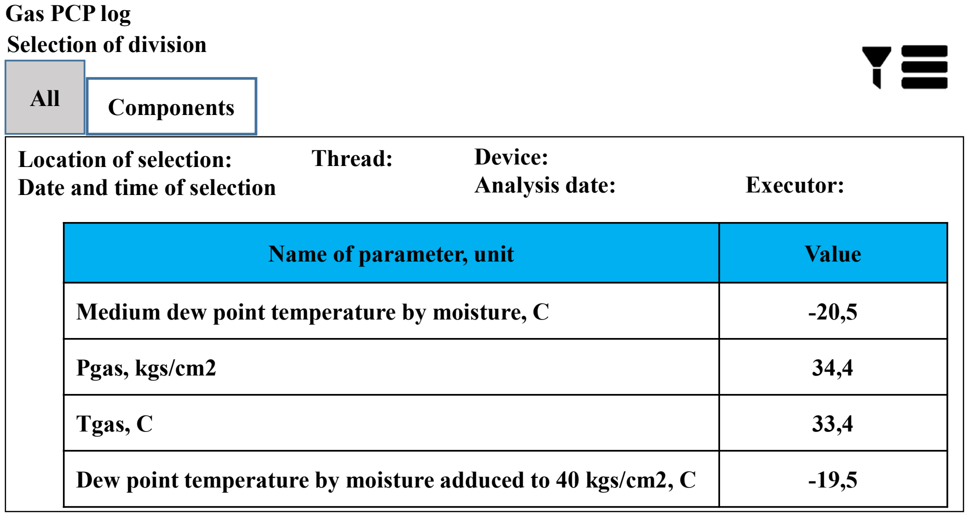


Fig. 2. An example of the interface of the “PChPs of Gas” function

In calculating, the sections of the gas pipeline can be in one of the three states: 1 is the section in operation; 2 is the area in the cylinder; 3 is the site that is disconnected and drained. To determine the state of the sections of the main gas pipeline, the function automatically builds their visual mnemonics (Fig. 4) on the basis of data from the AS database. The shift production manager makes changes to the mnemonic (switching crane assemblies) at the respective main gas pipeline service area. These changes are automatically saved in the database and displayed on the monitors of the shift manager of the adjacent sections of the main gas pipeline and the central control point. This solution allows all participants in the gas transportation process at all levels of management to obtain reliable information online [23].

The method of calculating the gas supply of the MG section depends on the condition of the section. In the case of determining State 1, the stock in this area is determined in the flow. In the case of determining State 2, the site is calculated separately. If condition 3 is determined for this section, no calculation is made.

The “Calculators” function is auxiliary and provides gas workers with separate calculators for estimates that are performed in daily work. Examples of interfaces for calculating the technological stock of gas and hydraulic calculation of the main gas pipeline are shown in Fig. 5 and Fig. 6, respectively.

The functional task “Administration” was developed to monitor the technical condition of the AS, and it contains the functions “Control Panel” and “Analytics”. The user of the task is the administrator of the AS.

The “Analysis and Reports” functional task was developed to automate the generation of basic analyses and reports by the dispatching services and the central dispatching department.

Thus, the operated part of the AS data collection, gas metering, and imbalance detection is currently focused on solving mainly the problems of operational metering and control. Therefore, the development of a method for determining the gas imbalance and the reasons of its occurrence largely depends on the features of the solution and the formation of the output data of the function “Gas Balance and Metering”.

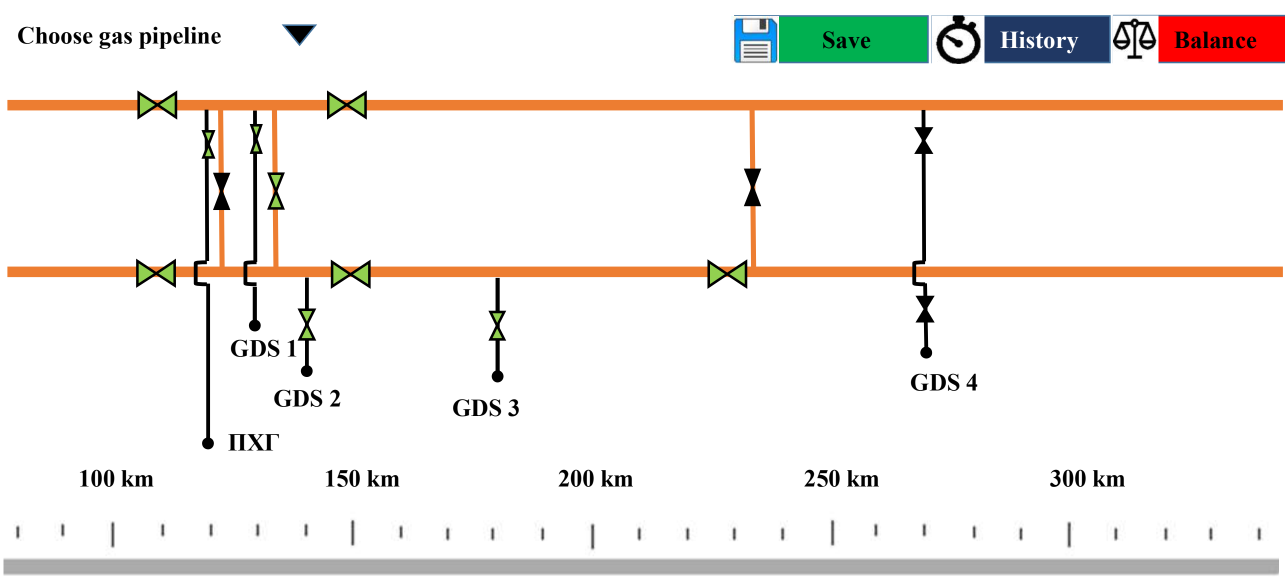


Fig. 3. An example of the “Gas Pipeline Section Selection” interface of the “Gas Balance and Metering” function

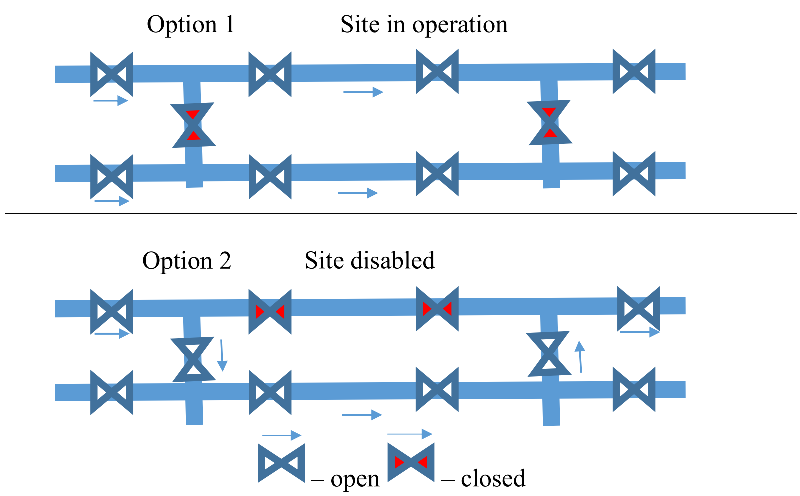


Fig. 4. Examples of the mnemonic display

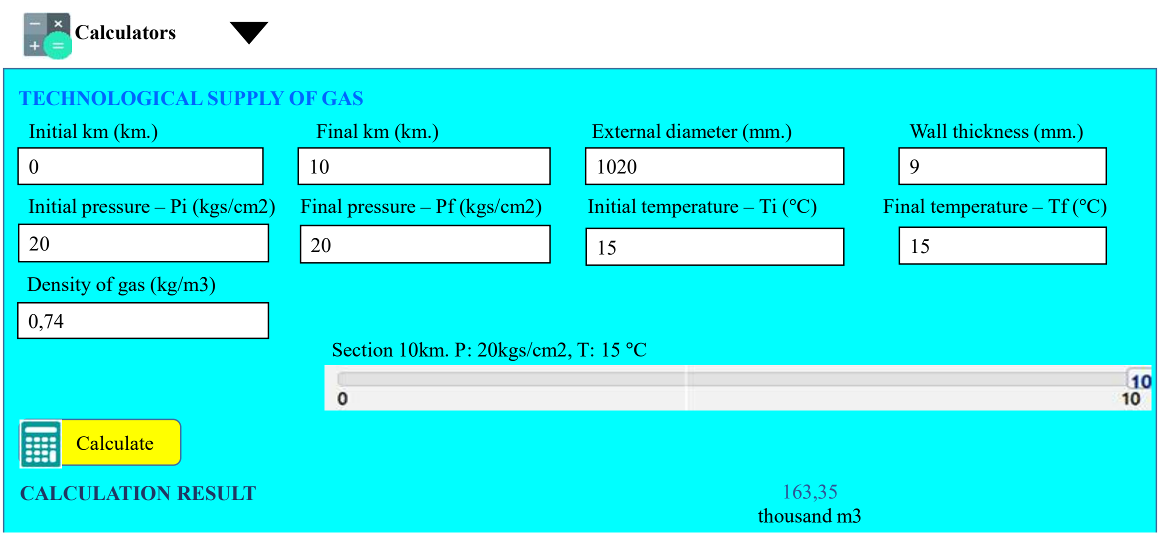
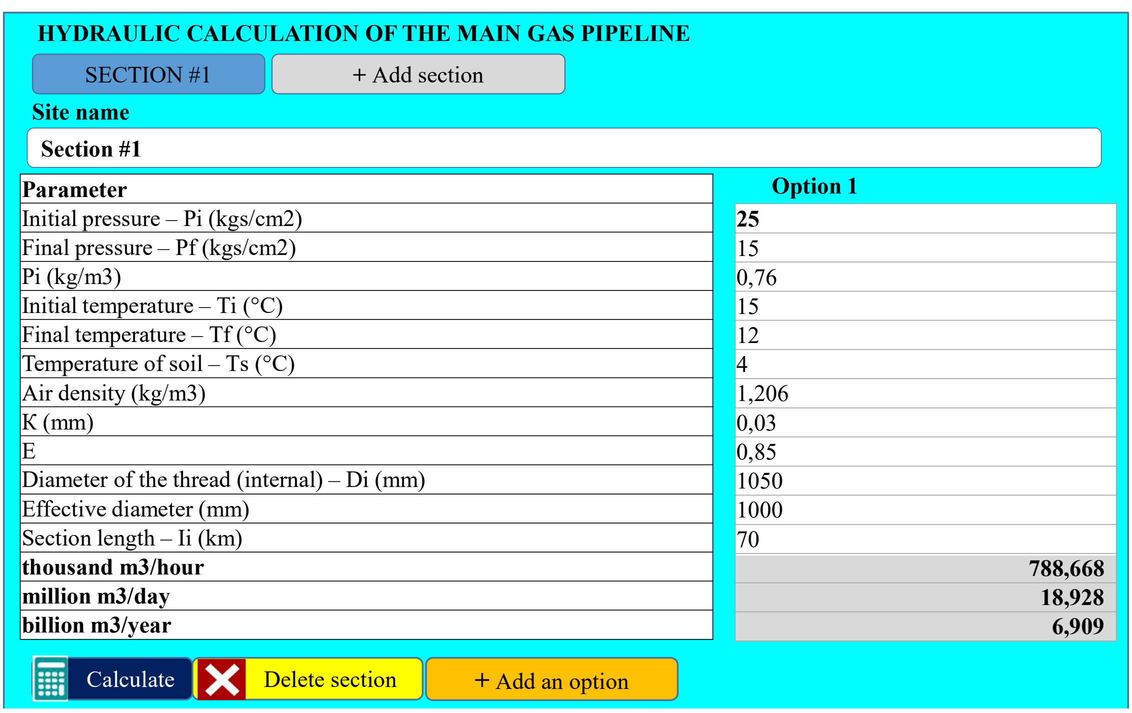


Fig. 5. The interface for calculating the technological stock of gas



Parameter	Option 1
Initial pressure – Pi (kgs/cm2)	**25**
Final pressure – Pf (kgs/cm2)	15
Pi (kg/m3)	0,76
Initial temperature – Ti (°C)	15
Final temperature – Tf (°C)	12
Temperature of soil – Ts (°C)	4
Air density (kg/m3)	1,206
K (mm)	0,03
E	0,85
Diameter of the thread (internal) – Di (mm)	1050
Effective diameter (mm)	1000
Section length – li (km)	70
thousand m3/hour	**788,668**
million m3/day	**18,928**
billion m3/year	**6,909**

Fig. 6. The interface of hydraulic calculation of the main gas pipeline

4. 2. Analysis of the peculiarities of determining the gas balance in the automated system of data collection, gas metering, and imbalance detection

The main initial data for solving the problem of determining the gas imbalance and identifying the causes of its occurrence are formed during the performance of the function “Gas Balance and Metering” in the AS. Therefore, it is necessary to analyse the peculiarities of input data formation, performance and representation of output data of this function.

The formation of the input data of the “Gas Balance and Metering” function in the AS of data collection, gas metering and imbalance detection is carried out in the following ways:

a) some data from production facilities come online directly from controllers;

b) some data from objects are entered into the system manually (from the keyboard or with the mouse);

c) some data from production facilities are received in Excel format by e-mail.

The reliability of the data generated by the second and third methods is not guaranteed due to the high probability of error from the human operator. However, these methods are currently used to enter the bulk of the data characterising the volume of gas in the nuclear power plant. This leads to an increase in risks during the implementation of the ‘Gas Balance and Metering’ function.

After generating the input data, the user of the “Gas Balance and Metering” function selects the section of the gas pipeline and records the state of this section. To calculate the gas balance of the main gas pipeline, it is necessary to know the volume of gas supply, the volume of transmitted gas, and the remaining gas amount in the gas pipeline. The function automatically determines the flow directions and calculates the technological stock of gas in the main gas pipeline at the specified time based on the results of determining the status of the selected section of the main gas pipeline. Technological parameters for calculating the gas supply in the main gas pipeline are taken from the “Mode Sheets” function. Data on the volumes of the inflow and transmitted gas are currently coming into operation as a result of measurements in the gas metering units. The reliability of data coming from measurement nodes is a separate topic for study and will not be considered in this article. The balance of gas in the main gas pipeline, i.e. the balance of the technological stock of gas at the time of calculation of the gas balance (commercial hour), is determined by means of calculations.

The calculation of the gas supply in the main gas pipeline is determined by the formula [24]:

$$V=\frac{\pi d^2}{4}\cdot LP_{av}\cdot\frac{T_0}{T_{av}Z\cdot 1.033}, \qquad (1)$$

where P_{av} is the average gas pressure at the site; T_{av} is the average gas temperature at the site; Z is the coefficient of compressibility; T_o is the gas temperature under standard conditions is 293.15 K; L is the length of the section; and d is the diameter of the pipe.

The results of the measurements and calculations are summarised in the final table, which is formed for each calendar month separately.

Statistical processing of the results is presented in [25].

In the process of forming the final table, the gas balance is determined by the following extended formula:

$$Q_x=\left(\Sigma Q_{i_{\text{cons}}}+\Sigma Q_{i_k}+Q_{z_1}\right)-\left(\Sigma Q_{i_{\text{supply}}}+Q_{z_2}\right), \qquad (2)$$

where $Q_{i_{\text{cons}}}$ is the volume of gas of the i-th consumer for the period of drawing up the balance; Q_{z_1} is the change in the gas supply in the pipeline during the balance sheet period; Q_{z_2} is the change in the gas supply from the pipeline during the balance sheet period; $Q_{i_{\text{supply}}}$ is the volume of gas of the i-th supplier for the period of drawing up the balance; Q_{i_k} is the volume of gas going to own needs and technological losses (ON&TLs) for the period of drawing up the balance.

The calculation of the gas balance takes into account only changes in the gas supply for the period of the balance. If the change in the stock has a negative value, then the receipts from the technological stock are taken into account. If the change in the stock has a positive value, then the placement of the gas placed in the technological stock is taken as consumption.

At the end of each calendar month, calculations of the total values of gas transportation for the month and Pearson’s correlation coefficients are performed. Pearson’s correlation coefficient is calculated as a function by the formula:

$$r_{xy}=\frac{n\Sigma xy-\Sigma x\Sigma y}{\sqrt{\left[n\Sigma x^2-\left(\Sigma x\right)^2\right]\times\left[n\Sigma y^2-\left(\Sigma y\right)^2\right]}}, \qquad (3)$$

where x is the volume of gas consumed by each consumer; y is the gas balance; n is the number of data pairs.

By constantly monitoring changes in gas supply and gas pressure in the pipeline, it is possible to automatically identify such discrepancies as incorrect technological data of gas in the pipeline and the trend of hydrotreatment, as well as locate areas where imbalances occur and assess the likelihood of leaks in the pipeline. In particular, a practical method confirms the direct relationship between balance deviations and readings of a single measuring unit in the balance for cases where the values of the Pearson correlation coefficient are below –0.35 and above +0.35.

After that, the analysis of the mode of gas consumption at the selected gas distribution and gas measuring stations is carried out. The risk group includes those stations where there have been significant changes in gas consumption under the influence of explanatory factors. Such factors include changes in the gas using regime of individual consumers; cooling; adding new consumers; scheduled preventive works, etc. Balance sheet specialists analyse cases that fall into the risk group. According to the results of the analysis, specialists are sent to the detected stations for a thorough inspection of measuring instruments. When checking measuring instruments on the basis of additional fuzzy information in the form of knowledge and experience of specialists (experts), the factors influencing gas metering are identified [26]. These factors can be burrs in the crown of the narrowing diaphragm, dirt on the diaphragm, incorrect or untimely introduction into the meter, for example, the gas density, etc. After identifying the factors that negatively affect the metering of gas, appropriate decisions are made to eliminate them and manage the process.

The main disadvantage of the existing solution of the “Gas Balance and Metering” function is the long period of time required to collect the original data. Gas balance and, accordingly, gas imbalance are determined in this function once a day (see column “IV. Gas Balance” Table 1). However,

to assess the impact on the degree of the gas imbalance produced by the errors of measuring instruments and individual devices of the station stations, it is necessary to collect and process data for a calendar month. Until the end of the month, it is impossible to detect such an effect in the operated AS. Therefore, it becomes necessary to develop a method that will determine the imbalance of the gas and identify the causes of its occurrence in the shortest possible time.

5. Formalisation of presenting the sections of the main gas pipeline to specify the purpose of gas transportation management at the section

When developing a method for determining a gas imbalance and identifying the causes of its occurrence, we will proceed from the following assumptions:

a) any section of the main gas pipeline in the GTS can be characterised as a combination of two systems: the gas supply system and the gas consumption system;

b) each of these systems operates independently, and the errors of the measuring equipment of these systems do not depend on each other.

This representation of the sections of the main gas pipeline helps to formulate the purpose of the management of gas transportation on the site as the coordination of the modes of operation of the gas supply system and the gas consumption system. In this case, the degree of the gas imbalance should be equal to zero, and the values of the variances of the samples of the values of supply and distribution of gas in the area are equal to each other. Such a representation of the goal is possible in the case of using a single scheme of adjustment and debugging of control and measuring equipment on the site. This will ensure the operation of the same type of control and measuring devices with the same errors.

It should also be noted that any interference in the operation of the main gas pipeline section (technological losses, unauthorised gas extraction, emergencies, change of gas pumping modes, etc.) will lead to a serious change in the values of gas supply and distribution values at the section. As a result of such a change, the variance values of these value samples will inevitably change. Therefore, the result of comparing the variance values of the sample values characterising the operation of the gas supply system and the gas consumption system within the section of the main gas pipeline can be considered the most general indicator of the presence of gas imbalance in the section.

To test the hypothesis of equality of variances of two samples of values, it is proposed to use a two-way F-test (Fisher's test). The null hypothesis H_0 of the F-test for samples of values distributed according to the normal law is as follows:

$$H_0 : \sigma_1^2 = \sigma_2^2, \tag{4}$$

where σ_1^2 is the value of the variance of the first sample of values (in our case, samples of values characterising the operation of the gas supply system); σ_2^2 is the value of the variance of the second sample of values (in our case, samples of values characterising the operation of the gas consumption system).

An alternative hypothesis H_1 of the F-test for samples of values distributed according to the normal law is as follows:

$$H_1 : \sigma_1^2 <> \sigma_2^2. \tag{5}$$

The point estimates of the variances of distributions σ_1^2 and σ_2^2 can be the values of the sample variances s_1^2 and s_2^2. Consequently, hypothesis H_0 will be accepted if the sample distribution of statistics for a sufficiently large sample size tends to the F-distribution of probability with (n_1–1, n_2–1) degrees of freedom:

$$F = \frac{s_1^2}{s_2^2} \sim F\left(n_1 - 1, n_2 - 1\right). \tag{6}$$

The values of the sample variances s_1^2 and s_2^2 are calculated by the formula

$$s^2 = \frac{\sum_{i=1}^{n}\left(X_i - \bar{X}\right)^2}{n-1}, \tag{7}$$

where $\bar{X}$ is the average value of the sample.

Hypothesis H_0 will be rejected if:

a) the sample distribution of statistics is greater than the upper $\alpha/2$ quantile of the F-distribution of probability with (n_1–1, n_2–1) degrees of freedom;

b) the sample distribution of statistics is less than the lower $\alpha/2$ quantile of the F-distribution of probability with (n_1–1, n_2–1) degrees of freedom.

The use of the F-test, among other things, will also allow assessing the significance of the change in a gas imbalance in the section of the main gas pipeline. If there is no imbalance, the value of expression (6) will be equal to 1. Therefore, the closer to 1 the values of expression (6), calculated for samples of values characterising the operation of the gas supply system and gas consumption system, the smaller the gas imbalance observed in this area, and the causes of this imbalance are less significant. The opposite statement is also true: the farther from 1 the values of expression (6) calculated for sampling the values characterising the operation of the gas supply system and gas consumption system, the greater the gas imbalance observed in this section and the more significant the reasons of this imbalance.

The use of the F-test made it possible to develop a method for determining the gas imbalance and identifying the causes of its occurrence, which can be used to improve the function "Gas Balance and Metering" of the AS data collection, gas metering, and imbalance detection. This method consists of the following steps.

Stage 1. Formation of initial samples of values characterising the operation of the gas supply system and the gas consumption system for the observed area.

Step 1. 1. Setting the current number of the current calendar month *n*.

Step 1. 2. In case of selecting the "Imbalance detection for the current month" mode, setting the start date *bd* as the first day of the current calendar month. In case of selecting the mode "Detection of imbalance taking into account the data of the previous month", setting the start date *bd* as the number *n* of the previous calendar month.

Step 1. 3. It is necessary to form arrays of samples of the values characterising the work of the gas supply system *m_supply* and the work of the gas consumption system *m_cons.* Thus, select the initial value of the array *m_supply* from the column "I Gas Resources in Total" of the source data table for the date *bd.* Select the final value of the array *m_supply* from the column 'I Gas Resources in Total' in the table of source data for the date *n.* Select the initial value of the array *m_cons* from the column "III Gas Distribution" in the

table of initial data for the date *bd*. Select the final value of the array *m_cons* from the column "III Gas Distribution" in the table of initial data for the date *n*.

Step 2. Testing the null hypothesis about the equality of variances of samples of values characterising the operation of the gas supply system and the gas consumption system.

Step 2. 1. Calculating the values of the sample variances s_1^2 and s_2^2 by formula (7) for the arrays *m_supply* and *m_cons*, respectively.

Step 2. 2. Calculating, by formula (6), the value of the F-test for the values of the sample variances s_1^2 and s_2^2.

Step 2. 3. Determining the values of the upper and lower $\alpha/2$ quantiles of the F-distribution of probability with $(n_1-1,\ n_2-1)$ degrees of freedom.

Step 2. 4. Calculating the values of

$$q_{up}=\frac{(\alpha/2)_{up}-1}{4};\quad q_{bottom}=\frac{1-(\alpha/2)_{bottom}}{4},\qquad(8)$$

where $(\alpha/2)_{up}$ is the value of the upper $\alpha/2$ quantile of the F-distribution of probability with $(n_1-1,\ n_2-1)$ degrees of freedom; $(\alpha/2)_{bottom}$ is the value of the lower $\alpha/2$ quantile of the F-distribution of probability with $(n_1-1,\ n_2-1)$ degrees of freedom.

Step 2. 5. Making one of the following decisions:

– if the condition $F\in\left(1;\left(1-q_{bottom}\right)\right]$ or condition $F\in\left(1;\left(1+q_{up}\right)\right]$, is met, make the decision 'The gas imbalance is insignificant';

– if the condition $F\in\left(\left(1-q_{bottom}\right);\left(1-2\times q_{bottom}\right)\right]$ or condition $F\in\left(\left(1+q_{up}\right);\left(1+2\times q_{up}\right)\right]$, is met, make the decision 'The gas imbalance is significant';

– if the condition $F\in\left(\left(1-2\times q_{bottom}\right);\left(1-3\times q_{bottom}\right)\right]$ or condition $F\in\left(\left(1+2\times q_{up}\right);\left(1+3\times q_{up}\right)\right]$, is met, make the decision 'The gas imbalance is high';

– if the condition $F\in\left(\left(1-3\times q_{bottom}\right);\left(1-4\times q_{bottom}\right)\right]$ or condition $F\in\left(\left(1+3\times q_{up}\right);\left(1+4\times q_{up}\right)\right]$, is met, make the decision "The gas imbalance is too high";

– otherwise, make the decision "The gas imbalance is unacceptable" and reject the hypothesis of equality of the variances of the sampled values characterising the operation of the gas supply system and the gas consumption system.

Step 3. Testing the null hypothesis about the equality of variances of the sample values that characterise the operation of individual elements of the gas supply system and the gas consumption system.

Step 3. 1. Selecting the data for the previous calendar month to compare with the current data.

Step 3. 2. Identifying all elements of the gas supply system for which the comparison will be made. If the sample values for an individual element are zero, then excluding this element from further consideration.

Step 3. 3. Identifying all elements of the gas consumption system for which the comparison will be made. If the sample values for an individual element are zero, then excluding this element from further consideration.

Step 3. 4. For each of the elements selected during Step 3.2 and Step 3.3, calculating the values of the sample variances s_1^2 and s_2^2 by formula (7) to select the values of the element for the previous calendar month and for the current calendar month, respectively.

Step 3. 5. For each of the elements selected during Step 3.2 and Step 3.3, calculating, by formula (6), the value of the F-test for the values of the sample variances s_1^2 and s_2^2.

Step 3. 6. Determining the values of the upper and lower $\alpha/2$ quantiles of the F-distribution of probability with $(n_1-1,\ n_2-1)$ degrees of freedom, where (n_1-1) is the number of days in the current calendar month and (n_2-1) is the number of days in the previous calendar month.

Step 3. 7. Calculating, by formula (8), the values of q_{up} and q_{bottom}.

Step 3. 8. For each of the items selected during Step 3. 2 and Step 3. 3, making one of the following decisions:

– if the condition $F\in\left(1;\left(1-q_{bottom}\right)\right]$ or condition $F\in\left(1;\left(1+q_{up}\right)\right]$, is met, make the decision 'The operating mode of the element has not changed';

– if the condition $F\in\left(\left(1-q_{bottom}\right);\left(1-2\times q_{bottom}\right)\right]$ or condition $F\in\left(\left(1+q_{up}\right);\left(1+2\times q_{up}\right)\right]$, is fulfilled, make the decision 'The operating mode of the element has changed';

– if the condition $F\in\left(\left(1-2\times q_{bottom}\right);\left(1-3\times q_{bottom}\right)\right]$ or condition $F\in\left(\left(1+2\times q_{up}\right);\left(1+3\times q_{up}\right)\right]$, is fulfilled, make the decision 'The operating mode of the element has changed significantly';

– if the condition $F\in\left(\left(1-3\times q_{bottom}\right);\left(1-4\times q_{bottom}\right)\right]$ or condition $F\in\left(\left(1+3\times q_{up}\right);\left(1+4\times q_{up}\right)\right]$, is fulfilled, make the decision 'The operating mode of the element has changed dramatically';

– otherwise, make the decision "The change in the operating mode of the element requires detailed analysis" and reject the hypothesis of equality of the variances of the sampled values characterising the operation of the element for the past and current calendar months.

Step 4. Determining the possible cause of the gas imbalance.

Step 4. 1. If for most of the elements selected during Step 3. 2 and Step 3. in Step 3. 8 the decision was "The operating mode of the element has not changed much" and in Step 2. 5 the decision was "The gas imbalance is insignificant", then make the decision "There is no obvious reason for the gas imbalance".

Step 4. 2. If for most of the elements selected during Step 3. 2 and Step 3. 3 in Step 3. 8 the decision was "The operating mode of the element has not changed much" and in Step 2. 5 the decision was one of the following – "The gas imbalance is significant", "The gas imbalance is high" or "The gas imbalance is too high", then make the decision "The cause of the gas imbalance is measurement errors".

Step 4. 3. If for most of the elements selected during Step 3. 2 and Step 3. 3 the decision made in Step 3. 8 was one of the following – "The operating mode of the element has changed", "The operating mode of the element has changed significantly" or "The operating mode of the element has changed dramatically" and in Step 2. 5 the decision was "The gas imbalance is insignificant", then make the decision "The cause of the gas imbalance is a change in the operating mode of the element".

Step 4. 4. If for most of the elements selected during Step 3. 2 and Step 3. 3 the decision made in Step 3. 8 was one of the following – "The operating mode of the element has changed", "The operating mode of the element has changed significantly" or "The operating mode of the element has changed dramatically" and in Step 2. 5 the decision was one of the following – "The gas imbalance is significant", "The gas imbalance is high" or "The gas imbalance is too high", then make the decision "There are several reasons of the gas imbalance".

Step 4. 5. If in Step 2. 5 it was decided to reject the hypothesis of equality of the sample variances, then make

the decision "The site is unbalanced. Additional analysis is required".

Step 4. 6. If for most of the elements selected during Step 3. 2 and Step 3. 3 in Step 3. 8 the decision was "The change in the operating mode of the element requires detailed analysis", then make the decision "The operating mode of the element is unbalanced. Additional analysis is required".

Step 4. 7. If for the observed section in Step 2. 5 the decision was "The gas imbalance is insignificant" and for all elements of the same section in Step 3. 8 the decision was "The operating mode of the element practically did not change", then make the decision "Significant causes of the gas imbalance are not observed".

Step 4. 8. If one of the decisions – "The gas imbalance is significant", "The gas imbalance is high" or "The gas imbalance is too high" – was made for the observed section in Step 2. 5 and the decision made for all elements of the same section in Step 3. 8 was "The operating mode of the element practically did not change", then make the decision "At the site, there are big errors in measurements".

Step 4. 9. If for the observed section in Step 2. 5 the decision was "The gas imbalance is insignificant" and for all elements of the same section in Step 3. 8 the decision was one of the following – "The operating mode of the element has changed", "The operating mode of the element has changed significantly" or "The operating mode of the element has changed dramatically", then make the decision "The operating mode of the site has changed".

Step 4. 10. If one of the decisions – "The gas imbalance is significant", "The gas imbalance is high" or "The gas imbalance is too high" – was made for the observed section in Step 2. 5 and for all elements of the same section in Step 3. 8 the decision was one of the following – "The operating mode of the element has changed", "The operating mode of the element has changed significantly" or "The operating mode of the element has changed dramatically", then make the decision "There are several causes of the gas imbalance".

Step 5. Displaying the results of determining the gas imbalance and identifying the causes of its occurrence for the site as a whole and for each element selected during Step 3. 2 and Step 3. 3. Completion of the method application.

The application of the developed method will allow not only to determine the quantitative and qualitative characteristics of a gas imbalance for the observed section of the GTS main gas pipeline but also to specify one of the two most common causes of this imbalance.

6. Results of checking the possibility of detecting a gas imbalance and deciding on the cause of its occurrence based on the results of the operation of the section "Bukhara Gas-Bearing Region-Tashkent-Bishkek-Almaty"

The experimental verification of the developed method was performed when analysing the output data of the "Gas Balance and Metering" function of the AS data collection, gas metering, and imbalance detection for the section "Bukhara Gas-Bearing Region-Tashkent-Bishkek-Almaty" for two calendar months. The initial data are given in Tables 1–6 [25].

Let us consider the application of the developed method to the given data.

During Step 1 of the method, the following values were set for the first calendar month: start date bd=1 and end date n=31. The array of samples of the values characterising the operation of the gas supply system *m_supply* for the first calendar month coincided with the array of values of the column "I Gas Resources in Total" in Tables 1–3 [25]. The array of samples of the values characterising the operation of the gas consumption system *m_cons* for the first calendar month coincided with the array of values of the column 'III Gas Distribution' in Tables 1–3 [25].

During Step 1 of the method, the following values were set for the second calendar month: start date bd=1 and end date n=30. The array of samples of the values characterising the operation of the gas supply system *m_supply* for the first calendar month coincided with the array of values of the column "I Gas Resources in Total" in Tables 4–6 [25]. The array of samples of the values characterising the operation of the gas consumption system *m_cons* for the first calendar month coincided with the array of values of the column "III Gas Distribution" in Tables 4–6 [25]. MS Excel 2016 functions were used for subsequent calculations.

During Step 2 for the first calendar month, the calculated value of the F-test was 0.85085894. The value of $(\alpha/2)_{up}$=2.35094123. The value of $(\alpha/2)_{bottom}$=0.425361548. The value of q_{up}=0.33773531. The value of q_{bottom}=0.14365961. As the condition $F \in (0.85634039;0.71268077]$ was fulfilled, the decision 'The gas imbalance is high' was made.

During Step 2 for the second calendar month, the calculated F-test value was 0.927442708. The value of $(\alpha/2)_{up}$=2.385967353. The value of $(\alpha/2)_{bottom}$=0.419117218. The value of q_{up}=0.34649184. The value of q_{bottom}=0.1452207. Since the condition $F \in (1;0.8547793]$ was met, the decision was "The gas imbalance is insignificant".

During Step 3, data on the operation of each element of the gas supply system and the gas consumption system for the first and second calendar months were compared. For the gas supply system, such elements were "MU 1"; "MU 2"; "MU 3"; "Drawing from UGS 1"; "Drawing from UGS 2"; "From the pipe"; "From MU 4 fld"; "MU 5"; and "MU 6".

Element "MU 3" was excluded from this list because the values of both samples for the element were zero.

For the gas consumption system, such elements included "Injection into UGS 1"; "Injection into UGS 2"; "Into the pipe"; "Own technological needs and technical losses"; "GDS 1"; "GDS 2"; "GDS 3 line 1"; "GDS 3 line 2"; "GDS 4"; "GDS 5"; "GDS 6 line 1"; "GDS 6 line 2"; "GDS 6 line 3"; "GDS 6 line 4"; "GDS 7"; "GDS 8"; "GDS 9"; "GDS 10"; "GDS 11"; "GDS 12"; "GDS 13"; "GDS 14"; "GDS 15"; "GDS 16"; "GDS 17"; "GDS 18"; "GDS 19"; "GDS 20"; "GDS 21"; "GDS 22"; "GDS 23"; "GDS 24"; "GDS 25"; "GDS 26"; "GDS 27"; "GDS 28"; "GDS 29"; "GDS 30"; "GDS 31"; "GDS 32"; "GDS 33"; "GDS 34"; "GDS 35"; "GDS 36"; "GDS 37"; "GDS 38"; "GDS 39"; "GDS 40".

The elements "Injection into UGS 1", "Injection into UGS 2", and "GDS 6 line 2" were excluded from this list because the sample values for these elements were zero.

The results of calculations for each element of the gas supply system are given in Table 7 [25]. The results of calculations for each element of the gas consumption system are given in Table 8 [25]. The value of $(\alpha/2)_{up}$=2.37500108. The value of $(\alpha/2)_{bottom}$=0.423381332. The value of q_{up}=0.34375027. The value of q_{bottom}=0.14415467.

During Step 4, it was found that for the eight elements of the gas supply system:

– the decision "The change in the operating mode of the element requires detailed analysis" was taken five times;

– the decision "The operating mode of the element has changed" was made twice;

– the decision "The operating mode of the element has changed dramatically" was made once.

Therefore, the solution for most elements of the gas supply system must be considered the decision "The change in the operating mode of the element requires detailed analysis".

For forty-five elements of the gas consumption system:

– the decision "The change in the operating mode of the element requires detailed analysis" was made 26 times;

– the decision "The operating mode of the element has changed" was made seven times;

– the decision "The operating mode of the element has changed significantly" was taken five times;

– the decision 'The operating mode of the element has changed dramatically' was made five times;

– the decision "The operating mode of the element has not changed much" was taken twice.

Therefore, the solution for most elements of the gas consumption system must be the decision "The change in the operating mode of the element requires detailed analysis".

Then for the elements of the analysed site the decision must be "The operating mode of the element is unbalanced. Additional analysis is required".

Overall, the results of applying the developed method to analyse the given data make it possible to sum up the following conclusions:

a) based on the analysis of data for the first calendar month, the decision was "The gas imbalance is high";

b) based on the analysis of data for the second calendar month, the decision was "The gas imbalance is insignificant";

c) based on the results of the comparative analysis of the data on the operation of elements of the gas supply and consumption systems for the two calendar months, the decision was "The change in the operating mode of the element requires detailed analysis";

d) on the basis of these solutions, it can be concluded that a significant reduction in the gas imbalance was achieved by a complete change in the modes of operation of the vast majority of elements of gas supply and consumption systems.

This conclusion is confirmed by the data given in Tables 1–6 [25].

The experimental test has confirmed the main advantages of the developed method over the existing results of similar studies. These benefits are as follows:

a) the ability of this method to analyse and display the dynamics of changes in a gas imbalance for calendar months, both quantitatively and qualitatively (in the form of a list of decisions made based on the results of data analysis for individual months);

b) the possibility, in contrast to existing models and methods, to decide on the various causes of a gas imbalance in the analysed section of the main gas pipeline.

The latter advantage of the developed method allows creating and further developing on its basis models, methods and information technology to suggest recommendations for eliminating the revealed gas imbalance at the analysed site of the main gas pipeline.

However, the developed method is not without drawbacks. One of the most significant disadvantages of this approach is the simplified method of forming decisions about the causes of an imbalance. The formed decisions have the general character and badly consider the influence of separate elements of the gas supply and consumption systems on the operating mode of all sections of the main gas pipeline.

Another disadvantage of the developed method is the solution proposed in Step 3 to compare the data on the operation of individual elements of the gas supply and consumption systems. The description of Step 3 suggests that the data for the current and previous calendar months should be compared. In practice, it may be useful to compare data for the current calendar month and a similar month last year. In general, it should be noted that the improvement of solutions proposed in the description of Step 3 of the method requires further research.

7. Discussion of the received theoretical and practical results

As has been stated above, the development of a method for determining the gas imbalance and the causes of its occurrence largely depends on the characteristics of the AS operation used to control the GTS and its individual sections. For the GTS of Kazakhstan, such an AS is the AS for data collection, gas metering, and imbalance detection. In particular, the main requirements for the developed method stemmed from the peculiarities of the design solutions and the formation of the output data of the function "Gas Balance and Metering" of this AS. Therefore, during the development of the method for determining a gas imbalance and the reasons of its occurrence, it was necessary to apply known models and methods of statistical analysis, taking into account the peculiarities of the data generation to form arrays of source data for such analysis.

It should also be noted that the vast majority of models and methods for detecting and analysing gas imbalances in sections of main gas pipelines have focused on studying only one of the possible causes of a gas imbalance. In contrast to these models and methods, the developed method makes it possible not only to detect a gas imbalance but also offers solutions that determine the various causes of a gas imbalance. In addition, the developed method allows visualising the dynamics of changes in quantitative and qualitative indicators of changes in a gas imbalance for each calendar month separately. This facilitates the perception of the results of applying the developed method by employees of enterprises servicing the sections of the GTS of Kazakhstan.

The approbation of the developed method was carried out when analysing the output data of the "Gas Balance and Metering" function of the AS of data collection, gas metering, and imbalance detection for two consecutive calendar months. As a result of the testing, it was revealed that the developed method forms the results of the analysis not only for the section of the main gas pipeline as a whole but also for each element of the gas supply and consumption systems in this section. This became possible due to the proposed idea to use, as a general indicator of the presence of a gas imbalance, the result of comparing the values of variances of the sample values characterising the operation of the gas supply and consumption systems as well as their individual elements.

The main feature that complicates the application of the developed method is its weak ability to establish solutions as to the causes and elimination possibilities in case of a gas imbalance in the analysed section of the main gas pipeline. This may result in situations in which the identification of

the most significant cause of the occurrence or elimination of an imbalance at the site does not occur due to lack of data. It should be recognised that the improvement of the elements of the developed method associated with the formation of solutions to the causes of imbalance of the main pipeline and its individual elements requires additional theoretical research and applied testing.

8. Conclusions

1. The study analysed the features of the designed AS of data collection, gas metering, and imbalance detection to specify the peculiarities of presenting the initial data of the developed method. The peculiarities of the main functions of the AS were considered. It was established that a separate group of methods for analysing the operating features of sections of the main gas pipeline in this AS does not exist. Therefore, it was decided that the development of a method for determining the gas imbalance and identifying the causes of its occurrence should be based on the features of the "Gas Balance and Metering" function of the AS. As a result of studying the features of the solution and presentation of the output data of the function "Gas Balance and Metering", it was found that the existing method of detecting gas imbalance is based on applying the Pearson correlation coefficient. This indicator helped reveal only a gas imbalance caused by the measurement error of individual measuring units of the site.

2. It was proposed to formalise the presentation of sections of the main gas pipeline to formulate the purpose of managing gas transportation in the section. The underlying idea was to compare the variances of individual samples of the analysed section of the main gas pipeline, which is presented as a combination of two systems – the gas supply system and the gas consumption system. To test the hypothesis of equality of variances, it was proposed to use a two-way F-test (Fisher's test). Unlike most existing models and methods, the developed method helped not only to identify and visualise indicators of a gas imbalance but also to determine the cause of this imbalance.

3. The possibility of applying the developed method was tested while analysing data on gas transportation at Bukhara Gas-Bearing Region – Tashkent–Bishkek–Almaty for two consecutive calendar months. The results of the inspection allow stating that the developed method detects a change in the gas imbalance not only in the section as a whole but also for each element of the gas supply and consumption systems of the section. In addition, the developed method forms solutions for the site as a whole and its individual elements. These solutions enable the user to draw a conclusion about the dynamics of changes in the gas imbalance in the analysed section of the main gas pipeline.

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