Досліджений газодинамічний подільник для завдання різновеликих тисків (перепадів) і одержані залежності для незмінності його коефіцієнтів поділу від зміни вхідного тиску. Розроблені схеми каскадного з'єднання і бінарного відгалуження лінійних подільників, які відтворюють різновеликі тиски (наприклад, перепади 1...10^4 Па) і які доцільно використовувати у задавачах мікровитрат, синтезаторах газових сумішей і калібраторах тисків

Ключові слова: відтворення тисків, капіляр, суматор і подільник потоків, лінійний подільник тисків

Исследован газодинамический делитель для задания существенно разных давлений (перепадов) и получены зависимости для постоянства его коэффициентов деления от изменения входного давления. Разработаны схемы каскадного и бинарного ответвлений линейных делителей, которые воспроизводят существенно разные давления (например, перепады 1...10^4 Па) и которые целесообразно использовать в задатчиках микрорасходов, синтезаторах газовых смесей и калибраторах давлений

Ключевые слова: воспроизведение давлений, капилляр, сумматор и делитель потоков, линейный делитель давления

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DEVELOPMENT OF GAS DYNAMIC LINEAR SYSTEMS FOR SETTING LOW PRESSURES

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1. Introduction

Development of modern technologies (microelectronics, medicine, biotechnology), expansion of gas analytical systems, in particular, for determining atmospheric air pollution, as well as conducting scientific research, will require high precision systems of stabilization of gas flow parameters, first of all, pressures, as they determine the flow rate in such gas-dynamic systems [1, 2].

Industrial setting devices (stabilizers) are generally designed to maintain relatively high pressures while gas-dynamic systems, in particular, gas analytical, often also need small excess pressures (pressure drops) – at the levels of hundreds, tens and less pascal [3, 4].

To prepare complex multicomponent mixtures (for example, with micro- and nano concentrations of components) by the gas-dynamic method, substantially different pressure drops at the mixer's capillaries for various components should be provided [5]. That requires a whole system of various means to stabilize the pressure of components. For example, to prepare synthetic natural gas with 13 components, a corresponding number of means is required. This makes the system cumbersome and imperfect because it is significantly affected by obstacles (pressures of source components, barometric pressure, temperature, etc.).

A similar situation exists in the chromatographs with the task of flow rate of gas-carrier, where the error of the flow rate determining may be up to 5 % [6].

Thus, the development of high-precision means of simultaneous generation of the pressures different in magnitude (drops), including very low ones, is relevant.

2. Analysis of publications and the problem statement

To ensure the quality of any gas-dynamic system (e. g., gas analyzers, chromatographs, setting devices of low rates), the parameters (obstacles) that affect their work should be stabilized. For example, with this purpose a block of stabilization of input parameters is used in the control system of composition of flue gases [7] because, if feeding the analyzed gas with unstabilized parameters directly to the measuring transducer, it will result in a large error of its composition information at the output.

At the same time, designers of gas analytical systems do not always pay sufficient attention to reduce the impact of obstacles, and sometimes consider it sufficient to initially adjust gas rate by throttle [8].

Traditionally, to reduce the impact of external factors, the pressures (pressure drops) are stabilized at the input of gas-dynamic system and its individual elements or gas rate.

Maintaining different pressures in one system is performed by installing several stabilizers, often different in the principle of performance, design, range and the type of stabilized pressures (excessive or absolute). For example, in the devices for dynamic preparation of gas mixtures, both typical reducers and pressure regulators of the type "to oneself" are used [9]. Particularly indicative is this situation in the gas-dynamic mixers of complex multicomponent gas mixtures with micro- and macro concentrations of components [10–12]. Due to nonidentity of characteristics of stabilizers by the value of the stabilized pressures in such gas-dynamic systems, the obstacles (e. g., pressure at the input and output of the system, barometric pressure, temperature) produce different effects both in magnitude and, sometimes, in direction.

Similar situation occurs with stabilization of the gas rate. Thus, the automatic gas mixing system is equipped with multiple, independently working, gas mass rate controllers with the tasks of the rate, different by magnitude, – 20 and 500 ml/min [13].

Research found that these factors cause errors of defining the parameters of different gas-dynamic systems, for example, error of gas mixture generators is 2–3 % [14]. In this regard, the actual task is compensation for the effects of these obstacles.

In addition, well known tools for stabilizing low pressures do not always meet modern requirements. For example, low pressure stabilizing sometimes is carried out using a fluid manostat, which is actually a laboratory instrument [15].

Thus, designing setting devices of the pressures different in magnitude, which could enable compensation for the impacts of obstacles and thereby could enable reducing errors of determining parameters of different gas-dynamic systems, should be considered promising. This, in particular, will enable solving the problem of changing stabilizers in the gas-dynamic system by pressure repeaters, which reproduce inter-throttle pressures of individual throttle circuit, which is not connected by gas flows with the main gas dynamic system [5, 6]. This can be, for example, a subsystem of setting stabilized pressures, built on the basis of serial and parallel connection of capillaries.

3. The aim and objectives of the study

The aim of the work is to improve characteristics of gas-dynamic systems by improving the accuracy of stabilization, particularly, of low pressures.

The tasks of the work are:

– research and construction of linear pressure dividers for their use in gas-dynamic systems of setting the pressures different in magnitude (drops);

– development of schemes to ensure a substantial increase in coefficients of pressure division compared to a separate divider;

– building a high-precision four-decade discrete device for setting absolute pressures (pressure drops), which provides their linearity at the change in supply pressure.

4. Linear capillary pressure dividers

Pressure divider is a serial connection of throttles Tr_j ($j=1,\ldots, m$), the gas-dynamic resistance of which causes a certain reduction in inter-throttle pressure ($P_{m-1}>\ldots>P_{j-1}>\ldots>P_1$) due to throttling the flow (Fig. 1). Mass rate through the throttles of a divider equals $G=G_m=\ldots=G_j=\ldots=G_1$ and the pressure drops on each of them equal $\Delta P_j=P_j-P_{j-1}$.

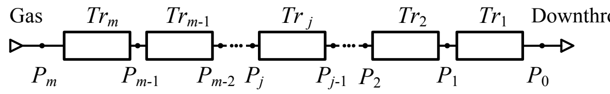

Fig. 1. Multithrottle pressure divider

To build pressure dividers one can use throttle elements that provide both laminar character (Re≤2320) of the throttle gas flow – capillary tubes (metallic or glass) and turbulent flow – diaphragms, nozzles, watch stones, etc. However, for gas-dynamic schemes, including pressure dividers, the most promising is the use of glass capillary elements CE. Such elements (capillaries) have stable consumption characteristics, they practically do not change geometrical dimensions (diameters d and lengths l) of passable channels at temperature change. Due to a smooth reduction of the length of the channel (e. g., grinding the end face) of the capillary, a precision matching of its gas-dynamic resistance is provided [6]. Due to the specified advantages, the capillaries are used as throttles in the designed schemes.

To increase the number of different values of inter-throttle pressures in the divider, instead of individual throttles Tr_j one can install a capillaries package Pc_j (parallel connection) or as block, formed by a combination of serial and parallel connections of capillaries. Package Pc_j of capillaries is made as a package of alternating gas dynamic resistance and the required capillaries are engaged by installing solenoid valves at their outputs.

The dependency of the mass gas rate G through the capillary CE_j of the divider will take the form [16].

$$G = A_j\left(\left[1+Y_j\Delta P_{j,j-1}\left(\Delta P_{j,j-1}+2P_{j-1}\right)\right]^{0,5}-1\right), \qquad (1)$$

where $A_j=a_1 l_j=\left(4\pi\mu\xi^{-1}\right)l_j$ is the coefficient of rate; μ is the coefficient of dynamic viscosity of gas; ξ is the coefficient of end effects; $Y_j=K_jX$ is the complex of the channel (pass) dimensions, parameters of type of gas and temperature; $K_j=\xi d_j^4 l_j^{-2}$ is the constructive complex; d_j, l_j are the diameter and length of the capillary channel; $\Delta P_{j,\,j-1}=P_j-P_{j-1}$ is the pressure drop in the capillary; X is the parametric gas complex, $X=(512R_gT\mu^2)^{-1}$; $R_g=R/M$ is the gas constant; R is the universal gas constant; T is the absolute temperature of gas; M is the molecular weight. Dimensions of passable channels of capillaries, which are used in gas-dynamic devices, are limited due to design considerations and are included in the ranges $d_j\in[0{,}05\cdot10^{-3};\ 0{,}5\cdot10^{-3}]$ m; $l_j\in[5\cdot10^{-3};\ 0{,}15]$ m.

When building the pressure dividers, it is important to ensure linearity of change in inter-throttle pressures on the change in pressure P_m at the input of divider. But this is possible only when all the elements of the divider are linear while consumption characteristic of a capillary in general is nonlinear. The linearity of consumption characteristic of a separate capillary can be provided at a certain ratio of its length and diameter of its channel and absolute constant temperatures and gas pressure at the output. As shown in Fig. 1, the specified requirements can be easily provided for the throttle Tr_1 in the pressure divider (capillary CE_1).

The condition of linearity of consumption characteristic of the capillary CE_1, obtained from $\partial^2 G/\partial(\Delta P_1)^2=0$ will take the form

$$Y_1P_0^2=1. \qquad (2)$$

Dependency of gas rate for linear capillary CE_1, taking into account (2), will take the form

$$G = a_1 P_0^{-1} \Delta P_1 l_1 = a_1 (\xi X)^{1/2} \Delta P_1 d_1^2. \quad (3)$$

Pressure dividers, particularly the capillary ones, in general are nonlinear systems, but choosing the design dimensions of their capillaries, as shown below, can provide the linearity of inter-throttle pressures P_j when changing the pressure at the input of divider P_m. Linear dividers open up a prospect of improving characteristics of gas-dynamic systems, in particular, for preparation of complex mixtures due to compensation of the change in components consumption at the change of pressures at the inputs of dosing capillaries [5, 16]. In this regard, further we will consider only linear capillary pressure dividers and the schemes based on them.

4. 1. A two-capillary pressure divider

The simplest linear capillary pressure device is built based on a two-element divider (Fig. 1 for m=2), where the capillary CE_j (j=1, 2) is installed in the place of each throttle Tr_j. With this divider one can set three drops ($\Delta P_1=P_1-P_0$, $\Delta P_{21}=P_2-P_1$, $\Delta P_2=P_2-P_0$), as well as three pressures (P_2, P_1 i P_0), which are connected by the dependency $P_1=f(P_2, P_0)$, which can be linear.

A necessary condition for building such dividers is the linearity of consumption characteristic (1) of capillary CE_1, which, in compliance with the condition $\partial^2 P_1/\partial P_2^2=0$ that means equality to zero of the curvature characteristic $P_1=f(P_2, P_0)$, provides linearity of the divider.

Dependency $P_1=f(P_2, P_0)$, obtained for the two-element divider with linear capillary CE_1, will take the form

$$P_1 = V^{-1}\left[(1-\lambda)P_0 + \left[\delta^4 V\left(P_2^2 - P_0^2\right) + W^2 P_0^2\right]^{1/2}\right], \quad (4)$$

where

$$V = 1+\delta^4,\ \delta = d_2/d_1,\ W = \lambda + \delta^4,\ \lambda = l_2/l_1.$$

From (4), with regard to the condition $\partial^2 P_1/\partial P_2^2=0$, the expression is obtained that connects dimensions of capillaries of the divider and which, along with the dependency (2), is the condition of linearity of a two-capillary pressure divider

$$\left.\begin{array}{l}\delta^4 = \lambda^2 (1-2\lambda)^{-1},\\ Y_1 P_0^2 = 1.\end{array}\right\} \quad (5)$$

After substituting the first equation of the system (5) to the expression (4), we obtain a dependency of inter-throttle pressure P_1 on the input pressure P_2 for a linear two-capillary divider in the form

$$P_1 = \lambda (1-\lambda)^{-1}(P_2 - P_0) + P_0. \quad (6)$$

The defining characteristic of a two-capillary divider is the coefficient χ_1 of pressure division

$$\chi_1 = (P_2 - P_0)/(P_1 - P_0) = \Delta P_2/\Delta P_1, \quad (7)$$

where ΔP_2, ΔP_1 is the pressure drop in the divider and in the first capillary, respectively.

4. 2. A multi-capillary divider

To set a larger number of different drops (absolute pressures) by a single divider, one can build multi-element dividers (Fig. 2), which, due to the appropriate dimensions of passable channels of capillaries, can provide necessary values of inter-throttle pressures P_j $(j=\overline{1, m-1})$, as well as their linearity from the change P_m, and thus constant coefficients of the division χ_j, which are determined according to the dependency

$$\chi_j = (P_m - P_0)/(P_j - P_0) = \Delta P_m/\Delta P_j, \quad (8)$$

where ΔP_m, ΔP_j is the pressure drop accordingly in the whole divider and in j capillaries, respectively (at the output).

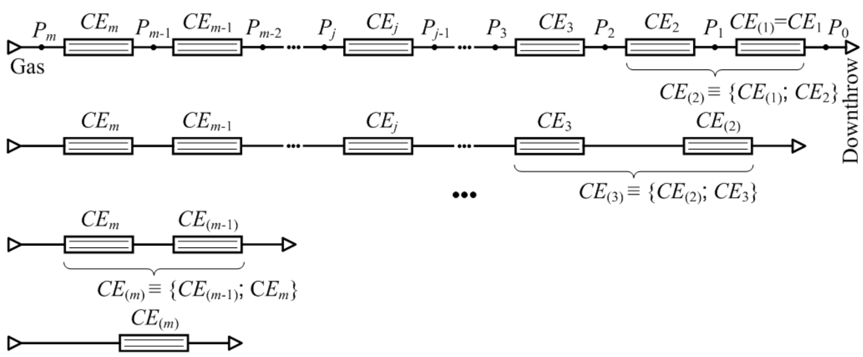

Fig. 2. Multi-capillary pressure divider and m-1 of its equivalent transformations

A necessary condition for building a linear multi-capillary pressure divider, as well as a two-capillary one, is the linearity of consumption characteristic of capillary CE_1.

To determine the rest of the dimensions (d_j and l_j for $j=\overline{2, m}$) of passable channels of linear m-capillary divider of pressures, a successive substitution is performed of m-l pairs of {CE_j; $CE_{(j-1)}$} of neighboring capillaries by an equivalent linear capillary $CE_{(j)}$ based on the dependencies (5) and (6), where $CE_{(j-1)}$ is the conditional sign of the equivalent linear capillary, which is a substitution of the sequence CE_1,..., CE_{j-1} of capillaries of the divider by an imaginary capillary with diameter $d_{(j-1)}$ and length $l_{(j-1)}$ (Fig. 2).

For any pair of capillaries, for example {CE_j; $CE_{(j-1)}$}, with the set pressures P_j, P_{j-1} and P_0, the dependency (6) will take the form

$$P_{j-1} = \lambda_{(j-1)}\left(1-\lambda_{(j-1)}\right)^{-1}\left(P_j - P_0\right) + P_0. \quad (9)$$

Taking into account that $\lambda_{(j-1)} = l_j / l_{(j-1)}$, from (9) we receive a dependency to determine the length l_j of a passable channel of capillary CE_j.

For the above mentioned pair of capillaries {CE_j; $CE_{(j-1)}$}, based on the first equation of the system (5), we receive the dependency

$$\delta^4_{(j-1)} = \lambda^2_{(j-1)}\left(1-2\lambda_{(j-1)}\right)^{-1}, \quad (10)$$

where $\delta_{(j-1)}=d_j/d_{(j-1)}$, and from which – the expression for the diameter d_j of capillary CE_j.

As a result, the system of equations for determining the dimensions (d_j, l_j) of passable capillary channels will take the form [16]:

$$\left.\begin{array}{l} d_j = d_{(j-1)}/g_j; \\ l_j = l_{(j-1)}/y_j, \end{array}\right\} \qquad (11)$$

where

$$j=\overline{2,m};\ \ d_{(j-1)} = \left[\sum_{k=1}^{j-1} d_k^{-4}\right]^{-1/4};\ \ g_j = \left[D_{(j-1)}^2 - 1\right]^{1/4};$$

$$l_{(j-1)} = \kappa d_{(j-1)}^2;\ \ y_j = D_{(j-1)} + 1;\ \ D_{(j-1)} = D_{j-1} D_j^{-1};$$

$$D_{j-1} = \Delta P_m/\Delta P_{j-1} = \chi_{j-1};\ \ \Delta P_{j-1} = P_{j-1} - P_0;$$

$$\kappa = P_0\sqrt{\xi X};\ \ d_{(1)} = d_1;\ \ l_{(1)} = l_1.$$

Dimensions (d_1, l_1) of the passable channel of linear capillary CE_1 are calculated with regard to provision of the required division coefficient and consumption through the capillary.

According to results of the research into linear pressure dividers, it was found that the maximum value of division coefficient χ_{max} as a rule does not exceed 30 and may be reached in a two-capillary divider only while it is slightly lower for multi-capillary ones [5].

4. 3. Scheme of cascade connection of pressure dividers

To set the pressure drops, different in magnitude (at the level of several orders of magnitude), and ensure constant division coefficients, a scheme of cascade connection of linear multi-capillary dividers (i=1,..., n) is proposed, with arbitrary number of capillaries $CE_{i,j}$, where j=1,..., m_i [5, 16].

The maximum value of division coefficient $\chi_{C\,max}$ of cascade scheme division, in the case of applying in each of n cascades of linear two-capillary dividers of pressure, equals $\chi_{C\,max} = \chi_{max}^n \approx 30^n$.

The scheme has one input channel, where the flow divides into n pressure dividers. At the input of each divider, the appropriate pressures are set: at the first – with a stabilizer of absolute or excess pressure, on the rest of dividers, the pressures are created by repeaters Rp_k (k=2,..., n), each setting section of which is connected to the first (from the gas outpit) inter-throttle section, formed by capillaries $CE_{k-1,2}$ and $CE_{k-1,1}$ of the previous k–1-th divider. The outputs of all pressure dividers are connected to the output channel (flow combiner), the pressure of gas P_0 in which is maintained constant with the help of stabilizer of absolute pressure [17]. The pressure stabilizers at the output and input of the scheme (Fig. 3) are not shown.

Represented below is a system of recurrent dependencies, built on the basis of the system (11), for determining the dimensions ($d_{i,j}$ and $l_{i,j}$) of all passable channels of capillaries $CE_{i,j}$ of a cascade connection of linear pressure dividers

$$\left.\begin{array}{l} d_{i,j} = d_{i,(j-1)}/g_{i,j}; \\ l_{i,j} = l_{i,(j-1)}/y_{i,j}, \end{array}\right\} \qquad (12)$$

where

$$i=\overline{1,n};\ j=\overline{2,m_i};\ \ d_{i,(j-1)} = \left[\sum_{k=1}^{j-1} d_{i,k}^{-4}\right]^{-1/4};\ \ g_{i,j} = \left[D_{i,(j-1)}^2 - 1\right]^{1/4};$$

$$l_{i,(j-1)} = \kappa d_{i,(j-1)}^2;\ \ y_{i,j} = D_{i,(j-1)} + 1;\ \ D_{i,(j-1)} = D_{i,j-1}/D_{i,j};$$

$$D_{i,j-1} = \Delta P_m^{(i)}/\Delta P_{j-1}^{(i)} = \chi_{i,j-1};\ \ \Delta P_{j-1}^{(i)} = P_{i,j-1} - P_0;$$

$$\kappa = P_0\sqrt{\xi X};\ \ d_{i,(1)} = d_{i,1};\ \ l_{i,(1)} = l_{i,1}.$$

The advantage of this scheme is that it remains linear when switching the sections of setting the repeaters Rp to other inter-throttle sections of dividers of higher pressure. Due to this, without modification of capillaries design of each divider, the scheme may provide a significant increase in the number of set inter-throttle pressures $P_{i,j}$.

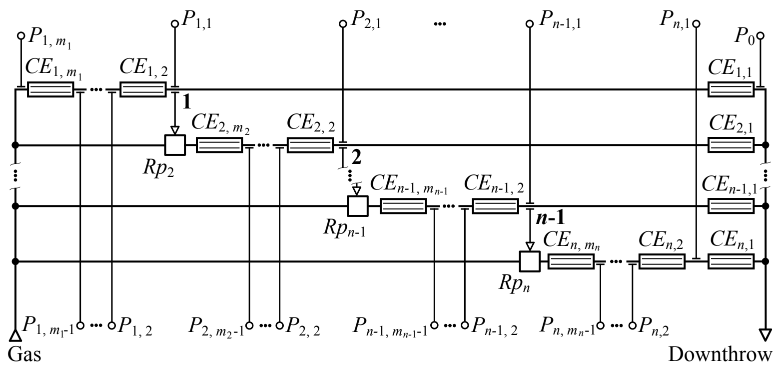

Fig. 3. Generalized schematic diagram of cascade connection of pressure dividers to set the pressures, different in magnitude (drops)

However, this scheme is limited in the value of the lower limit of the set pressure that is associated with errors of pressure reproductions by repeaters. Thus, for the repeaters of individual manufacture and adjustment of their pair "nozzle-valve", the absolute error of reproduction (repetition) of pressure may amount to a few tens of pascal and for the industrial repeaters it is higher by an order of magnitude [18].

The error of pressure reproduction can be significantly reduced when using a separate node of pressure reproduction. This node is a system of automatic control with negative feedback, which contains a high-sensitive null indicator to detect the pressure differences ΔP_{NI} on the node's output of pressure reproduction and in the chamber of a repeater setting, to which a controlled throttle is connected, by changing the gas-dynamic resistance of which ΔP_{NI} is eliminated.

4. 4. Scheme with a binary ramification of dividers

Promising for building the systems of setting the pressures, different in magnitude, is the scheme of binary ramification of dividers, shown in Fig. 4. In general, each of its n pressure dividers is multi-element and contains, accordingly, m_i (i=1,..., n) of capillaries. With this scheme, in contrast to the cascade one, one can obtain a value of inter-throttle pressures at the level of particles of pascal.

Gas under pressure of P_{1,m_1} is supplied to the input of the scheme, which is also the input of the first divider. In the flow chamber of this divider, formed by capillaries $CE_{1,1}$ and $CE_{1,2}$, the flow branches off to the input of the second divider. Then every subsequent i-th divider, which is connected to the corresponding inter-throttle chamber of the i–1-th divider, formed by capillaries $CE_{i-1,1}$ and $CE_{i-1,2}$, branches off a part of the flow.

As a result of this connection of n pressure dividers, n–1 of nodes form in the scheme, in Fig. 4 they are indicated by numbered (1,..., n–1) dots. The outputs of all pressure dividers are combined in one channel, which maintains constant pressure P_0.

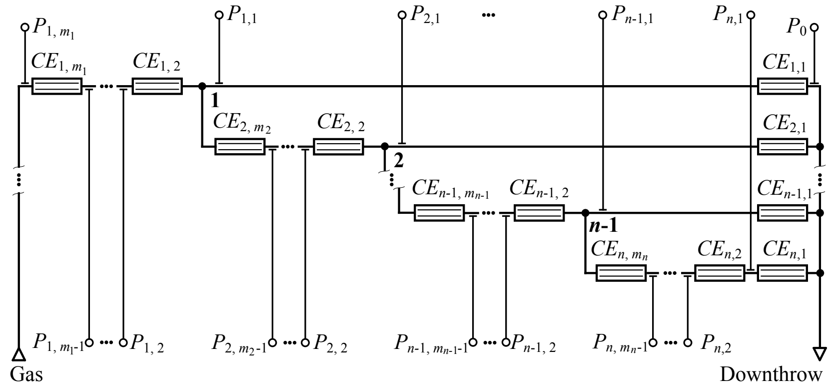

Fig. 4. Generalized principal scheme with binary ramification of dividers for setting low pressures (drops)

To implement a linear function of the change in inter-throttle pressures $P_{i,j}=f(P_{1,m_1})$, an algorithm was developed for determining dimensions of passable channels of capillaries of the scheme, presented in [5].

Based on the laws of conservation of mass and Kirchhoff, using the dependency (1) for a scheme of binary ramification of pressure dividers, its mathematical model is received

$$\left.\begin{array}{l} G_{i,m_i}=G_{i,m_{i-1}}; \\ \ldots \\ G_{i,j}=G_{i,j-1}; \\ \ldots \\ G_{i,3}=G_{i,2}; \\ G_{i,2}=G_{i,1}+G_{i+1,m_{i+1}}, \end{array}\right\} \qquad (13)$$

where

$$G_{i,j}=\varphi(P_{i,j},P_{i,j-1})= =A_{i,j}\left(\left[1+Y_{i,j}\,\Delta P_j^{(i)}\left(\Delta P_j^{(i)}+2P_{i,j-1}\right)\right]^{0,5}-1\right)$$

is the mass rate of gas through the capillary $CE_{i,j}$ ($i=\overline{1,n}$ is the number, n is the number of branches; $j=\overline{1,m_i}$ is the number of capillary in the branch from the output to the input of gas, m_i is the number of capillaries of the i-th branch); $A_{i,j}=a_1 l_{i,j}$; $Y_{i,j}=\xi d_{i,j}^4 l_{i,j}^{-2} X$; $\Delta P_j^{(i)}=P_{i,j}-P_{i,j-1}$; $G_{n+1,m_{n+1}}=0$ as the n+1-th branch does not exist.

Mathematical model (13) is a system $\sum_{i=1}^{n}(m_i-1)$ of nonlinear equations relative to the inter-throttle pressures $P_{i,j}$ and enables exploring the impact of the pressure changes P_{1,m_1}, P_0 and the temperature T of gas on the division coefficients $\chi_{i,j}$ of pressures of the considered scheme. The maximum coefficient χ_{Bmax} of the scheme division with a binary ramification of dividers with the linear function $P_{i,j}=f(P_{1,m_1})$ equals χ_{Cmax}.

5. Decade device for setting low pressures

There are known ways for setting excessive pressures and drops that operate in the range with a lower limit, as a rule, exceeding 10 kPa. In gas analytical practice, there is often a need for setting stabilized pressures, different in magnitude, and pressure drops in the range, the upper limit of which does not exceed 10 kPa. In this regard, a four-decade capillary setting device is designed in the ranges: {1, 2,...,9}, {10, 20,...,90}, {10^2, $2\cdot10^2$,...,$9\cdot10^2$}, {10^3, $2\cdot10^3$,...,10^4} Pa (Fig. 5).

The scheme of the setting device (Fig. 5) is based on the principal scheme with binary ramification of the pressure dividers shown in Fig. 4. The setting device is created by four branches, each of which contains a pressure divider of 10 capillaries. The scheme is fed with air, the pressure of which at the input $P_{1,10}$=115 kPa and at the output P_0=105 kPa of a throttle scheme is maintained stable by, respectively, a stabilizer of absolute pressure Sp_1 and stabilizer Sp_0. All scheme's elements are placed to the thermostat Ts, which keeps the temperature at T=313 K.

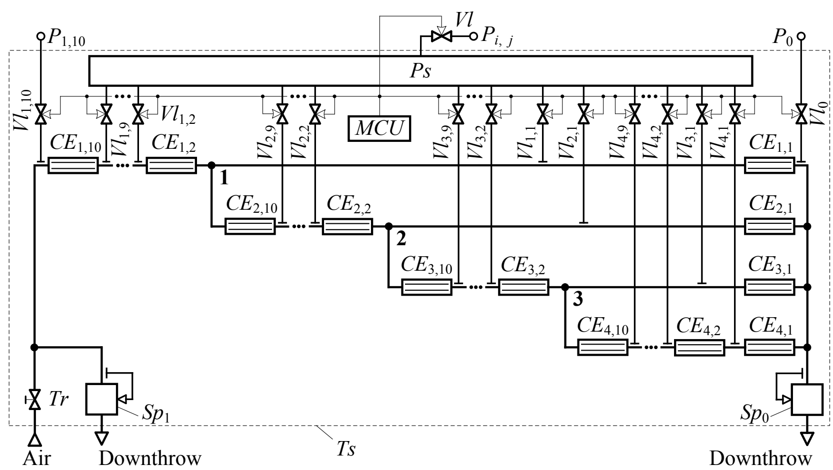

Fig. 5. Schematic of a four-decade pressure setting device: Ps is the pneumatic switch; MCU is the microprocessor control unit; $Vl_{i,j}$ is the electromagnetic valve, set up on the line of pressure selection $P_{i,j}$ from the inter-throttle chamber, formed by capillaries $CE_{i,j+1}$ and $CE_{i,j}$; Tr is the alternative throttle; Ts is the thermostat; Sp_1, Sp_0 are the stabilizers of absolute pressure

For alternate setting of inter-throttle pressures $P_{i,j}$, the corresponding chambers with the help of electromagnetic valves $Vl_{i,j}$ are connected to the pneumatic switch Ps, the output channel of which is connected with a consumer by the valve Vl. Setting a certain sequence (separate value) of pressures is controlled by MCU, which switches on corresponding electromagnetic valves.

All inter-throttle pressures $P_{i,j}$, as well as the input $P_{1,10}$ and the output P_0 pressures of the setting device, can be reproduced simultaneously without using the switch Ps.

A number $k_{\Delta P}$ of different drops of pressures in the case of setting within the i-th divider of equal drops of pressures on each of its capillaries (Fig. 4), that is, $\Delta P_1^{(i)}=\Delta P_2^{(i)}=\ldots=\Delta P_{m_i}^{(i)}$, is determined by the dependency

$$k_{\Delta P}=m_1+\sum_{i=1}^{n-1}\left\{\left[m_i-\mathrm{sgn}(i-1)\right]\cdot\left[\sum_{j=i+1}^{n}(m_j-1)\right]\right\}. \qquad (14)$$

Thus, the setting device shown in Fig. 5 can set simultaneously 523 different pressure drops.

To ensure linearity and decade division of pressures in each of the scheme's dividers, the dimensions of passable channels are defined by the algorithm, presented in [5].

A mathematical model of the designed device for setting pressures will take the form

$$\left.\begin{array}{l} G_{1,10}=G_{1,9};\;\; G_{1,9}=G_{1,8},\;\; \ldots\;\; G_{1,3}=G_{1,2};\;\; G_{1,2}=G_{1,1}+G_{2,10}; \\ G_{2,10}=G_{2,9};\;\; G_{2,9}=G_{2,8},\;\; \ldots\;\; G_{2,3}=G_{2,2};\;\; G_{2,2}=G_{2,1}+G_{3,10}; \\ G_{3,10}=G_{3,9};\;\; G_{3,9}=G_{3,8},\;\; \ldots\;\; G_{3,3}=G_{3,2};\;\; G_{3,2}=G_{3,1}+G_{4,10}; \\ G_{4,10}=G_{4,9};\;\; G_{4,9}=G_{4,8},\;\; \ldots\;\; G_{4,3}=G_{4,2};\;\; G_{4,2}=G_{4,1}, \end{array}\right\}(15)$$

and is the system of 36 nonlinear equations relative to inter-throttle pressures $P_{i,j}$, where $i=\overline{1;4};\; j=\overline{1;9}$.

Modeling the operation of a setting device scheme, presented in Fig. 5, demonstrated that the change in the input pressure does not lead to the change in the division coefficients $\chi_{i,j}$. However, the change of the pressure P_0 causes a slight change of $\chi_{i,j}$, for example, at the unidirectional change in the supply pressure ($P_{1,10}$, P_0) by ±50 Pa, the maximum deviation of division coefficients $\chi_{i,j}$ does not exceed 0.005 %. The temperature change by up to ±5 K causes a deviation of division coefficients by the magnitude of up to 0.2 %.

6. Discussion of results of the research into linear dividers and development of devices for setting the pressures, different in magnitude

The results of the study of two- and multi-capillary dividers of pressures allowed the development of cascade connection schemes and binary ramification of dividers. The use of devices for setting pressures, built on the basis of these dividers, enables compensation of uncontrollable effects of external factors in different gas-dynamic systems, in which pressures should be stabilized. Thus, for example, in gas -dynamic synthesizers of gas mixtures, proportional changes in pressures at the inputs of dosing capillaries are achieved due to them, and, therefore, the rates of all dosed components are provided so that their concentrations in the mixture remain unchanged. This effect is virtually impossible when using certain independent pressure stabilizers for each component of the synthesized mixture.

Along with the mentioned advantages of the designed setting devices, one should admit the need of using a stabilizer of absolute pressure in them at the output, though the nonlinearity of divider without it is not substantial.

Research into pressure dividers revealed the prospects of their use in the devices for setting pressures, different in magnitude, i. e., for simultaneous setting of a large number of pressures (drops), significantly different in the value of absolute pressure. Such setting devices are particularly promising for the construction of synthesizers of gas mixtures with micro-concentrations of the components. In this regard, two schemes were designed – cascade and the scheme with binary ramification of pressure dividers. The advantage of the first one is the possibility of its adjustment for setting other pressures by switching the chambers of setting of repeaters to other inter-capillary chambers of dividers. The disadvantage is the need to use pressures repeaters to build the scheme, which limits the coefficient of pressures division. The advantage of the second scheme is its functioning without pressure repeaters, which removes the restrictions for setting any low pressures, which occur in gas-analytical practice. The disadvantage of this scheme is the inability of its adjustment to other inter-throttle pressures (drops) without replacing of all capillaries.

The use of such schemes in the devices for setting pressures opens up the prospect of constructing high precision gas-dynamic tools, in particular, to obtain complex mixtures with micro-concentrations of the components, setting low and micro rates of gas, testing micromanometers.

Quite a variety of tasks in the practice of scientific research into the area of gas-analysis requires the development of tools for providing the deployment of pressures by the dependencies that are different from the linear ones. Therefore, a solution of this problem requires separate study in future of capillary pressure dividers.

7. Conclusions

1. The possibility of providing the linearity of changing the inter-throttle pressures of capillary pressure dividers was shown, and thus the constancy of the coefficients of pressure division.

2. Based on the connection of linear pressure dividers, the schemes were built that provide the coefficients of division at the level of several orders of magnitude.

3. With the help of the scheme with binary ramification of capillary pressure dividers, a linear four-decade device for setting absolute pressures (drops) in the range of 105–115 kPa (0–10 kPa) was proposed. The setting device is almost insensitive to the effects of supply pressures on the coefficients of division and their deviation is less than ±0.2 % at the change in temperature within ±5 K.

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