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THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF IDENTIFYING PRESSURE LOSS IN FILTER ELEMENTS OF COARSE AND FINE GAS PURIFICATION WHEN PLACED IN ONE BODY

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Statement of the problem. Reliable operation of modern high-precision gas flow reduction and control systems located in cabinet, block and capital gas distribution points calls for the use of two-stage cylindrical gas purification plants containing preliminary and fine filters. An urgent task is to design and scientifically substantiate the use of cost-effective two-stage natural gas purification devices located at gas distribution points as well as the development of analytical calculation methods for identifying pressure losses in the filter elements of two-stage cylindrical installations and the timing of their regeneration.
Results. Theoretical and experimental identification of pressure losses depending on the degree of clogging of a multilayer filter element with mechanical impurities is given.
Conclusions. Analytical equations for identifying pressure losses are obtained which differ from the known solutions in that the effect of clogging with mechanical impurities in a multilayer filter cloth is first presented as the sum of pressure losses on a number of clean calibrated grids located one after another, with the cell sizes of each subsequent grid less than the previous one.

Keywords: pressure loss, clogging degree, multilayer filter element, two-stage cylindrical installation, mechanical impurities, natural gas.

Introduction. Reliable operation of modern high-precision systems for reducing and controlling gas flows located in cabinet, block and capital gas distribution points (GDP) and ensuring the maintenance of outlet pressure and flow rate with an error of 2.5% [2, 9] calls for the use of two-stage cylindrical units (DCU) for gas purification containing filters of preliminary and fine purification [7, 12]. These filters, locared in separate cylindrical housings, account for about 94 % of the total number of those installed in hydraulic fracturing and have proved to be the most economical and convenient in operation.

However, the disadvantage of the existing DCU is high financial investments and metal consumption, as cylindrical filter elements (CFE) for fine and preliminary cleaning are set up in separate housings. On top of that, their placement calls for appropriate areas of the hydraulic fracturing room. What is also required is an increase in the amount of thermal energy for heating and ventilation of hydraulic fracturing units housing filters with two separate housings.

1. Theoretical studies to identify the pressure loss in the filter elements of preliminary and fine gas cleaning when placed in one building block. A lot of studies have been dedicated to the solution of certain issues of the development and calculation of the DCC of preliminary and fine cleaning: by foreign authors V. Straus [8], B. Guo [15], S. Mokhatab [17], I. M. Hutten [16], K. Sutherland [18], Ch. Tien [19], S. Trevor [20], X. Wang [21], and by domestic scientists: V. V. Belousova [1], P. A. Kouzova [6], etc.

Hence, in 2010 A. L. Shurayts and V. P. Zhelanov [4] substantiated the maximum cell size of a gas CEF; in 2011, A. L. Shurayts [13, 14] set forth methodological principles for preventing CEF deformation by enclosing them in a shell of a thickened corrugated mesh. A. P. Usachev and S. V. Gustov [10] in 2012 identified the optimal height-diameter ratio of a cylindrical gas filter, and in 2014 S. V. Gustov [3] suggested the principles of intensive CEF corrugation. However, neither of the approaches was designed to improve the methods of calculation and analytical identification of pressure losses in the CEF when they are clogged with mechanical impurities.

In order to identify the pressure losses depending on the degree of clogging of a multilayer filter element with mechanical impurities, the following methodological provisions were developed.

1.1. Statement of the problem. In the general case, the filter material is made of n meshes set up one after another. The working medium at a constant design flow rate V with a high content of mechanical impurities is cleaned, moving through a series of grids n (Fig. 1).

These grids are sequentially set up one after another in the direction of movement of the working medium and have square cells with a side size equal to m_n.

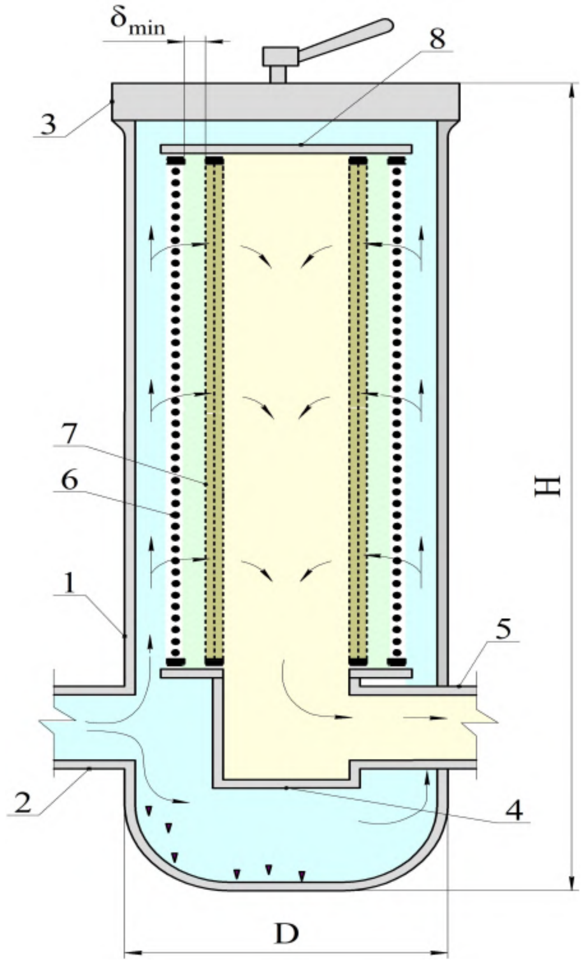

Fig. 1. Scheme of DCU with CEF of preliminary and fine cleaning placed in the same body of the product: 1 — body of the DCU having a cylindrical shape; 2 — inlet pipe; 3 — body cap; 4 — glass; 5 — outlet pipe; 6 — CEF pre-treatment; 7 — CPE fine cleaning; 8 — CEF plug

The ordinal number of the grid n in the row along the gas flow changes in the interval $n = 1$; 2; 3; …, I (Fig. 2). During clogging of each subsequent grid, mechanical impurities of a smaller size are deposited. Therefore each next grid n in the direction of gas flow has a smaller initial size and thereby the sizes following it compared to the previous one. In the process of clogging of the grid cells, the size of each grid n in a row changes to the following values: $m_n = a_n, c_n, e_n, ..., j_n$. An enlarged fragment of the grid is shown in Fig. 3.

The spacing between two adjacent cells $L_{n=i.m=j_{n=i}}$ having a square shape (Fig. 3) has a smaller initial and subsequent distance $L_{n=i-1.m=j_{n=i-1}}$ compared to the previous one, i.e., $L_{n=i-1.m=j_{n=i-1}} > L_{n=i.m=j_{n=i}}$.

At the initial moment of the operation on the living section of the grid $b^2_{n=i.m=a_{n=i}} / \left(b_{n=i.m=a_{n=i}} + \mathrm{L}_{\mathrm{n=i.m=a_{n=i}}}\right)^2$ which is set at the point $n = i$ in the direction of the gas flow corresponds to the degree of clogging with mechanical impurities $\theta_{n=i.m=a_{n=i}}$. At this point, with these parameters, the degree of mesh clogging equals zero.

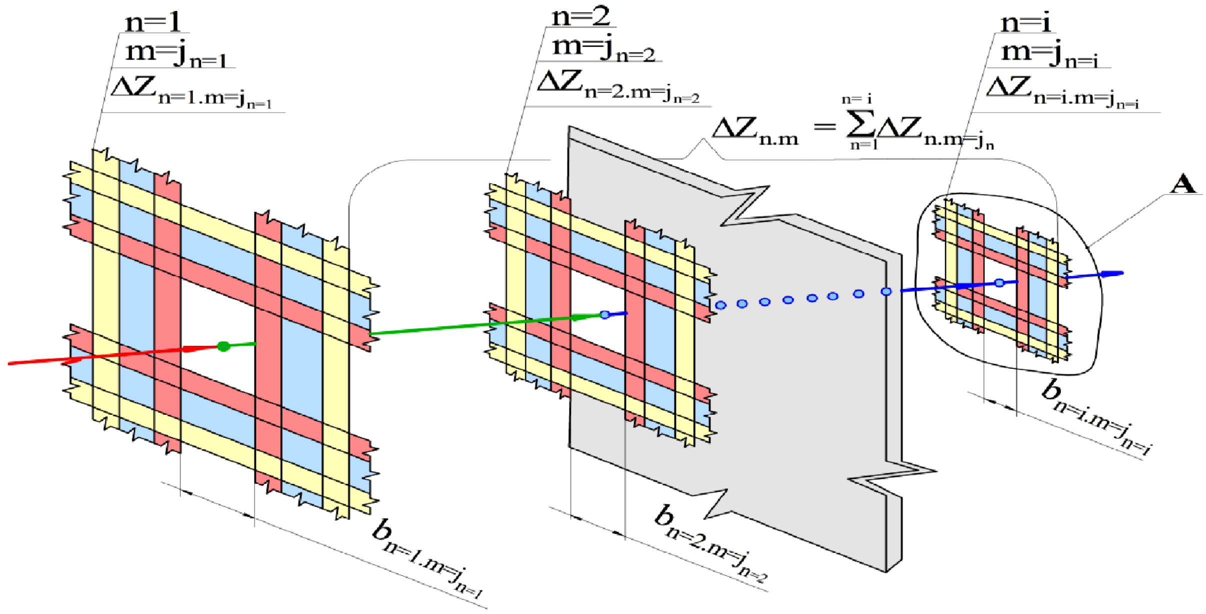

Fig. 2. Scheme of sequentially arranged fragments of CEF grids in the interval n = 1; 2; 3; …, i with the grid cell size equal to m_n

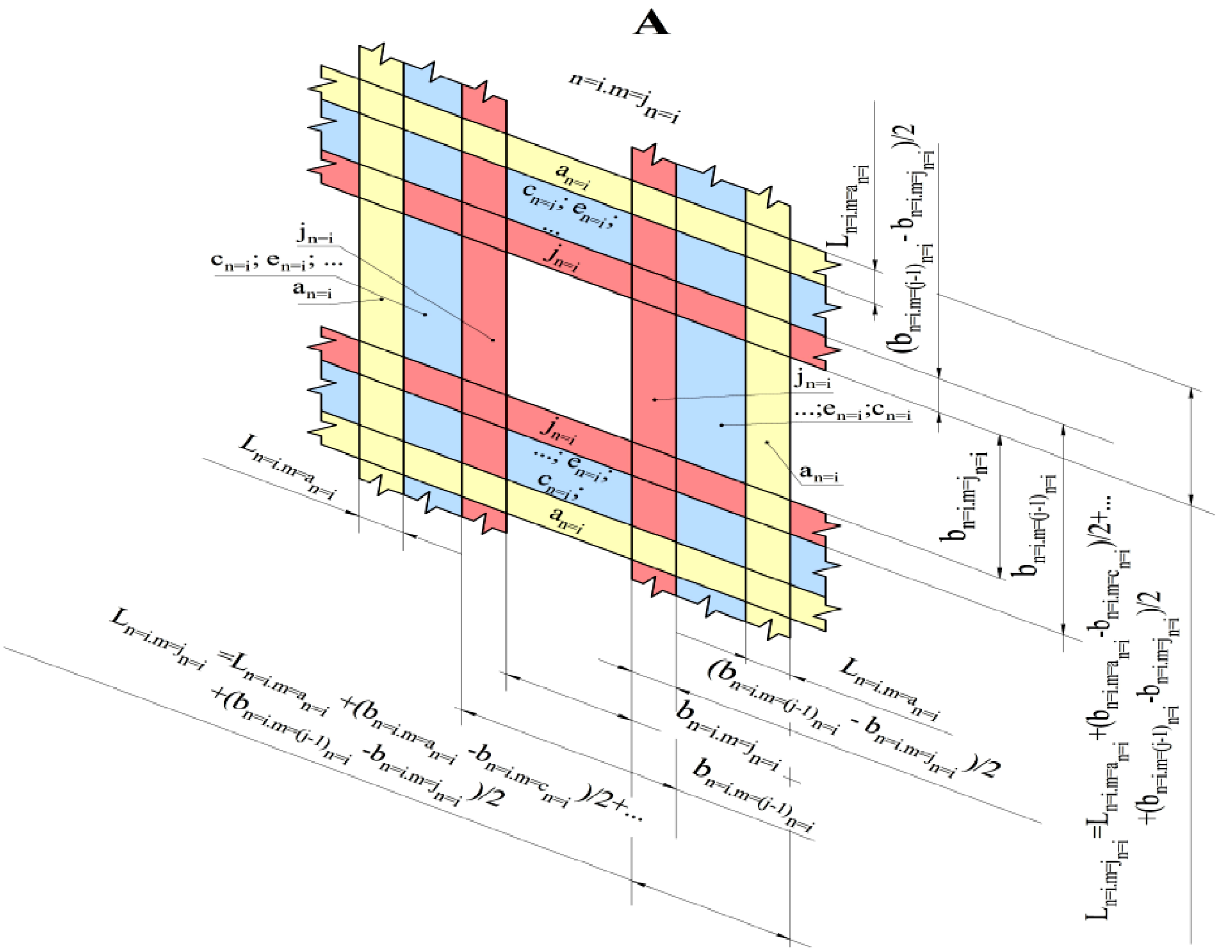

Fig. 3. Grid fragment (enlarged) with number n = i and initial cell size $b_{n\,=\,i.m\,=\,an\,=\,i}$ with the distance between the cells $L_{n\,=\,i.m\,=\,an\,=\,i}$

In case if $m = j$, as a contaminated element located at the point $n=i$, a filter element with a cell having a smaller nominal side size is conditionally accepted to be $b_{n=i.m=j_{n=i}}$ (at $m = j$) compared to the size of the cell $b_{n=i.m=j_{n=i-1}}$, in case if $m = j_{n=i\text{-}1}$ (Fig. 2).

Change in any previous grid cell size (set at the point $n=i$ in the direction of gas flow) from $b_{n=i.m=j_{n=i-1}}$ to $b_{n=i.m=j_{n=i}}$ to the smaller side when the grid is clogged will be defined as an increase in the distance between the cells of the grid to the value

$$L_{n=i.m=j_{n=i}} = \sum_{m=1}^{m=j}(b_{n=i.m=j_{n=i-1}} - b_{n=i.m=j_{n=i}}) + L_{n=i.m=a_{n=i}}. \quad (1)$$

The area of the open section of the grid (absolute value) having a square shape and located at the point $n = i$ along the gas flow considering the changing distance $L_{n=i.m=j_{n=i}}$ between the cells for any time of operation $m = j_{n=i}$ will be given by the formula:

$$F_{ж.n=i.m=jn=i} = \frac{F \cdot b^2_{n=i.m=j_{n=i}}}{\left[b_{n=i.m=j_{n=i}} + L_{n=i.m=a_{n=i}} + \sum_{m=1}^{m=j}(b_{n=i.m=j_{n=i}-1} - b_{n=i.m=j_{n=i}})\right]^2}, \quad (2)$$

where F is the total filtering area of the mesh element in compliance with the product passport, m^2; $b_{n=i.m=a_{n=i}}$ is the nominal size of the grid cell in the light (at the initial moment) not contaminated with mechanical impurities and placed at the point $n = i$ in the direction of the gas, for $m = a_{n=i}$ (Fig. 3), m; $L_{n=i.m=a_{n=i}}$ is the nominal distance in the light between the cells of the grid (Fig. 3) located at the point $n = i$ in the direction of the gas, for $m = a_{n=i}$, m.

The formula that identifies the total pressure loss during the flow of gas through a series of grids $n = 1; 2; 3; \ldots, i$ sequentially located one after another (Fig. 2) provided that each subsequent grid in the direction of the gas has a smaller initial and subsequent sizes compared to the previous one, is written as [11]:

$$\Delta Z_{n.m} = \sum_{n=1}^{n=i}\Delta Z_{n.m=jn} = \sum_{n=1}^{n=i}\zeta_{n.m=j_{n=i}} \cdot \frac{\omega^2_{n.m=j_{n=i}}}{2 \cdot g} \cdot \rho_{n.m=j_{n=i}}, \quad (3)$$

where $\Delta Z_{n=i.m=jn=i}$ is the pressure loss on the grid located at the point $n = i$, for $m = a_{n=I}$ sized $b_{n=i.m=j_{n=i}}$ which is caused by contamination with mechanical impurities, Pa; $\zeta_{n=i.m=j_{n=i}}$ is the coefficient of local resistance of the mesh [5] set up at the point $n = i$, for $m = j_{n=I}$, sized $b_{n=i.m=j_{n=i}}$ which is caused by contamination with mechanical impurities; g is the acceleration of gravity accepted to be 9,8 m/sec^2; $\omega_{n.m=j_{n=i}}$, $\rho_{n.m=j_{n=i}}$ is the speed and density of the working medium when passing through a grid cell at the point $n = i$ under the operating pressure, m/sec and kg/m^3. Substituting equation (2) into equation (3) and presenting the speed of the working medium ω_p as the ratio of the passing capacity V to the cross-sectional area of the grid $F_{жс.n=i.m=jn=i}$, we get the following equation:

$$\Delta Z_{n.m} = \sum_{n=1}^{n=i} \zeta_{n.m=j_n} \cdot \frac{V^2 \left[b_{n.m=a_n} + L_{n.m=a_n} + \sum_{m=1}^{m=j} (b_{n.m=j_n-1} - b_{n.m=j_n}) \right]^4}{b^4_{n=i.m=j_n} \cdot F^2 \cdot 2 \cdot g} \cdot \rho_г , \qquad (4)$$

where V is the passing capacity of the filtering setup under the operating pressure, m^3/sec.

Also, using formula (4), it is possible to identify the pressure loss of the CEF of pre-treatment if the value is $n = 1$.

At any point of the operation of DCU at $m = j_{n=i}$ the net cross section is determined by formula (2), which will correspond to a certain degree of clogging with mechanical impurities.

The degree of clogging of the CEF, which is a series of grids (average integral indicator), is defined as the sum of the clogging degrees of all the grids divided by their total number:

$$\theta_{cp.n.m} = \frac{\sum_{n=1}^{n=i} \left\{ \dfrac{\dfrac{b^2_{n.m=an}}{\left(b_{n.m=an} + L_{n.m=an}\right)^2} - \dfrac{b^2_{n.m=jn}}{\left[b_{n.m=an} + L_{n.m=an} + \sum_{m=an}^{m=j_n} (b_{n.m=jn-1} - b_{n.m=jn}) \right]^2}}{\dfrac{b^2_{n.m=an}}{\left(b_{n.m=an} + L_{n.m=an}\right)^2}} \right\}}{n = i} . \qquad (5)$$

The above formulas (2)—(5) make it possible to identify the values of the pressure losses on the filtering element and the average integral degree of clogging of the CEF, depending on the decrease in the free section of the filtering meshes when clogged.

2. Experimental verification of theoretical equations for identifying pressure losses in the filtering elements of preliminary and fine gas cleaning when placed in one body. An important stage of the research is the experimental verification of the obtained theore-tical results which was performed on a pilot plant (Fig. 4) of the test site of JSC "Giproniigaz".

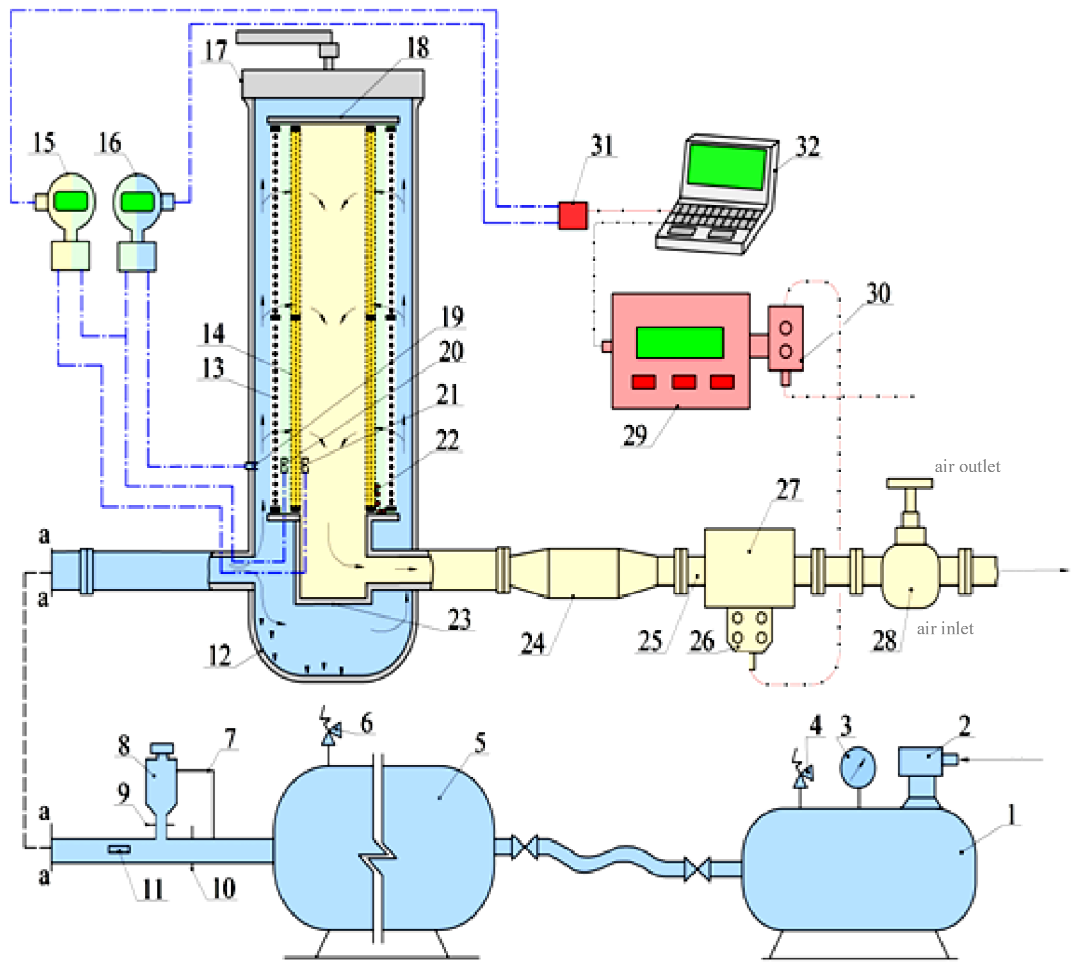

Fig. 4. Scheme of an experimental setup:
1, 2 — receiver and compressor; 3 — manometer; 4 — safety valve; 5 — receiver for accumulating compressed air;
6 — safety valve of receiver 5; 7 — impulse tube for supplying pressure;
8 — container with sand particles; 9 — dosing hole; 10 — nozzle for supplying mechanical impurities;
11 — distributor of mechanical impurities in the stream; 12 — two-stage DCU;
13 — cylindrical pre-filtering element; 14 — CPE fine cleaning;
15 — transducer for measuring the pressure drop on the CEF pre-treatment;
16 — sensor-converter for measuring the pressure drop on the CEF of fine cleaning; 17 — DCU;
18 — CEF plug; 19, 20, 21 — pressure sensors for crude, coarse and fine gas;
22 — filtered mechanical impurities; 23 — a glass of DCU; 24 — turbulator for the flowmeter;
25 — vortex counter IRVIS-RS4-Pp-16-PPS with a receiving unit for converting pressure, temperature and flow;
26, 27; 28 — control valves; 29 — signal processing unit; 30 — registration device; 31 — interface;
32 — computer equipped with software for graphical display of pressure losses

Experimental verification of equations (3)–(5) was performed for the CEF of preliminary and fine cleaning. For CEF pre-cleaning, one layer of a high-precision mesh according to GOST 6613-86 from a half-pack $n = 1$ with the mesh size of 0.2 mm was used as a filter cloth. In order to ensure the high accuracy of the results of experimental studies on trapping finely dispersed impurities in the CPE of fine purification, through the course of the experiments, a web of seven layers of grids based on the “semi-tompak” alloy according to GOST 6613-86 with the thickness of 1.18 mm was used with the cell sizes, mm, respectively

0.18 (n = 1); 0.14 (n = 2); 0.12 (n = 3); 0.09 (n = 4); 0.071 (n = 5); 0.05 (n = 6); 0.04 (n = 7). As the results of the specially performed experiments showed, the error from the accepted assumption for the replacement of non-woven filter cloths with the thickness of 1.2 mm, used in industrial fine filtering, with a cloth of seven layers of the above meshes with the thickness of 1.18 mm was 13.5 %.

While performing experiments for verification of equations (3)—(5), the following degrees of contamination were taken: 0.0; 15.0; 30.0; 45.0; 60.0; 75.0; 80.0 %. The calculated degree of clogging of the working grid was simulated by applying a thin low-permeability film to the outer surface.

The results of the calculations to identify the theoretical values of the pressure losses on the gas filtering elements of fine and preliminary cleaning according to formulas (3)—(5) depending on the degree of clogging are shown in the graph in the form of solid lines (Fig. 5). The experimental data in Figure are presented as points. The experimental values of the pressure losses were measured using remote transducers 18 and 17 depending on the degree of clogging of the CEF.

In Fig.5a and 5b there are also changes in the specific flow rate as the ratio of the calculated flow rate to the area of the grid cells, m^3/hour·m^2, depending on the degree of clogging in the form of descending graphs (dashed lines). Based on the graphs in Fig. 5, the growth rate of the pressure loss at a clogging degree from 65 % for fine CPE to 70 % for preliminary CPE is 3.75 times higher compared to those at a clogging degree of 50 %.

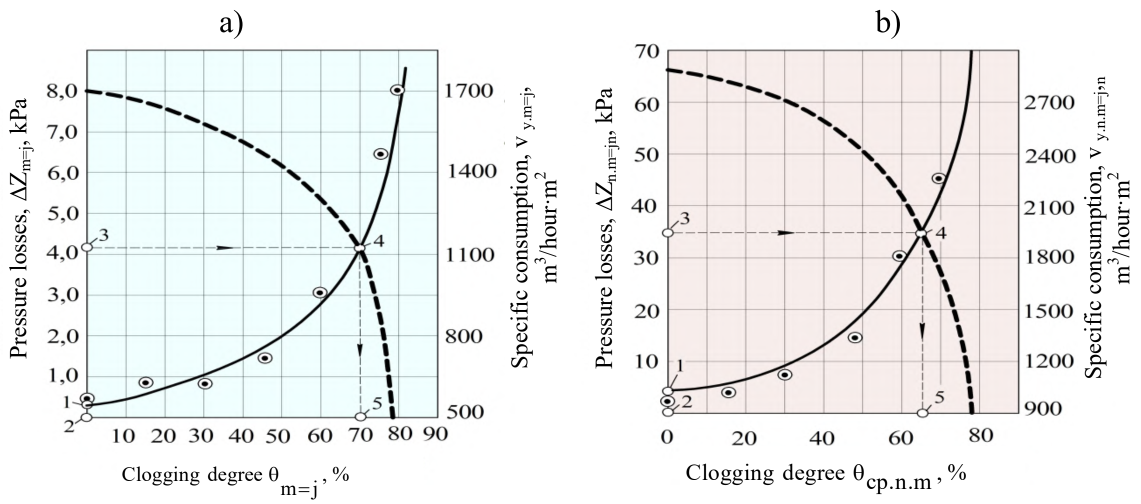

Fig. 5. Change in pressure loss (solid lines) and specific flow rates (dashed lines) while passing the gas through the filter elements of fine (b) and preliminary (a) cleaning depending on their degree of contamination:
⊙ are the experimental points for the pressure losses

Based on the the graph, with a clogging degree of 65 % or more for fine CPE and 70 % or more for preliminary CPE, there is a rapid increase in pressure losses, which causes a decrease in the specific flow rate below the permissible value and generates a risk of their deformation and failure. Therefore it is advisable that regeneration (cleaning) for pre-treatment CPE with a clogging degree of 70 % is performed and replaced with new ones for fine CPE with a clogging degree of 65 %. These degrees of clogging correspond to the value of the pressure drop across the filter element, equal to $\Delta Z_{\mathbf{m}=j}$ = 4.2 kPa for CEF pre-cleaning $\sum_{n=1}^{n=7} \Delta Z_{n.m=j_n}$ =34.0 kPa for CEF fine cleaning (the points 3→4→5 in Fig. 5). For these degrees of fouling and the corresponding pressure drops on the CFE, there is a considerable decrease in the passing capacity.

Therefore the obtained experimental data confirm the analytical dependences (3)—(5) for identifying the values of the pressure losses on the gas filtering elements of fine and preliminary cleaning depending on the degree of their clogging and enabled us to recommend them for use in design and operational practice. According to the research results, technical and operational documentation complied with by Giproniigaz JSC to prepare and produce the suggested DCU.

Conclusions

1. Analytical equations (3)—(5) are obtained for identifying the pressure losses differing from the known solutions in that the effect of clogging with mechanical impurities in a multilayer filter cloth is first presented as the sum of the pressure losses on a number of clean calibrated grids located one after another with the dimensions cells of each subsequent grid less than the previous one. The suggested equations are implemented in STO 03321549-047-2016 and allow for a 1.8-fold reduction in operating costs in two-stage setups by optimizing the time period between filter element regenerations.

2. The experimental verification confirms the analytical dependences (3)—(5) for identifying the values of the pressure losses on gas multilayer filtering elements.

3. Based on the data, it has been established that it is advisable coarse filters are regenerated at the clogging degree of 70 %, and fine filters are replaced with new ones at the clogging degree of 65 %. If the specified values of the degree of clogging are exceeded, there is a rapid increase in the pressure losses leading to a significant decrease in the specific consumption of the purified gas and the design of a high probability of filter deformation. According to the results, technical and operational documentation was prepared complied to by Giproniigaz JSC in preparing and producing the suggested DCU.

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