Development of Principle and Methodological Provisions for Installation Site and Design of Pressure Drop Sensors for Coarse and Fine Purification Filtering Cartridges Located in a Single Vessel of a Two-Stage Gas Filter

A P Usachev¹, A L Shurayts², A A Pikalov³

¹Gagarin Saratov State Technical University, Polytechnic street, 77, Saratov, 410000, Russia
²Joint-Stock-Company “Giproniigaz”, Kirova street, 54, Saratov, 410012, Russia
³Joint-Stock-Company “Reviziya Controlling Consulting”, Kirova street, 54, Saratov, 410012, Russia

E-mail: usachev-ap@mail.ru

Abstract. The article is dedicated to the development of principles and methodological provisions for pressure drop sensors layout for coarse and fine purification filtering cartridges located in a two-stage gas filter vessel. It has been found out that static gas pressure in the lower part of the coarse and fine purification filtering cartridges is always greater than in the upper part. This conditions proportionately higher amount of flowing gas, and hence greater amount of solid particles deposited in the lower part of cylindrical filtering cartridges and, as a consequence, greater degree of filtering material contamination. Measuring pressure drop in the lower part of filtering cartridge, which is more clogged with solid particles, makes early signal at the operator console possible, which provides time for technical staff to urgently remove accumulated blockages from the coarse purification cartridge and replace the cylindrical fine purification filtering cartridges.

These methodological provisions allow the possibility for reliable sensor design and precise determination of installation locations in filter parts designed for crude, coarsely purified and finely purified gas flow, which can be used within engineering practice.

1. Introduction

High demand for natural gas, and, consequently, gas networks and gas pressure reduction stations (GPRS) with high throughput is primarily conditioned by harsh climatic conditions of the Russian Federation.

That is why, the scale of use of modern high-capacity gas pressure reduction stations, equipped with modern high-performance gas equipment, is currently growing.

Reliable operation of high-precision gas regulating equipment currently used in the Russian Federation, according to the requirements of the state standard [1], is ensured due to the use of cylindrical coarse and fine purification filters, which are installed in separate vessels.
2. Development relevance for methodological provisions used for determining installation site and design of differential pressure sensors for coarse and fine purification filtering cartridges located in a single gas filter vessel

Placing cylindrical coarse and fine purification filtering cartridges in separate vessels operated at high pressure and having in this case large thicknesses of connecting flanges and walls of cylindrical shells [2, 3] condition their high capital-output ratio and metal-related consumption, as well as heating costs and ventilation of additional floor, wall and ceiling structures for their placement.

To eliminate this disadvantage, Gipronigaz JSC proposed to place the coarse CFC made of net and the fine CFC made of cloth one inside the other within the internal space of one vessel 1 (Figure 1) [4]. At that, coarse and fine filtering cartridges are not solid, but made of blocks containing several similar CFCs [5]. Every block is made of pleated filtering material enclosed in pleated protective nets to prevent the block’s deformation when differential pressure drop on the CFC exceeds the calculated value [6]. Here, cylindrical coarse filtering cartridges, made of single-layer metal net, accumulate mechanical impurities on their outer surface only, quickly become clogged and require a significant number of operations to remove them [7-11], which are carried out, according to [12], when clogging on the net reaches the estimated clogging degree, which corresponds to the CFC pressure drop, which equals 5.0 kPa. Cylindrical fine filtering cartridges made of non-woven fabric (felt) accumulate the impurities over their thickness, making it almost impossible to remove the impurities, therefore, after reaching the calculated degree of clogging, the fine CFC is replaced with a new one [13]. The calculated degree of clogging, according to [12], corresponds to pressure drop on the CFC that equals 35.0 kPa.

Figure 1. Gas flow pattern in a two-stage filter with identification of pressure drop sensor location spots for coarse and fine purification filtering cartridges placed within a single vessel:

1 – cylindrical vessel; 2, 5 – inlet joining pipe, outlet joining pipe; 3 – impulse tube; 4 – bowl; 6, 8 – two vertical coarse filtering CFCs; 7, 9 – two vertical fine filtering CFCs; 10 – insulation space between vessel 1 and the block made of CFC 6 and 8; 11.a – differential pressure gauge for measuring pressure drop on sensors 14 and 15 for coarse filtering cylindrical cartridges 6; 11.b – differential pressure gauge manometer for measuring pressure drop on sensors 15 and 16 for fine filtering cylindrical cartridges 7; 12 – annular space between blocks made of CFC 6 and 8 and blocks made of CFC 7 and 9; 13 – caps for vessel 1 and coarse filtering cylindrical cartridge 8 and fine filtering cylindrical cartridge 9; 14, 15, 16 – pressure drop measuring sensors for coarse filtering 6 and fine filtering 7; 17 – space for collecting and removing fine purified gas from the filter.
The existing reference material [14-16] lacks methodological provisions regarding installation site definition and structural design for pressure drop sensors used in coarse and fine filtering cartridges placed within one gas filter vessel.

An urgent task for the development of two-stage high-capacity filters is the development of the principle and methodological guidelines for determination of installation site and design of pressure drop sensors for coarse and fine filtering cartridges.

3. Task description and development of methodological guidelines for choosing installation site of pressure drop sensors for coarse and fine purification filtering cartridges placed in a single vessel of a two-stage gas filter

3.1. From the review of literature [7, 8, 13, 14], it follows that, at present, modern filters do not use pressure drop measurement on coarse and fine filtering cartridges directly, but only measure total pressure drop between inlet 2 and outlet 5 of filter nozzle (Figure 1) using differential pressure gauges. In this case, it is impossible to accurately measure the pressure drop across the CFC, since it can only be measured combined with the pressure loss $\Delta P_f$ on the filter vessel. The value of $\Delta P_f$ is calculated using the formula [17]:

$$\Delta P_f = \Delta P_{kop} + \Delta P_{f.G} + \Delta P_{f.i} = \frac{\sum \zeta_i \cdot \omega_i^2 \cdot \rho_{G,i}}{2 \cdot g} + \Delta P_{f.G} + \Delta P_{f.i},$$

where $\Delta P_f$ - pressure drop at inlet 2 and outlet 5 of filter nozzles (Figure 1), daPa; $\Delta P_{kop}$ - pressure loss in the filter vessel, daPa; $\Delta P_{f.G}$, $\Delta P_{f.i}$ - magnitude of the pressure drop on the CFC of coarse 6; 8 and fine 7; 9 purification, daPa; $i$ - a number of structural elements of the filter vessel, including: input 2 and output 5 filter nozzles, 90° rotation from nozzle 2 into the insulation space 10 between vessel 1 and the 6 and 8 CFC unit, 90° rotation from area 17 to outlet nozzle 5, insulation space 10; $\omega_i$ - gas velocity value in the $i$-th element of the filter, m/s; $\rho_{G,i}$ - gas fuel density in the $i$-th element of the filter at its actual pressure, kg/m³; $g$ - acceleration of free fall, equal to 9.8 m/s²; $\zeta_i$ - value of the coefficient of local resistance of the $i$-th element of the filter.

From the known values of $\omega_i$, $\rho_{G,i}$, $g$, and $\zeta_i$ in formula (1), it is possible to measure the pressure loss $\Delta P_{kop}$ in the filter vessel. If there is one filtering cartridge, for example, a cartridge for a coarse purification for a single-stage filter, knowing the $\Delta P_{kop}$ we can use formula (1), where $\Delta P_{f.G}=\Delta P_f - \Delta P_{kop}$. If there are both coarse and fine filtering cartridges for the case of a two-stage filter, using formula (1) we can determine only the total value of pressure drop on the CFC of coarse 6; 8 and fine 7; 9 purification, that is $\Delta P_{f.G}+\Delta P_{f.i}=\Delta P_f - \Delta P_{kop}$. At the same time, to determine the time for removal of impurities, according to [18, 19], you should know the value of pressure drop on the CFC coarse 6; 8 and on the CFC fine 7; 9 purification separately.

This shows that the use of the existing method for measuring the degree of clogging of filtering cartridges from formula (1) by the total pressure drop on the CFC of coarse and fine purification is not possible.

3.2. Analysis that has been carried out shows that the choice of installation site for sensors measuring differential pressure on the CFC should be based on the following conditions: gas pressure sensor should be located at a minimum distance from the CFC to eliminate the error due to pressure losses in the adjacent filter vessel elements; the section of the CFC at the measurement site should be clogged with solid impurities to a greater extent than another areas and, as a result, should be the site of the greatest pressure drop during the entire period of operation.

The choice of the site for pressure drop sensors was made on the basis of flow pattern analysis from gas inlet (H) to outlet (K) from the filter (Figure 1), characterized by change in flow directions. Gas flows in the filter due to pressure drops created by its extraction through nozzle 5, when outlet pressure (point K) will always be less than at the inlet (point H). The total pressure drop
(P_H – P_k) determines the distribution of gas pressure values along the entire route from point H to point K as follows.

For example, for the upper part of the filter: 1) P_H > P_V - for crude gas in area 10; 2) P_V > P_C - for unpurified gas in the course of its flow through the upper part of the CFC 8; 3) P_C > P_n - for coarse purified gas when it flows through the upper part of the CFC 9; 4) P_n > P_k - for fine purified gas when it flows in area 17. Hence, the value of P_H – P_k is measured as:

\[ P_H - P_k = (P_H - P_V) + (P_V - P_C) + (P_C - P_n) + (P_n - P_k). \]  \tag{2}

Thus, when gas moves through each cross section along the height of a two-stage filter, approximately the same flow pattern takes place. For example, when gas moves through the upper cross section (points H → V → C → N → K), gas flow rises vertically from H to V, then takes a 90° turn, passes along the horizontal line through coarse filtering cartridge 8 from B to C, continues to move along the horizontal line through fine filtering cartridge 9 from C to N, after which it takes a 90° turn and moves down vertically from N to K. In Figure 1, the pattern of gas flow in separate sections is illustrated with a black dashed line. Let us take a picture of the flow in separate areas for crude, coarsely purified and finely purified gas.

3.3. Flow chart in the unpurified gas section in area 10. For unpurified gas as it flows along the block of two filtering cartridges 6 and 8, which are mounted vertically one on the other (Figure 1), the site of the pressure drop sensor was determined based on the analysis of hydraulic losses of the gas flow in this area.

From Figure 1 it can be seen that due to the total pressure drop (P_n – P_v) between points H and K the gas flow is created as a result of its extraction into outlet nozzle 5. In annular area 10, the crude gas flow occurs due to pressure drop (P_n – P_v) along filtering cartridges 6 and 8, from the bottom up, from point H to point V, which leads to hydraulic friction losses. In this area 10 some part of the gas continuously separates from the total flow and passes through coarse filtering cartridges.

The crude gas pressure at the lower point H is measured according to [17]:

\[ P_H = P_V + \Delta P_{fr} = P_V + \frac{\lambda \cdot L \cdot \omega^2 \cdot \rho_{g,i}}{2 \cdot d_{ek} \cdot g}, \]  \tag{3}

P_v - crude gas pressure at point B of annular area 10, daPa; \( \Delta P_{fr} \) – hydraulic friction losses during the flow of the unpurified gas in the area between points H and V, daPa; \( \lambda \) - coefficient of the wall roughness of area 10 located between the inner surface of the filter vessel and the outer surface of CFC 6 and 8; L - length of internal area 10 at the site of CFC 6 and 8, m; \( d_{ek} \) - equivalent diameter of inner annular area 10 between the inner and outer surfaces of the filter vessel and the CFC, m; \( \omega \) - flow rate of the crude gas in the inner annular area 10, m/s; \( \rho_{g,i} \) - gas density in internal area 10 at its actual pressure, kg/m³.

Analysis of formula (3) shows that the longer the length L and the smaller the diameter \( d_{ek} \), the higher the value of friction losses \( \Delta P_{fr} \). According to research results for new filter designs, for example, those produced by “Giproniigaz” JSC, the minimum metal consumption and costs for a cylindrical filter are achieved with a ratio of its vessel height to diameter that equals 4.5 [20]. Then length L, which is equal to total height of the CFC 6 and 8, will be 65% of the height of the filter vessel. In this case, the value of friction losses \( \Delta P_{fr} \), according to formula (3), significantly increases, compared with the existing filter designs, having a small ratio of vessel height to its diameter.

Analysis of the formula (3) also demonstrates crude gas pressure P_n in the lower part (H) of filtering cartridge 6 will always be greater than at the top (V) at the CFC site 8, that is, \( P_n > P_V \), by the amount of pressure loss friction \( \Delta P_{fr} \) in the section of annular area 10 between inner and outer surfaces of the filter vessel and the coarse CFC.
3.4. Unpurified gas flow pattern illustrating its movement through the coarse purification CFC. For crude gas, according to the general pattern described above, its flow for each cross section passes horizontally through coarse filtering cartridges 6 and 8. For example, in the upper cross section the gas flow moves along horizontal line from point V to point C through coarse filtering cartridge 8.

Since gas pressure in each higher cross section, from point H, will decrease in annular area 10 due to the differential \((P_n - P_s)\), pressure drops through coarse filtering cartridges in these sections will decrease as well. For example, in the upper cross section where gas flows along the horizontal line from point V to point C, pressure drop \((P_c - P_s)\) will be smaller than in lower cross sections, including the pressure drop \((P_n - P_s)\) in the lowest cross section from point H to point V.

This conditions greater amount of flowing coarse gas, and, consequently, higher amount of solid impurities deposited in the lower part of coarse CFC 6, and, as a consequence, greater degree of contamination of its filtering net.

It follows that measurement of static pressures in the lower part of filtering cartridge 6 at point B will show a higher value than in the upper part (point C) at the CFC 8 site.

At the same time, maximum permissible value of pressure drop \(\Delta P_{w6}=5.0 \text{ kPa} \ [12,19]\) in the lower part of filtering device 6 will be achieved earlier than at other higher measurement points.

3.5. Flow pattern in the coarse purified gas area, where the gas moves through the fine CFC. For coarsely purified gas, according to the general pattern described above, its flow through fine filtering cartridges 7 and 9 for each cross section, as well as for coarse filtering cartridges, occurs in the horizontal direction. For example, in the upper cross section the gas flow moves along the horizontal line from point C to point N through filtering cartridge 9.

Since in the annular area 12 due to pressure drop \((P_n - P_s)\) between points H and V created in area 10, gas pressure in each higher cross section from point V, will decrease, then pressure drops through the fine filtering cartridges in these sections will also decrease. For example, in the upper cross section with gas flowing along the horizontal line from point C to point N, pressure drop \((P_c - P_s)\) will be smaller than in the lower cross sections, including pressure drop \((P_b - P_s)\) in the lowest cross section from point V to point K. This causes greater amount of flowing fine gas, therefore, higher amount of solid impurities deposited in the lower part of CFC 7 as compared with CFC 9 and, as a consequence, greater degree of contamination of its filter cloth. It follows that measurement of static pressures in the lower part of filtering cartridge 7 at point V will show a higher value than in its upper part (point C) at the CFC 9 site. At the same time, the maximum allowable value of pressure drop \(\Delta P_{w7}=35.0 \text{ kPa} \ [12]\) at the bottom of filtering device 7 will be reached during an earlier period than at other higher measurement points.

3.6. Fine purified gas flow pattern in inner area 17 of fine purification filtering cartridges. For fine purified gas, the flow passes under the total pressure drop \((P_n - P_b)\) along the vertical line from top to bottom from point N to point K along the block of filtering cartridges 9 and 7 inside area 17. Analysis shows that the pressure of fine purified gas \(P_b\) in the lower parts (point K) of filtering cartridge 7 will always be greater than at the top (point N) at CFC 9 site, that is, \(P_b > P_n\) as well as in area 1, by the amount of pressure drop, due to friction in inner area 17 of fine purifying cartridges 7 and 9.

It follows that static pressure measurement in the lower part of filtering cartridge 7 at point K will show a higher value than in the upper part (point N) at CFC 9 site.

4. Development of design and principle of pressure sensors for filtering cartridges of coarse and fine purification, placed in a single gas filter vessel

4.1. According to formula analysis results \((1) - (3)\) and gas flow pattern analysis in all the sections described above, we designed the devices that measure static pressure on the filtering elements of coarse and fine purification with the minimum level of error (Figure 2), which according to Pascal’s law, are applied to all filter walls, pipelines and parts with equal force. Important feature of this method is to eliminate the flow velocity influence at the point of static pressure measurement. To eliminate this effect, the gas flow is directed strictly along the side surface or strictly tangential to the side surface of the sensor tube, where the holes for measuring static pressure are located.
Let us discuss the development of devices for measuring pressure drop on coarse and fine filtering cartridges separately.

![Axonometric scheme of pressure sensors installation and their functional configuration](image)

**Figure 2.** Axonometric scheme of pressure sensors 14, 15 and 16 installation and their functional configuration.

4.2 The pressure drop on the coarse purification filtering cartridge, according to the proposed method (Figure 2), is measured using two sensors: sensor tube 14 and sensor tube 15. Sensor tube 14 is designed to measure static pressure of unpurified gas $P_h$; it is located at the bottom of coarse cartridge 6 and connects its opening with area 10. This allows the unpurified gas to flow through pulse tube 3 to differential pressure gauge type 11.a. Sensor tube 15 for measuring static pressure of coarse purified gas $P_b$ is located at the bottom of coarse purifying cartridge 6 and its opening 18 on the side surface of tube 15 is connected to area 12. This allows coarse purified gas to flow through one of the pulse tubes 3 to a differential pressure gauge 11.a. Opening 18, which is designed to communicate with area 12 in the installation site of the filtering cartridge 6, is placed on the side surface of sensor tube 15 at the level of sensor input location 14 for measuring static pressure of unpurified gas. At that the flow of coarse purified gas is directed strictly tangentially to the side surface of sensor tube 15 at the location of opening 18 for measuring static pressure. The upper end of sensor tube 15 is sealed with plug 19.

We measure the pressure drop using pressure values $P_h$ and $P_b$ with differential pressure gauge type 11.a, namely, we measure the pressure difference, that is, $(P_h - P_b)$ on the coarse purification cartridge 6. Diameter $D_h$ of sensor tube 15 and diameter of opening 18 on its side surface, are taken on the basis of structural considerations.

4.3 Pressure drop on the filtering cartridge of fine purification, according to the proposed method (Figure 2), is measured using two sensors: sensor tube 15 and sensor tube 16. Sensor tube 15 is designed to measure static pressure of coarse purified gas $P_b$, and is located at the bottom of fine purification cartridge 7 and is connected via its opening with area 12. This allows coarse purified gas to flow through one of the impulse tubes 3 to differential pressure gauge type 11.b.

Sensor tube 16, which is used for measuring static pressure of fine purified gas $P_k$, is located in the lower part of the fine purification cartridge 7 and connects via its opening with area 17. This allows fine purified gas to flow through one of the impulse tubes 3 to the differential pressure gauge type 11.b.

Opening 20, which is designed to communicate with area 17 of filtering cartridge 7, is located on the side surface of sensor tube 16 at the level of sensor 14 input for measuring static pressure of unpurified gas, at the position of opening 18 of sensor tube 15. The fine purified gas flow is directed strictly tangential to the side surface of sensor tube 16 at the location of opening 20 for measuring static pressure. The upper end of sensor tube 16 is sealed with plug 19.

We measure the pressure drop using pressure values of $P_b$ and $P_k$ with differential pressure gauge type 11.b, determine their difference, that is, the difference $(P_b - P_k)$ on fine purified gas cartridge 7.
Diameter $D_k$ of the sensor tube 16, and diameter of openings 20 on its side surface are taken on the basis of design considerations.

4.4 Therefore, one of the differential pressure gauges 11.a measures the difference between static pressures of unpurified and coarse purified gas flowing from sensors 14 and 15, before and after the CFC 6, that is, the pressure drop on this CFC; the second differential pressure gauge 11.b measures the difference between static pressure of coarse and fine purified gas flowing from sensors 15 and 16 before and after CFC 7, that is the pressure drop on this CFC. The proposed principles for measuring the pressure drop at the CFC of coarse and fine purification significantly increase the possibility for timely removal of mechanical impurities from the CFC of coarse purification and replacement of CFC of fine purification with a new one, as well as for preventing deformation and malfunction of CFC due to an increased pressure drop value on CFC, which exceeds the calculated one.

5. Conclusion
1. It has been established that static gas pressure value in the lower part of coarse and fine filtering cartridges is always higher than in their upper part. This conditions a proportionately higher amount of flowing gas, and hence a greater amount of solid particles deposited in the lower part of the CFC and, as a consequence, greater degree of contamination of its filtering material.

2. Measuring pressure drop in the lower part of the filtering cartridge, which is mostly clogged with solid particles, makes early signal at the operator console possible as a consequence of deformation and malfunction of CFC due to an increased pressure drop value on CFC, which exceeds the calculated one.

References
[1] GOST P 54960-2012 2012 Gas distribution systems Block gas delivery stations Cabinet gas delivery stations General technical requirements (Moscow: Rosstandard) 65
[2] GOST P52857.2-2007 2009 Vessels and apparatus Norms and methods of strength calculation Calculation of cylindric and conic, shells convex and flat bottoms and covers (Moscow: Standardinform) 42
[3] GOST 14249 – 89 1989 Vessels and apparatus Norms and methods of strength calculation (Moscow: Izdatelstvo standartov) 80
[4] Shurayts A L, Usachev A P, Salin D V, Khomutov A O 2017 Device for high-pressure natural gas purification from solid particles (Utility patent № 174446, registered on 13.10.2017) 6
[5] Usachev A P, Shurayts A L, Rulev A V, Salin D V 2015 Patent 158000 Russian Federation, MIK B 01 D 53/00 An indoor unit for coarse gas purification from solid particles (Patent applicant and patent holder – Open Joint Stock Company “Giproniigaz” № 2014151034/05 application 16.12.2014 published on 20.12.20.15 Bulletin 35) 7
[6] Usachev A P, Shurayts A L, Rulev A V 2016 Patent 166735 Russian Federation, MPK B 01 D 53/00 Device for prevention of debris’ spread outside natural gas filtering element (Patent applicant and patent holder Open Joint Stock Company “Giproniigaz” Priolrity dated 27.04.2016 Published on 10.12.2065 Bulletin 34) 6
[7] Mokhatab S, Poe W A 2012 Handbook of Natural Gas Transmission and Processing Second Edition (Elsevier Inc.) 802
[8] Liu Z 2018 Improved design of two-stage filter cartridges for high sulfur natural gas purification (Separation and Purification Technology 198) 155-162
[9] Hutten I M Handbook of Nonwoven Filter Media 2nd Edition 2016 (Butterworth Heinemann) 660
[10] Purchas D *Handbook of Filter Media* 2002 (Elsevier Science, 2 edition) 572
[11] Trevor Sparks *Filters and Filtration Handbook - 5 edition* 2016 (Elsevier Butterworth Heinemann) 444
[12] Shurayts А L, Usachev А P, Biriukov A V, Khomutov А О 2018 *Design of mathematical model for dynamics of two-stage natural gas filtering cartridges clogging with mechanical impurities depending on gas-dynamic loss changes* (Herald of Volgograd State Technical University of Architecture and Civil Engineering Series: Heat supply, ventilation, air conditioning, gas supply and lighting 53(72) 100 – 113
[13] *Industrial gas equipment: reference book. 6th edition, updated and revised* 2013 (Saratov: Gazovik) 112
[14] Guo B, Ghalambor A 2012 *Natural Gas Engineering Handbook: 2nd edition* (Gulf Publishing Company, Houston, Texas XX) 472
[15] Thomas D, Charvet A, Bardin-Monnier N, Appert-Collin J-C 2016 *Aerosol Filtration* (ISTE Press – Elsevier) 218
[16] Sutherland K 2008 *Filters and Filtration Handbook 5 edition* (Elsevier Science) 523
[17] Chugaev R R 1982 *Hydraulic Engineering Textbook. 4th edition: updated and revised* (Leningrad: Energoizdat Leningrad department) 672
[18] Set of Rules 42-101-2003 General provisions for the design and construction of gas distribution systems made of metal and polyethylene pipes [Text] (Moscow: Stroiizdat) 214
[19] Set of Rules 62.13330 2011 *Gas distribution systems Updated version of Construction Norms and Regulations (CHuII) 42-01-2002* (Moscow: Minregion Rossii) 66
[20] Usachev А P, Gustov S V, Shurayts А L 2013 *Theoretical and applied foundations for improving the efficiency and safety of operating coarse gas purification plants from solid particles within gas distribution systems* (monograph Saratov: Saratov State Technical University) 172