Feasibility of construction and installation site of differential pressure sensors for gas energy efficient plant for coarse and fine purification

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Abstract. The paper substantiates the construction and location of differential pressure sensors for a coarse and fine gas energy-saving plant. Energy saving is achieved by installing filtering cylindrical elements of fine and coarse purification one inside the other, optimizing their shape and substantiating the location of the differential pressure sensors. The results of the studies show that the total specific heat consumption for heating and ventilation of purification plants from all energy-saving measures for the proposed option is 1.85 times lower than the existing analogue of the non-optimized shape and measuring the pressure drop at the inlet and outlet branch pipes. The article also proved that the static gas pressure in the lower part of filter elements of the coarse and fine purification will always be higher than in their upper part. This results in a proportionally higher amount of inlet gas and therefore more solids settling in the bottom of the filter element. Measurement of the pressure drop in the lower part of the filter element, the most clogged with solid particles, makes it possible to receive a signal at the dispatching console earlier and provides a time reserve for technical personnel to timely remove accumulated blockages from coarse purification elements and prompt replacement of fine purification elements.

Key words: gas purification, installation site, sensor, pressure drop, filter element.

1. Introduction. Introductory part and relevance of the development of methodological provisions for substantiating the location of differential pressure sensors located in one body of a gas purification plant

Equipping gas networks with modern high-throughput capacity gas reduction points (GRP) is primarily due to the high demand for natural gas due to the harsh climatic conditions of the Russian Federation. At present, more than fifty gas reduction points (GRP) equipped with high-precision gas equipment of high throughput capacity are successfully operated.

Reliable operation of high-throughput capacity gas control equipment currently used in the Russian Federation, according to modern requirements [1], is ensured through the use of cylindrical two-stage units (CTU) of coarse and fine purification, which are installed in separate buildings (Figure 1). An example of a reduction line for head GRPs with a total throughput capacity of 500 thousand m³/h with a high-throughput capacity CTU for coarse and fine purification installed on it is shown in Figure 1.
Figure 1. Gas equipment of a modern domestic GRP, including cylindrical units of coarse and fine purification for the main and reserve reduction lines, located in separate buildings. 1 – ball valve with electric 2 and manual 3 drives at the entrance to the main reduction line; 4, 5 – installations for coarse and fine purification, located on the main reduction line; 6, 11 – ball valves with electric and manual drives at the inlet and outlet of the reserve reduction line; 7, 8 – working and reserve gas pressure regulators located on the reserve reduction line; 9, 10 – installations of fine and coarse purification, which are part of the reserve reduction line; 12 – one of the windows; 13 – red lines that limit the area of the floor structure required to accommodate one purification unit; 14 – ceiling structures; 15 – one of the walls.

At present, priority attention in the design of reduction points, including gas purification plants, is given to the issues of energy and resource conservation associated with the reduction of heated area and the use of renewable energy sources [2-7]. In order to reduce the capital and energy consumption of purification plants and building fences allocated for their placement, as well as the cost of heating and ventilation of additional premises for their placement (red lines in Figure 1 limit the floor area required to accommodate one body of a one-stage purification plant), JSC "Gipronigaz" is proposed to place in the internal volume of one body 1 (Figure 1), filtering cylindrical elements (FCE) of coarse purification 7 of the mesh and FCE of fine purification 8 of the filter cloth, installed one inside the other [8] and enclosed in corrugated protective nets to prevent deformation when the pressure drop on them rises above the design value. In order to further reduce the capital and energy consumption of the purification plants the optimal ratio of the height H of the body 3 to the diameter D, equal to (H/D) opt = 3.3 [1] was substantiated (Figure 1), at which its dimensions, area and thermal losses decrease.

Clogging of the filter meshes corresponds to a strictly defined pressure drop across the FCE, which is determined by measuring the latter using differential pressure gauges that receive a pulse from differential pressure sensors. In the known literature [9-14] there are no clear recommendations on the place of installation and design of differential pressure sensors, as a result of which they are installed at arbitrary points along the height of filter elements of the coarse and fine purification and along the horizontal distance to the FCE. So for the existing technical solutions [1], differential pressure sensors are installed at the inlet and outlet branch pipes of the CTU, which significantly increases the distance between the two housings of the purification plants, limited by red lines 13 in Figure 1, and conse-
quently, the material and energy consumption of the purification plants and for their placement of building fences.

In this regard, an urgent task in the development of energy-saving two-stage purification plants of high throughput capacity is the substantiation of the installation site and the structural arrangement of differential pressure sensors for coarse and fine purification FCE.

2. Materials and Methods. Feasibility of the location of differential pressure sensors for filtering cylindrical elements of coarse and fine purification, located in a single body of a two-stage purification unit

In order to select the location of the differential pressure sensors, let us analyze the flow pattern from the gas inlet (point S) to its outlet (point K), shown on the left side of the CTU (Figure 2). We split the entire length of the FCE into a number of sections \( \delta=a, b, ..., j-1, j \) of equal length \( L_a, L_b, ..., L_{j-1}, L_j \). The section boundaries in Figure 2 are shown with solid red lines.

The gas flow in the CTU is carried out due to the pressure difference created by taking it into the outlet branch pipe 6, when the pressure at the outlet (point K) will always be less than at the inlet (point S). The total pressure drop \( (Ps - Pk) \) determines the distribution of gas pressures along its entire path from point S to K as follows.

For example, for the upper part of the CTU: 1) \( Ps > Pm \) - for crude gas in space 10; 2) \( Pm > Pc \) - for crude gas during its flow through the upper part of FCE 7 in space 10; 3) \( Pc > Pn \) - for a coarsely purified gas during its flow through the upper part of FCE 8; 4) \( Pn > Pk \) - for a finely purified gas during its flow in space 12. Hence, the value \( Ps - Pk \) is defined as:

\[
Ps - Pk = (Ps - Pm) + (Pm - Pc) + (Pc - Pn) + (Pn - Pk). \tag{1}
\]

Thus, when the gas moves through each cross-section along the height of the CTU, approximately the same flow pattern takes place. For example, when gas moves through the upper cross section, (points \( S \to M \to C \to N \to K \)), the gas flow rises vertically up from point S to point M, then turns 90 \( ^\circ \) passes along a horizontal line through a filter element 7 of coarse purification from point M to point C, continues to move along a horizontal line through the filtering cylindrical element 8 of fine purification from point C to point N, after which it turns 90o and moves vertically downward from point N to point K. In Figure 2, the gas flow pattern in individual sections is shown with brown solid line. Let us consider the flow pattern in its individual sections for crude, coarsely purified and finely purified gas.

For the crude gas during its flow in space 10 along the vertically installed filtering element 7 (Figure 1), the location of the differential pressure sensor was determined based on the analysis of the pressure losses of the gas flow in this area.

Figure 1 shows that the gas flow in the annular space 10 is due to the created pressure drop \( (Ps-Pk) \) along the filtering element from bottom to top from point S to point M, which leads to friction losses. In this case, part of the gas in space 10 is continuously separated from the total flow and passes through the coarse filter element 7.

The value of the pressure of the crude gas in the lower point S is determined according to [16]:

\[
P_s = P_m + \Delta P_{tr}, \tag{2}
\]

where: \( Pm \) - quantity of pressure of the crude gas in point M of the annular space 10, daPa;
\( \Delta P_{tr} \) - gas-dynamic friction losses during the flow of a crude gas in the section between point S and point M, daPa.
Gas-dynamic frictional losses and local resistances in formula (2) occurring during the flow of a crude gas flow in the section between point S and point M are determined according to [16]:

\[
\Delta P_{tr} = \left( \sum_{a=1}^{j-1} \frac{\lambda \cdot L_{\delta=a}}{d_{ek}} + \zeta_{\delta=j} \right) \frac{\left( V_{\delta \text{in}} / F \right)^2 \cdot \rho}{2 \cdot g},
\]

where: \( \lambda \) is the coefficient of roughness of the walls of the space 10, located between the inner surface of the CTU body and the outer surface of FCE 7;
\( L_{\delta} \) is the length of the section \( \delta \) located along the FCE 7, m;
\( d_{ek} \) is the equivalent constant diameter of the inner annular space 10 between the inner and outer surfaces of the body of CTU 1 and FCE 7, m;
\( \sum_{a=1}^{j-1} \zeta_{\delta=a} \) is the total quantity of the coefficient of local resistance in the sections \( a, b, \ldots, j-1, j \) for the case of a vertical flow along the body with uniform extraction of a part of the gas in the FCE for coarse purification with a rotation of 90°;
\( V_{\delta \text{in}} \) and \( F \) are transit flow rate and flow section of the annular space between the inner and outer surfaces of the body of CTU 1 and FCE 7;
\( \rho \) is gas density in the internal space 10 at its actual pressure, kg/m\(^3\).
Figure 2 shows that the gas from the inlet branch pipe 2 spreads over the entire lower part of the flow section of the gap between the housing 1 and FCE 7, from here rising upwards, it evenly enters the filter meshes along the FCE 7 height.

We will replace the uniformly distributed flows passing through the filtering surfaces of the FCE with a number of concentrated $V^a = V^b = V^{j-1} = V^j$ within each section $a, b, ..., j-1, j$... Moreover, all concentrated flows are equal to each other $V^a = V^b = V^{j-1} = V^j$.

The total flows will be written as:

$$V = V^a + V^b + ... + V^{j-1} + V^j.$$  \hspace{1cm} (4)

Transit flows for each section are calculated as:

$$V^{a, in} = V - 0.5V^a;$$ \hspace{1cm} (5)

$$V^{b, in} = V - (0.5V^b + V^a);$$ \hspace{1cm} (6)

$$V^{j-1, in} = V - (0.5V^{j-1} + V^a + V^b);$$ \hspace{1cm} (7)

$$V^{j, in} = V - (V^a + V^b + ... + V^{j-1} + 0.5V^j).$$ \hspace{1cm} (8)

Formula for determining the concentrated gas flow rate within each section $a, b, ..., j-1, j$ is

$$V^\delta = \frac{V}{\delta}. $$ \hspace{1cm} (9)

An analysis of formulas (5) - (8) shows that the values of the transit flow rate as the gas flow rises upward uniformly decreases. So, for example, in the presence of four sections - $a, b, j-1, j, j$ and under the assumption of uniform gas distribution along the entire path from $a$ to $j$, the quantity of the transit flow rate in section $j$, according to (8), will be $V^{j, in} = 0.5V^j = 0.5(V/4) = 0.125V$, that is, approximately 12.5% of the total flow rate gas $V$.

An analysis of formula (3) shows that the larger the total length $L$ and the smaller the diameter $d_{ek}$, are the higher the friction loss $\Delta P_{fr}$ is. According to the results of research for new designs of the CTU, for example, manufactured by AO (JSC) "Giproniigaz", the minimum metal consumption and costs for a cylindrical filter are achieved when the ratio of the height of its body to the diameter is equal to 3.3 [1]. Then the length $L$, which is equal to the total height of FCE 7, will be 65% of the height of the CTU body. In this case, the quantity of friction losses $\Delta P_{fr}$, according to formula (3), significantly increases in comparison with the existing designs of the CTU, which have a small ratio of the body height to the diameter.

An analysis of formula (3) also shows that the pressure of the crude gas $P_s$ in the lower part of the FCE 6 (point S) will always be higher than in the upper part (point M), that is, $P_s > P_m$ by the amount of pressure losses due to friction $\Delta P_{fr}$ in the section the annular space 10 between the inner and outer surfaces of the filter housing 1 and FCE 7 of coarse purification.

For the crude gas, according to the general picture described above, its flow for each cross section passes in the horizontal direction through FCE 7. For example, in the upper cross section, the gas flow moves along a horizontal line from point M to point C through FCE 7.

Since in the annular space 10, due to the difference $(P_s - P_m)$, the gas pressure in each higher cross section, counting from point S, will decrease, then the pressure drops through the FCE of coarse puri-
fication in these sections will also decrease. For example, in the upper cross-section with a gas flow along a horizontal line from point M to point C, the pressure drop (Pm - Pc) will be less than in lower cross-sections, including the pressure drop (Ps - Py) in the lowest cross-section from point S to point Y.

This leads to a larger amount of coarsely purified gas flowing, and, consequently, a higher amount of solid impurities settling in the lower part of the FCE 7 of coarse purification and, as a consequence, a greater degree of clogging of its filter mesh.

It follows that the measurement of static pressures in the lower part of the FCE 7 at point Y will show a higher value than in the upper part (point C).

In this case, the maximum allowable pressure drop in the lower part of the filtering device 7 will be reached at an earlier period than at other higher measuring points.

For coarsely purified gas, according to the general picture described above, its flow through the FCE of fine purification 8 for each cross section, as well as for the FCE of coarse purification, runs in the horizontal direction. For example, in the upper cross-section, the gas flow moves along a horizontal line from point C to point N through FCE of fine purification 8.

Since in the annular space 11 the pressure difference (Ps - Py) between the lowest points S and point Y is the highest in space 11, the gas pressure in each higher cross section, counting from point Y, will decrease. The pressure drops across the filter elements of fine purification in these sections will also decrease. For example, in the upper cross-section with a gas flow along a horizontal line from point C to point N, the pressure drop (Pc - Pn) will be less than in lower cross-sections, including the pressure drop (Py - Pk) in the lowest cross-section from point Y to point K.

This leads to a greater amount of finely purified gas flowing, and, consequently, a higher amount of solid impurities settling in the lower part of FCE 7 and, as a consequence, a greater degree of clogging of its filter cloth. Hence it follows that the measurement of static pressures in the lower part of the FCE 7 at point Y will show a higher value than in the upper part (point C). In this case, the maximum allowable pressure drop, \( \Delta P_{md} = 35.0 \text{ kPa} \) [12] in the lower part of the filtering device 7 will be reached in an earlier period than at other higher measurement points.

For a finely purified gas, the flow also passes under the action of a total pressure drop (Ps - Pk) along a vertical line from top to bottom from point N to point K along the filter element of fine purification 8 inside space 12. Analysis shows that the pressure of the finely purified gas Pk in the lower part (point K) of the filter element 7 will always be more than in the upper (point N), that is, Pk > Pn, as well as in section 1, by the amount of pressure loss due to friction in the inner space 12 of the FCE fine purification 8.

It follows that the measurement of static pressures in the lower part of the filter element 7 at point K will show a higher value than in the upper part (point N).

3. Results. Development of the design of sensors and determination of the pressure drop filter elements of coarse and fine purification located in a single building of the CTU

Based on the results of the analysis of formulas (3) - (8) and the analysis of the gas flow patterns in all the sections considered above, devices have been developed that measure with a minimum error the static pressure drop directly on the filter elements of coarse and fine purification (Figure 3), which, according to the law Pascal impacts all walls of the CTU and the pipelines and parts located in it with the same force. An important feature of the method is the elimination of the influence of the flow rate at the point of static pressure measurement. In order to eliminate this effect, the gas flow is directed strictly along the lateral surface or strictly tangentially to the lateral surface of the sensor tube, on which the holes for measuring static pressure are located.

Let us consider separately the development of devices for measuring the pressure drop across the FCE for coarse and fine purification.

The pressure drop across the FCE of coarse purification, according to the proposed method (Figure 3), is measured using two sensors: a sensor tube 13 and a sensor tube 14. The sensor tube 13 designed to measure the static pressure of the crude gas Ps is located in the lower part of the FCE of coarse purification 7 and is connected by its hole with the space 10. This allows the crude gas to flow
through the impulse tube to the differential pressure gauge. The tube-sensor 14 for measuring the static pressure of the coarsely purified gas Py is located in the lower part of element 7 of coarse purification and is connected by its hole 16 on the lateral surface of the tube 14 with the space 11. This allows the coarsely purified gas to flow through one of the impulse tubes to differential pressure gauge. The hole 16, designed to communicate with the space 11 at the location of the filter element 7, is located on the lateral surface of the sensor tube 14 at the location mark of the sensor 13 inlet for measuring the static pressure of the crude gas. In this case, the flow of coarsely purified gas is directed strictly tangentially to the lateral surface of the sensor tube 14 at the hole 16 location for measuring the static pressure. The upper end of the sensor tube 14 is sealed with a plug 17.

**Figure 3.** Axonometric diagram of the installation of differential pressure sensors 13, 14 and 15, as well as their design.

By the values of the pressures Ps and Py by means of a differential pressure gauge, their difference is determined, that is, the difference (Ps-Py) on element 7 of the coarsely purified gas. The diameter Dy of the sensor tube 14, as well as the diameter of the hole 16 in its lateral surface, are taken on the basis of design considerations.

The pressure drop across the filtering element of fine purification, according to the proposed method (Figure 3), is measured using two sensors: a sensor tube 14 and a sensor tube 15. The sensor tube 14 designed to measure the static pressure of the coarsely purified gas Py is located in the lower part element of fine purification 8 and is connected by its hole with the space 11. This allows the coarsely purified gas to flow through one of the impulse pipes to the differential pressure gauge. The tube-sensor 15 for measuring the static pressure of the finely purified gas Pk is located in the lower part of the element 8 of fine purification and is connected by its hole with the space 12. This allows the finely purified gas to flow through one of the impulse pipes to a differential pressure gauge.

The hole 18, designed to communicate with the space 12 of the filter element 8, is located on the lateral surface of the sensor tube 15 at the location mark of the sensor 13 inlet for measuring the static pressure of the crude gas and at the mark of the location of the hole 16 of the sensor tube 14. In this case, the flow of finely purified gas is directed strictly tangential to the lateral surface of the sensor tube 15 at the location of the hole 18 for measuring static pressure. The upper end of the sensor tube 15 is sealed with a plug 17.
According to the values of the pressures \( P_y \) and \( P_k \), by means of a differential pressure gauge, their difference is determined, that is, the difference \((P_y - P_k)\) on the element 8 of a finely purified gas. The diameters \( D_k \) of the sensor tube 15, as well as the diameter \( d_k \) of the holes 18 in its lateral surface, are taken on the basis of design considerations.

Thus, one of the differential pressure gauges measures the difference between the static pressures of the crude and coarsely purified gas coming from sensors 13 and 14, before and after FCE 7, that is, the pressure drop across this FCE; the second differential pressure gauge measures the difference between the static pressures of the coarsely purified and finely purified gas coming from sensors 14 and 15, before and after the FCE 8, that is, the pressure drop across this FCE.

The proposed principles for measuring the pressure drop across FCE of the coarse and fine purification make it possible to significantly increase the possibilities for the timely removal of mechanical impurities from the FCE of coarse purification and replacing the FCE of finely purification with a new one, as well as to prevent deformation and destruction of the FCE due to an increase in the pressure drop on the CPE in excess of the calculated one.

For the purpose of experimental verification of the theoretical provisions (3) - (8) to substantiate the location of the pressure loss sensors, an experimental sample of the CTU was manufactured and tested. The results of tests on the change in pressure losses along the length of the gas flow in the annular space 10 are shown in Figure 4 as separate experimental points. Here, for comparison, the theoretical values obtained from formulas (3) - (8) are shown in the form of a solid line 1. The experimental points shown in the graph are taken as the average value over four measurements \((n = 4)\). The Student's coefficient for four measurements made \((n = 4)\) with a given reliability of the results obtained equal to \( \alpha = 0.9 \) is \( t_{\alpha=0.9} = 0.9 = 2.35 \). The average deviation of the calculated and experimental values \( \Delta P_{tr} \) is 18.3%.

Figure 4 also shows that the growth dynamics of pressure losses along the length of the filter element 7 is significantly reduced. This situation is explained by a decrease in the transit gas flow rate \( V^{^m} \) in the formula (3) along the length of the filter element 7.

![Figure 4. Change in pressure losses along the length of the gas flow in the annular space 10.](image)
4. Conclusion

1. Formulas (5) - (8) are proposed for determining the transit gas flow rates in the annular space between the CTU housing and the filtering element of coarse purification within each section \( a, b, \ldots, j-1, j \) in the presence of a uniform flow distribution along the FCE length. The analysis of formulas (5) - (8) showed that the values of the transit flow rate decrease uniformly as the gas flow rises upward. So, for example, in the presence of sections \( a, b, j-1, j \) and under the assumption of uniform distribution of gas along the entire path from \( a \) to \( j \), the value of the transit flow in section \( j \), according to (8), will be \( V^{\text{jm}} = 0.5V^j = 0.5(V/4) = 0.125V \), that is, 12.5% of the total gas consumption \( V \).

2. Formula (9) has been obtained for determining the concentrated gas flow rate within each section \( a, b, \ldots, j-1, j \). Analysis of formula (9) shows that the values of the concentrated flow rate as the gas flow rises upward in each section \( a, b, \ldots, j-1, j \) under the assumption of uniform distribution of the flow along the entire path of movement from \( a \) up to \( j \) remain practically constant.

3. The calculation results, according to formulas (2) and (9), show that the maximum pressure drop across the FCE takes place in its lower part and it is always greater than in its higher located parts. This leads to a proportionally higher amount of flowing gas, and hence a larger amount of solid particles settling in the lower part of the FCE and, as a consequence, a greater degree of clogging of its filtering material.

4. Measurement of the pressure drop in the lower part of the filter element, which is the most clogged with solid particles, makes it possible to receive a signal at the dispatching console earlier and provides a time reserve for technical personnel to timely remove accumulated clogs and timely replace the filter FCE of fine purification.

5. The gas pressure sensor is proposed to be made of a bent steel tube, installed in the lower part of the inner volume of cylindrical filter elements of coarse and fine purification so that the hole for connection with the inner space is located on their lateral surface, at the same mark as the sensor hole crude gas pressure. In this case, the upper end of the pressure sensor tube is sealed with a plug.

6. The results of the experiments (Figure 4) show higher experimental values of pressure drops for the lower sections of the FCE in comparison with the theoretical quantities for the same sections. This is explained by the better conditions for the flow into the lower sections of the FCE, which have a shorter length, and, therefore, lower gas-dynamic resistance. The figure also shows that the dynamics of the growth of pressure losses along the length of the filtering element 7 is significantly reduced. This situation is explained by a decrease in the transit gas flow rate \( V^{\text{jm}} \) in the formula (3) along the length of the filter element 7.

7. The coincidence of theoretical and experimental data on \( \Delta P_{\text{tr}} \) with an average deviation of 18.3% allows us to recommend formulas (3) - (9) to determine the pressure loss of the gas flow along the length of the annular space 10.

8. The results of the calculations show that the total specific heat consumption for heating and ventilation of purification plants from all energy-saving measures for the proposed option with the location of the coarse and fine purification FCE inside one building is 1.85 times lower compared to the existing CTU of the non-optimized form and measuring the pressure drop across the inlet and outlet branch pipes.

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