Clogging Model for Coarse and Fine Filtering Cloths of Filtering Cylindrical Elements, Preventing Sedimentation of Mechanical Impurities in Their Gap

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Abstract. In this paper we propose a method for preventing sedimentation of solid particles in the lower part of the gap between filtering cylindrical elements of coarse and fine purification by increasing the size of the meshes and total thickness of the first downstream gas flow layers of the fine filtering element in excess of the maximum diameter of solid particles. Experimental corroboration for the proposed method showed absence of solid particles’ sedimentation in the lower part of the gap between filtering cylindrical elements of coarse and fine purification and clogging of their meshes. As a result of the experiments, we found that the maximum sedimentation of mechanical impurities inside the first screens of the fine filtering cloth is achieved when their meshes’ size and screens’ thickness are, respectively, equal to three and two and a half maximum diameters of a solid particle.

We developed a mathematical model that describes the clogging dynamics of filtering elements, where pressure losses in the first section with constant mesh sizes of all screens and in the second section with a sequential decrease in mesh sizes have different clogging rates and therefore are calculated separately from each other. The clogging process at each section of the multilayer filter cloth is represented as a successive decrease in the effective screening area of the screen meshes. The mathematical model makes it possible to prevent the sedimentation of mechanical impurities in the gap between gas filter elements of coarse and fine purification and allows to analytically determine the clogging degree at any time of operation, depending on the pressure losses’ values.

1. Relevance of Designing a Mathematical Model to Determine the Clogging Degree and to Prevent Sedimentation of Mechanical Impurities in the Gap Between Gas Filtering Elements of Coarse and Fine Purification

In accordance with the requirements of [1], ensuring reliable operation of high-precision gas control equipment with high throughput can be achieved through the use of devices, which contain cylindrical units of coarse and fine purification, for two-stage gas purification from mechanical impurities [1]. The need for two-stage purification of natural gas from mechanical impurities in such units is described in [2-7].

In the already existing cylindrical two-stage units (CTSU) for coarse and fine gas purification, filtering cylindrical elements (FCE) are located in separate bodies operating under high pressure and,
therefore, having significant wall thicknesses of shells, bottoms and flanges, and, consequently, high metal and capital intensity [3, 8]. In order to reduce the capital and metal intensity of the existing CTSU for gas purification AO “Gipronigaz” [9] proposes the principle of placing 1 (mono-body) and two coaxially installed FCE of coarse 7 and fine 8 purification, located at the minimum allowable distance from each other in the internal volume of one body (Fig. 1). The disadvantage of such CTSU is sedimentation and accumulation of small solid particles in the lower part of the gap 12 between the FCE of coarse and fine purification, since solid particles, which are exiting it and colliding with its surface, with a size larger than the meshes of the first layers of the filter cloth partially sediment on it and partially fall into the lower part of the gap between the FCE of coarse and fine purification. Solid particles gradually accumulate there, form a continuous layer and clog the lower part meshes of the FCE of coarse and fine purification, which leads to a decrease in their throughput.

Figure 1. Diagram describing purification of natural gas from mechanical impurities. Fragment A - Geometric parameters of the screens on the enlarged lower part of the FCE of coarse and fine purification.
1 - vertical cylindrical body; 2, 6 - inlet and outlet joining pipes; 3, 4 - flange and filter cover; 5 - bowl; 7, 8 - FCE of coarse and fine purification; 9 – FCE cover 7 and 8; 10 - meshes of the FCE of coarse purification; 11 - first downstream filter layers of the FCE of fine purification; 12 - gap between FCE of coarse and fine purification; 13 - third and subsequent downstream filter layers of the FCE of fine purification; 14 - lower part of the gap 12; 15 - solid particle of a maximum diameter that passes through the screen meshes of the FCE of coarse purification; 16 - boundary between the gap 12 and the first downstream filter layers of the FCE of fine purification.

In this regard, the relevance of this work lies in solving the problem of preventing the sedimentation of solid impurities in the gap 12 and developing a mathematical model that analytically
describes the dynamics of clogging of multi-layer natural gas filter cloths, taking into account prevention of solid impurities’ sedimentation in the gap 12 at any time of operation.

2. Justification of the Method for Preventing Mechanical Particles’ Sedimentation in the Gap Between the Gas Filter Elements of Coarse and Fine Purification

The multi-layer fine filter cloth is made in the form of a row of screens located one after another. In accordance with GOST (National State Standard) 5542 [10], pipeline gas with an estimated flow rate $V_p = \text{const}$ is purified in coarse screen 7 and in n-number of fine screens 8 (Fig. 1), sequentially located along the gas flow, with meshes in the form of a square and a standard size of a screen mesh equal to $m_n$. The screen number $n$ in a row varies within the interval: $n = (1, 2, ..., k)$, where $b_{n=1+k}$ is the constant mesh size of the first row of fine screens, m; $b_{n=1+h}$ is the mesh size of the second row of fine screens, m; $d_{\text{max}}$ is the maximum diameter of solid particles at the outlet from the FCE of coarse purification.

As shown in the enlarged Fragment A (Fig. 1), the mesh size of each screen $n$ in the course of its clogging changes to values: $m_{n=i} = a_{n=i}, c_{n=i}, e_{n=i}, ... j_{n=i}$.

In order to prevent the sedimentation of solid particles in the gap between coarse and fine FCE 12, we propose [11] the following: meshes 10 of the coarse filter element 7 of a woven metal screen must have the size $b_{cr}$ equal to the maximum diameter $d_{\text{max}}$ of solid particles 15, in other words, $b_{cr} = d_{\text{max}}$; multi-layer cloth of fine purification must be divided into two sections. The first section is made of the row of screens $(1; 2; ... k)$, which have meshes with a constant size $b_{n=k,m=a_{n=k}}$ and a constant screen thickness $S_{n=k,m=a_{n=k}}$, which is larger than the maximum diameter $d_{\text{max}}$ of solid particles 15. In this case, we achieve their free passage into the meshes of the first row of screens, their capture inside the cloth, their gradual accumulation and minimization of the sedimentation of solid particles 15 on the surface of the FCE of fine purification 7.

In order to determine the specific dimensions $b_{n=k,m=a_{n-k}}$ and $S_{n=k,m=a_{n-k}}$, the research and production center of AO “Giproniigaz” (Saratov) manufactured and then tested a CTSU with an inner diameter of $D = 160$ mm with coarse FCE made on the basis of a high-precision metal screen made of bronze with a square mesh size of 0.08 mm and fine FCE based on a number of high-precision metal screens made of bronze with a square mesh, according to [12]. When performing the experiments, we used fine purification cloth with seven layers of screens based on the “low brass” alloy according to GOST 6613-86 with a thickness of 1.18 mm with mesh sizes in mm, respectively: 0.25 mm (n = 1 and n = 2); 0.071 mm (n = 3); 0.063 mm (n = 4); 0.056 mm (n = 5); 0.05 mm (n = 6); 0.04 mm (n = 7).

The results of the experimental corroboration for the proposed method showed the absence of solid particles’ sedimentation in the lower part of the gap 12 between the FCE of coarse and fine purification, clogging of their meshes and a decrease in throughput. As a result of experiments, we found that maximum sedimentation of mechanical impurities inside the first $n = 1$ and $n = 2$ screens of the filter cloth is achieved when their mesh size is equal to three maximum diameters of a solid particle $3d_{\text{max}}$, that is:

$$b_{n=1+k,m=j_{n=1+k}} = 3d_{\text{max}}$$  \hspace{1cm} (1)

and with screen thickness equal to two and a half maximum diameters of a solid particle, that is:

$$S_{n=1+k,m=j_{n=1+k}} = 2.5d_{\text{max}}.$$  \hspace{1cm} (2)

The dimensions obtained as a result of the experiments are shown in Figure 1.
Analysis of the conducted experiments showed that relatively large mesh sizes of the first screens of the filter cloth are conditioned by the imposition of the wires of the subsequent (second \( n = 2 \)) screen on the flow area of the previous (first \( n = 1 \)) screen. As a result, the combined flow area of the first screens of the filter cloth decreased below the \( 3d_{\text{max}} \) value. At the same time, the size of the combined flow area of the first two screens of the filter cloth did not decrease below particle diameter \( d_{\text{max}} \).

### 3. Designing a Mathematical Model of Multi-Layer Filtering Cloths Clogging, Which Prevents Sedimentation of Particles in the Gap Between the FCE of Coarse and Fine Purification

An important operational parameter of the CTSU is the degree of FCE clogging at any moment of its operation. The works \([5, 13-20]\) are devoted to the issues of clogging of filtering cloths with mechanical impurities. In \([20]\) the authors propose a model for analytical determination of clogging degree depending on the pressure loss at the FCE. However, it lacks a method for calculating the degree of FCE clogging at any time of operation, which takes into account the conditions that prevent sedimentation of mechanical impurities in the gap between the FCE of coarse and fine purification. It does not take into account the increase in the dimensions of the first downstream (in the direction of the gas flow) layers \( n_{1, k} \) up to a value \( b_{n=1+k, m=j_{n-1+k}} > d_{\text{max}} \) of solid particles \( 15 \), which occurs in the proposed method for preventing clogging of the gap \( 12 \). It also does not take into account the specific thickness \( S_{n=1+k, m=j_{n-1+k}} \) of the first layers \( 1 \), which is greater than the maximum diameter \( d_{\text{max}} \) of solid particles \( 15 \). Ignoring these factors gives an unreliable estimate and leads to an overestimation of the clogging degree for the proposed design of multi-layer FCE. In this regard, it is important to develop a model for analytical determination of the clogging degree depending on the pressure loss at the FCE, taking into account conditions preventing sedimentation of mechanical impurities in the gap between the FCE of coarse and fine purification.

In the proposed formulation of the problem, the screen number \( n \) in the row varies within the interval: \( n = (1, 2, ..., k) \). Mechanical particles of the size \( d_{\text{max}} \) first pass through the first screen rows of the filter cloth with constant mesh sizes \( b_{n=1+k, m=j_{n-1+k}} = \text{const} \). Next, these particles pass into screens with smaller mesh sizes \( b_{n=q+i, m=j_{n-q+i}} < d_{\text{max}} \), settle on their surface and so on until the very first (in the direction of the gas flow) screen with dimensions \( b_{n=i, m=j_{n-i}} \). In the process of clogging, mechanical impurities of a smaller size sediment on each subsequent screen. Therefore, as it follows from Figure 2 and Figure 3, each subsequent screen \( n \) (in the direction of the gas flow) has a smaller initial size and smaller subsequent sizes compared to the previous screen.
Figure 2. Diagram of successively located (in the direction of the gas flow) fragments of fine purification screens with a number varying in the interval \( n = (1; 2; ... k) \) and the standard size of each screen meshes in the process of clogging \( m = j_{n=1} \), \( n = (q, h, ..., i) \) and in the direction of gas flow in the process of contamination with mechanical impurities, \( m \).

Figure 3. Fragment A of the screen number \( n = (q, h, ..., i) \) with a mesh size \( b = i, m = j = 1 \).
A decrease in any previous mesh size $b_{n=k,m=(j-1)b}$ when gas passes through the first rows of screens $n=\{1;2;\ldots;k\}_{b_{n=1}=3d_{\text{max}}}$ to the subsequent $b_{n=k,m=j_{n=k}}$ (Fig. 2) in the process of clogging is represented as an increase in the distance between screen meshes to the value:

$$L_{n=k,m=j_{n=k}} = L_{n=k,m=a_{n=k}} + \sum_{m=a_{n=k}}^{j_{n=k}} (b_{n=k,m=(j-1)b} - b_{n=k,m=j_{n=k}}) \begin{bmatrix} b_{n=k,m=j_{n=k}} \end{bmatrix} \text{(const)} = 3d_{\text{max}} \quad (3)$$

where: $b_{n=k,m=(j-1)b}$ and $b_{n=k,m=j_{n=k}}$ are the previous and subsequent dimensions of a square mesh of the filtering screen when the gas passes through the first rows of screens $n=\{1;2;\ldots;k\}_{b_{n=1}=3d_{\text{max}}}$ in the direction of its flow in the course of contamination with mechanical impurities, $m$.

A decrease in any previous mesh size $b_{n=i,m=(j-1)b_{n=i}}$ when gas passes through a row of screens $n=(q,h,\ldots,i)_{b_{n=1}=3d_{\text{max}}}$ to the subsequent $b_{n=i,m=j_{n=i}}$ (Fig. 2) in the process of clogging is represented as an increase in the distance between screen meshes to the value:

$$L_{n=i,m=j_{n=i}} = L_{n=i,m=a_{n=i}} + \sum_{m=a_{n=i}}^{j_{n=i}} (b_{n=i,m=(j-1)b_{n=i}} - b_{n=i,m=j_{n=i}}) \quad \text{if } b_{n=q+i} < d_{\text{max}}. \quad (4)$$

where: $b_{n=i,m=(j-1)b_{n=i}}$ and $b_{n=i,m=j_{n=i}}$ are the previous and subsequent dimensions of a square mesh of the filtering screen when gas passes through the row of screens.

During the passage of gas through the row of screens the pressure losses $\Delta Z_{n=1;\ldots;m} \text{ increase in the process of clogging. For example, for the } n=1 \text{ screen, the increase occurs up to values:}$

$$\Delta Z_{n=1,m=j_{n=1}}; \Delta Z_{n=2,m=j_{n=2}}; \ldots; \Delta Z_{n=k,m=j_{n=k}} \text{ if } b_{n=k,m=j_{n=k}} = 3d_{\text{max}} \quad \ldots \quad (5)$$

The formula for determining total pressure loss, where gas passes through the row of screens sequentially located one after another (Fig. 2) along its flow, is written as:

$$\Delta Z_{n,m} = \sum_{n=1}^{m} \Delta Z_{n,k,m=j_{n=k}} \quad \text{if } b_{n=k,m=j_{n=k}} = 3d_{\text{max}} + \sum_{n=q}^{m} \Delta Z_{n,i,m=j_{n=i}} \quad \text{if } b_{n=q+i} < d_{\text{max}}. \quad (6)$$

The total pressure loss $\Delta Z_{n,m}$ during gas passage through the row of screens $n$ is determined according to the Weisbach equation [21], taking into account formula (6), as follows:
\[
\Delta Z_{n,m} = \frac{\rho V^2}{2g} \sum_{n=1}^{n_{k}} \sum_{m=1}^{m_{a}} \left[ b_{n=i,m=1,a} + L_{n=i,m=1,a} + \sum_{m_{a}}^{m_{a}} \left( b_{n=i,m=1,a} \cdot b_{n=i,m=1,a} \right) \right] + \frac{\rho V^2}{2g} \sum_{n=q}^{n_{q}} \sum_{m=1}^{m_{o}} \left[ b_{n=i,m=1,o} + L_{n=i,m=1,o} + \sum_{m_{o}}^{m_{o}} \left( b_{n=i,m=1,o} \cdot b_{n=i,m=1,o} \right) \right]
\]

Here \( \rho \) is the density of the pipeline gas at the FCE inlet at the value of the excess pressure at the FCE inlet, kg/m^3; \( g \) is the value of acceleration due to gravity, which is equal to 9.8 m/s^2; \( V_p \) is the throughput of the FCE at the value of excess gas pressure at the FCE inlet, m^3/s; \( \zeta_{n=1}^{n_{k}}(k-1,m_{a}) \) and \( \zeta_{n=1}^{n_{q}}(k-1,m_{o}) \) are the values of the screen local resistance coefficient in the direction of gas flow through the row of screens \( (1, 2, \ldots, k) \) and \( (q, h, \ldots, i) \), which are characteristic of the current sizes \( b_{n=i,m=1,a} \) and \( b_{n=i,m=1,o} \) due to contamination with mechanical impurities [22]; \( F_{n=k,m=1,a} \) and \( F_{n=i,m=1,o} \) are the total areas of screens, which are required for purification of natural gas with a flow rate \( V_p \) in the direction of the gas flow, respectively, through the row of screens \( (1, 2, \ldots, k) \) and \( (q, h, \ldots, i) \), which are determined by the formula:

\[
\text{At any moment of operation at } m = j_n, \text{ the value of the total pressure loss calculated by the formula (7) corresponds to a certain degree of its clogging by mechanical impurities.}
\]

The average clogging degree of the filter cloth in fractions of a unit is determined by the formula:
Formulas (7) and (8) are also valid for determining pressure losses and the degree of clogging of one filter screen, for example, for FCE of coarse purification, if we take the n = 1 value.

The experimental corroboration showed the same clogging degree of filter screens in the first section with constant mesh sizes of all screens, which is significantly (8.5 times) lower than the clogging degree in the second section, where there is a consistent decrease in mesh sizes. In this case, the clogging degree of filter screens and pressure losses in the first and second sections are calculated separately from each other.

Thus, the mathematical model (1) - (8) makes it possible to approach the determination of the average value of the FCE clogging degree and the value of pressure losses before the next removal of mechanical impurities from the CTSU in a more substantial manner.

4. Conclusions
1. We proposed the principle for preventing sedimentation of solid particles in the lower part of the gap between the FCE of coarse and fine purification and maintaining the throughput of the CTSU by increasing the size of the meshes and the total thickness of the first downstream layers of the fine FCE in excess of the maximum diameter of solid particles.

2. The experimental corroboration for the proposed method showed practical absence of sedimentation of solid particles in the lower part of the gap between the FCE of coarse and fine purification and, as a consequence, clogging of their meshes and a decrease in throughput. As a result of the experiments, we found that maximum sedimentation of mechanical impurities inside the first screens of the filter cloth is achieved when their mesh size and screen thickness are equal, respectively, to three and two and a half of the maximum diameter of a solid particle.

3. We designed the mathematical model of FCE clogging dynamics, where pressure losses in the first section with constant mesh sizes of all screens and in the second section with a sequential decrease in mesh sizes, have different dependencies from the degree of clogging and, therefore, are calculated separately from each other. The clogging process at each section of the multi-layer filter cloth is represented as a successive decrease in the effective screening area of the screen meshes.

The mathematical model allows to analytically determine the degree of FCE clogging in the first and second sections at any time of operation, depending on the value of pressure losses.

4. The experimental corroboration showed the same clogging degree of the filter screens in the first section with constant mesh sizes of all screens, which is significantly (8.5 times) lower than the clogging degree in the second section, where there is a consistent decrease in mesh sizes. In this case, the clogging
degree of the filter screens and pressure losses in the first and second sections are calculated separately from each other.

5. References

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