Development of methodological provisions for reducing the resource and energy intensity of cylindrical two-stage natural gas filters

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Abstract. The article presents the development of methodological provisions for reducing the resource and energy intensity of cylindrical two-stage natural gas filters. In order to reduce consumption in filtering cylindrical elements and vertical barriers used for their dismantling, we proposed a layout plan for several short filtering cylindrical elements, located one on top of the other, instead of one existing analogue, i.e. a one-piece unit. At that, the height of the dismountable unit does not exceed the height of the standard structure. According to the proposed technique, we carried out calculations, the results of which show that minimum consumption in cylindrical two-stage filters is achieved when the number of filtering cylindrical elements located one on top of the other is doubled if compared with the existing analogue.

1. Introduction

Ensuring the required quality of gas purification at the head gas pressure regulating stations (GPRS) involves the use of two-stage cylindrical gas filters (TSCGF) with coarse and fine filtering cylindrical elements (FCE) in separate housings [1–6]. The first stage of coarse purification here uses the metal mesh as filtering material [7], and the second stage of fine purification uses non-woven synthetic fabrics as filtering material [8, 9]. In this case, the filtering equipment is installed in the heated GPRS [5, 6].

In order to reduce the resource and energy intensity, we proposed to place FCEs of coarse and fine purification in one housing [10]. In this case, there is no need for additional space for installation of two separate TSCGF housings, and no costs for their heating and ventilation are required [10].

Based on research results obtained by A.P. Usachev, A.L. Shurayts, and S.V. Gustov, from the point of view of economic feasibility, it is recommended to manufacture modern cylindrical gas filters designed so that the ratio of the housing height to its diameter equals 3.0–4.0 [11, 12]. At the same time, the FCE of coarse and fine purification is installed in the TSCGF housing and is manufactured as a one-piece non-separable device. During construction, a significant additional height of the GPRS is provided for dismantling of such a FCE; it must be not less than the height of the filter element \( H_f \).

To eliminate this drawback, we propose to install several devices of a lower height of \( n_f \) number, which will be placed one on top of the other (figure 1), with the height of each of them equal to \( h_f = H_f/n_f \), rather than one FCE with a height of \( H_f \) [13].
However, there are no recommendations in the technical reference literature for determining the optimal number of filtering devices when the FCE of coarse and fine purification is located in one housing. In this regard, determination of the optimal number of such filtering devices is a high-priority problem that needs to be solved.

2. Development of a mathematical model to determine the optimal number of filtering cylindrical elements of coarse and fine purification

The proposed mathematical model for determining the optimal number of FCEs, which corresponds to the minimum additional integral costs in FCE and external barriers, includes a design scheme (Figure 1), an objective cost function (1) – (10) and a set of constraints for the control parameter (11). The calculation scheme for determining the optimal number of FCE is shown in figure 1.

![Figure 1. Calculation scheme for substantiating the optimal number of FCEs installed one on top of the other in the GPRS: 1 – bowl; 2 – inlet gas pipeline; 3,4 – inlet joining pipe and filter housing; 5 – bottom coarse filtering device and fine filtering device located inside it with the same height \( h_f \); 6 – part of the wall of the GPRS building of the height \( h_f \), required to extract the TSCGF; 7 – floor structure and roof of the building; 8 – upper FCE of the coarse purification and FCE of the fine purification located inside it with the same height \( h_f \); 9, 10 – gas equipment located in conjunction with the TSCGF; \( C_f \) – length of the inlet and outlet joining pipes of the TSCGF; \( D \) – diameter of the TSCGF; \( L \) – length of the GPRS premises, used to locate a piece of equipment located next to the TSCGF; \( b \) – distance between side surfaces of the GPRS premises and the equipment.

According to [14], the criterion for the optimum of the objective function is the minimum integral costs in the FCE:
\[ \Delta Z = \left[ \sum_{p=1}^{P} \Delta K_p \left( \frac{H_f}{h_f} \right) + \sum_{i=1}^{T} \sum_{m=1}^{M} \phi_{m,p} \sum_{p=1}^{P} \Delta K_p \left( \frac{H_f}{h_f} \right) \right] = \min; \]  
\[ a_t = (1 + E)^t; \quad p = 1, P, \quad m = 1, M, \]  
where \( \Delta K_p \left( \frac{H_f}{h_f} \right) \) is the capital cost of manufacturing the \( p \)-th element of the FCE, rubles; \( p \) is the element of capital costs in the FCE; \( a_t \) is the discount coefficient; \( E \) is the discount rate, 1/year; \( t \) is the target year of the FCE operation, years; \( m \) is the element of operating costs for FCE; \( \phi_{m,p} \) is the share of annual deductions from \( \Delta K \) of the \( m \)-th type for the repair and maintenance of the \( p \)-th element of the FCE, 1/year.

Capital costs for the production of the \( p \)-th element of the FCE unit located in the GPRS are determined by the formula:

\[ \sum_{p=1}^{P} \Delta K_p \left( \frac{H_f}{h_f} \right) = \Delta K_{p-1} + \Delta K_{p-2}, \]  
where \( \Delta K_{p-1}, \Delta K_{p-2} \) are the capital costs for the production of the amount of FCE equal to \( n_f \), taking into account the connecting clamp and all the walls of the GPRS with the height of \( h_f = H_f / n_f \), used for dismantling the short FCE, rubles.

Capital costs for the production of the amount of FCE equal to \( n_f \), are calculated using the formula:

\[ \Delta K_{p-1} \left( \frac{H_f}{h_f} \right) = k_{p-1} \cdot S_j \cdot F_f, \]  
\( k_{p-1} \) is the value of the specific capital costs in the manufacture of FCE, rubles/kg; \( S_j, F_f \) are the average FCE wall thickness and area, m and \( m^2 \); \( \rho_f \) is the metal density for FCE, kg/m\(^3\).

The area of FCE with a smooth side surface is determined as follows:

\[ F_f = \pi \cdot D_f \cdot h_f, \]  
\( D_f, h_f \) are the values of the diameter and height of short FCE with a smooth side surface, m.

For FCE with a corrugated side surface, the value \( F_f \) is determined according to the recommendations given in [15].

In case of placement TSCGF and control equipment \( \Delta K_{p+2} \) in the PRG, capital costs for the external barriers of the GPRS, used for dismantling the FCE, are a significant part in the total capital costs. The growth in the size of the FCE or other equipment located next to it leads to an adequate increase in capital costs.

The value \( \Delta K_{p+2} \) is found according to the formula:

\[ \Delta K_{p+2} \left( \frac{H_f}{h_f} \right) = k_{p+2} \cdot \rho_c \cdot S_c \cdot F_c, \]  
\( k_{p+2} \) is the value of specific capital costs for external vertical barriers of the GPRS, referred to the unit of their material intensity, rubles/kg; \( \rho_c \) is the value of material density of the GPRS external vertical barriers, kg/m\(^3\); \( S_c \) is the value of average thickness of the GPRS external vertical barriers, m; \( F_c \) is the area value of the part of the GPRS external vertical barriers, used for dismantling the FCE, \( m^2 \).

Value \( F_c \) is calculated using the formula following:

\[ F_c = \frac{H_f}{n_f} \left\{ [(D + 2C_f) + 3L] + [(D + 2C_f) + 2b] \right\}, \]
$C_f$ – the length of inlet and outlet filter joining pipes (Fig. 1), m; $D$ – TSCGF diameter, m; $L$ – GPRS length, required for locating a piece of equipment installed next to the TSCGF, m; $b$ – distance between side surfaces of GPRS, m.

Operating costs in the formula (1) for any $p$-th element of the FCE, which are associated with the capital ($m = 1$) and ongoing ($m = 2$) repairs, maintenance ($m = 3$) and dismantling of removable covers and FCE ($m = 4$), are calculated as a share of the capital costs $\varphi_{m,p}$, according to the formula:

$$\sum_{i=1}^{T} \sum_{m=1}^{m_{=d}} \varphi_{m,p} \sum_{p=1}^{p} \Delta K_p \left( H_{f_{i}} / h_{f} \right) = \sum_{i=1}^{T} \sum_{m=1}^{m_{=d}} \varphi_{m,p} \left( \Delta K_{p_{1}} + \Delta K_{p_{2}} \right). \tag{8}$$

The annual costs associated with thermal energy ($m=5$) to compensate for heat losses through the external barriers used for dismantling the FCE are calculated using the formula:

$$Z_{m=5} \left( H_{f} / h_{f} \right) = Q_{m=5} \cdot C / \tau \cdot \eta, \tag{9}$$

where $Q_{m=5}$ is the value of heat losses through the outer walls, used for dismantling the FCE, MW; $C$ is the value of the specific cost of heat at the point of its supply for heating the GPRS, rubles/MW*h; $\tau$ is the operating time of the GPRS heating system during the year, h; $\eta$ is the coefficient of efficiency of the GPRS heating system, unit fraction.

In this case, heat losses are numerically equal to heat power of the GPRS heating system.

According to [16], value $Q_{m=5}$ in the formula (9) is determined from the equation:

$$Q_{m=5} \left( H_{f} / h_{f} \right) = (t_b - t_{c,o})(1+\beta) \cdot F_{e} / R_{t}, \tag{10}$$

where $t_b$ is the air temperature in the GPRS, $^\circ$C; $t_{c,o}$ is the average value of the outside air temperature, $^\circ$C, taken for the time range at temperatures below and equal to zero; $\beta$ is the coefficient that takes into account corrections for the cardinal points, for infiltration, for the outer corners of the GPRS premises, unit fraction [17]; $R_{t}$ is the resistance to heat transfer for external enclosing structures, (m$^2$*K)/W.

Value $R_{t=4}$ is found from [18, 19] and takes into account the type of barriers, the temperature difference $(t_b - t_{c,o})$, the duration of the period with temperatures below and equal to zero.

The air temperature values inside the technological premises and the average temperatures inside and outside the GPRS premises are taken in accordance with standards [20] and [21].

The area $F_{e}$ of the GPRS external vertical barriers, used for dismantling the FCE, is determined from the equation (6).

$(H_{f_{i}} / h_{f})$ parameter in equations (1) – (10) is the control parameter, since it has the opposite effect on various elements of capital and operating costs.

The inequation limiting the extreme values of the control parameter in equations (1) – (10) is written as:

$$(H_{f_{i}} / h_{f})_{\min} \leq (H_{f_{i}} / h_{f}) \leq (H_{f_{i}} / h_{f})_{\max}. \tag{11}$$

Analysis of the minimum and maximum values $(H_{f_{i}} / h_{f})$, carried out in accordance with (10), and the calculations performed show that for a non-separable FCE, the minimum value will be equal to $(H_{f_{i}} / h_{f})_{\min} = 1.0$. The maximum number of FCEs in one unit will be $n_f = (H_{f_{i}} / h_{f})_{\max} = 4.4$. Above this value, there is a decrease in the filtration surface of over 30% due to the growth of non-filtering surfaces of covers and bases for any of the FCEs of height $n_f$.

From the analysis of equations (1) – (10), it can be seen that the value of the original objective function for the FCE of the given geometric parameters can be written as:

$$\Delta Z = f \left( H_{f_{i}} / h_{f} \right). \tag{12}$$
In order to optimize the number of FCEs, it is advisable to use the numerical method [22, 23]. Taking a number of values \((H_f / h_f)_1, (H_f / h_f)_2, (H_f / h_f)_3, \ldots, (H_f / h_f)_n\) with known geometric parameters of the FCE, we find the integral costs \(\Delta Z_1, \Delta Z_2, \Delta Z_3, \ldots, \Delta Z_n\).

The optimal number of FCEs, equal to \((H_f / h_f)_{opt}\), corresponds to the option with minimal costs \(Z_{min}\).

According to the above technique, we carried out calculations to determine \(n_f\) with the diameter of the TSCGF inlet and outlet joining pipes equal to 350 mm, the results of which are presented in the graph (figure 2).

![Figure 2. Graph for determining the amount of FCEs for TSCGF DN 350 placed in the GPRS.](image)

From the graph it follows that the optimal number of FCEs for TSCGF located in the GPRS is \(n_{f_{opt}} = 2.0\).

Additional calculations show that the value \(n_{f_{opt}}\) decreases with the decrease in the diameter of the TSCGF inlet and outlet joining pipes.

At the same time, the value \((H_f / h_f)\) of FCEs produced by the Russian enterprises is \((H_f / h_f) = 1.0\). Comparison of the optimal amount of FCEs, which equals \(n_{f_{opt}} = 2.0\), for the proposed design with the value \(n_f = 1.0\), showed that the minimum costs in the TSCGF were achieved when the number of FCEs located one on top of the other was doubled in comparison with the existing analogue.

The minimum value of the integral costs for the TSCGF with the diameter of the inlet and outlet joining pipes equal to 350 mm is \(\Delta Z_{min} = 161000\) rubles.

3. Conclusion
1. In order to reduce capital and energy costs for the FCE and the vertical barriers used for its dismantling, we propose to install several FCEs, placed one on top of the other, with the height of any of them equal to \(h_f\), which is the total height \(H_f\) of the whole unit divided by their amount \(n_f\).

2. We proved that the parameter \(n_f\) was the control parameter for equations (1) – (10), since it had the opposite effect on the values of capital and operating costs, on the one hand, for the outer walls...
required for dismantling the FCE, and, on the other hand, for production of several shortened FCEs $n_j$ with a height of $h_j$ instead of one solid FCE with a height of $H_f$.

For example, with an increase in the value of $n_j$ there was an increase of capital and operation costs, expenses for production and dismantling of several FCEs with a height of $h_j$, but the costs for external vertical barriers, used for dismantling FCEs, decreased, and vice versa.

3. According to the proposed technique, we carried out calculations, the results of which show that the minimum costs for the TSCGF for gas purification were achieved when the number of FCEs located one on top of the other was doubled in comparison with the existing analogue.

References
[1] Guo B and Ghalambor A 2012 Natural Gas Engineering Handbook: 2nd edition (Gulf Publishing Company) p 472
[2] Hutten I M 2016 Handbook of Nonwoven Filter Media (Elsevier Butterworth Heinemann) p 660
[3] Mokhatab S and Poe W A 2012 Handbook of Natural Gas Transmission and Processing. Second Edition (Elsevier Inc.) p 802
[4] Sutherland K 2008 Filters and Filtration Handbook (Elsevier Science) p 523
[5] Shurayts A L, Gustov S V and Usachev A P 2010 High-technology hydraulic fracturing – the way to improving reliability of gas transmission grid Gas of Russia 41 56–60
[6] Usachev A P, Shurayts A L and Gustov S V 2013 Theoretical and applied foundations for improving the efficiency and safety of operating coarse natural gas purification from solid particles within gas distribution systems: monograph (Saratov: Saratov State Technical University) p 172
[7] Trevor S 2016 Filters and Filtration Handbook (Elsevier Butterworth Heinemann) p 444
[8] Tien Ch 2013 Principles of Filtration (Elsevier) p 360
[9] Thomas D, Charvet A, Bardin-Monnier N and Appert-Collin J-C 2016 Aerosol Filtration (ISTE Press, Elsevier) p 218
[10] Khomutov A O, Usachev A P, Shurayts A L and Salin D V 2017 Appliance and development of gas filters with cylindrical filtering elements of preliminary and fine cleaning placed in one building Regional architecture and construction 3 165–171
[11] Usachev A P, Shurayts A L and Sherstyuk P V 2010 Development of mathematical model of operating filters shapes placed in cabinet gas-distribution plants Collection, preparation and transportation problems of oil & oil products 4 (82) 145–155
[12] Usachev A P and Gustov S V 2014 Mathematical model of geometric optimization parameters of filters placed in heated rooms Oil & Gas Engineering 4 279–301
[13] Shurayts A L, Usachev A P, Salin D V and Rulev A V 2015 Coarse natural gas purification plant with cylindrical filter element of the mesh type Patent No 158000 35
[14] Methodological recommendations for evaluating the investment projects effectiveness 2000 (Moscow: Economics) p 285
[15] Salin D V, Usachev A P and Shurayts A L 2016 Development of the design and determination geometric parameters of the corrugated mesh shell, preventing the destruction of the filter element of gas cylindrical filters Collection, preparation and transportation problems of oil & oil products 1 (103) 95–106
[16] Bogoslovsky V N 1982 Construction thermal physics (basic thermal physical heating, ventilating and air conditioning) (Moscow: HSE) p 415
[17] Bogoslovsky V N and Scanavi A N 1991 Heating: University Handbook (Moscow: Construction Publishing Company) p 736
[18] Letter of State Committee for Construction of the Russian Federation dated 26.03.2004 No LB-2013/9. SP 23-101-2004 2004 (Moscow: Design of building thermal protection) p 196
[19] Set of Rules No 113 State Committee for Construction of the Russian Federation dated 26.06.2003 (SNiP) 23-02-2003 Building thermal protection 2004 (Moscow: State
Committee for Construction of the Russian Federation, FGUP CPP) p 34

[20] Set of Rules No 45 State Committee for Construction of the Russian Federation dated 11.06.1999 (SNiP) 23-01-99* Construction norms and rules of the Russian Federation, Construction climatology 2003 (Moscow: State Committee for Construction of the Russian Federation, FUP CPP) p 225

[21] Order of the Ministry of Regional Development of the Russian Federation No 279 dated 30.06.2012. CII 60.13330.2012. Set of rules. Heating, ventilating and air conditioning. Updated edition (SNiP) 41-01-2003 2012 (Moscow: Ministry of Regional Development of the Russian Federation) p 52

[22] Boglaev Yu P 1990 Computation and Programming (Moscow: HSE) p 544

[23] Petrov A V, Alekseev V E and Vaulin A S 1990 Computation and Programming (Moscow: HSE) p 478