Modeling and Calculation of Flow Filter

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Abstract. The relevance of the use of flow filtering is considered in the work. A mathematical model of the flow filter is presented. An algorithm for calculating the flow-through filter and the main parameters of its filtering surface is developed; experimental data of flow filtration based on a simulation model are presented.

1. Introduction
Filtering is one of the most widely used processes in the processing of products differing in their properties. The process of filtering of industrial suspensions is a complex physicochemical and hydrodynamic process. The physico-chemical composition of the fluid, the concentration and properties of suspended solids in it, as well as the properties of the filter septum, its porosity, the size of pores and other factors have a significant impact on the course of filtration.

A characteristic feature of the development of the technology of filtration of suspensions is the effort to implement the process in a continuous mode.

Flow-through filters (Figure 1) often are made either as an extended channel with a coaxial filter insert, or as a channel with walls made as a filter partition. Most commonly, they are used to remove the load from the main apparatus, such as centrifuges, filters, settlers, and so on [1]. These filters can be both distributing, and collecting liquid.

![Figure 1. A schematic diagram of the flow-through filter](image-url)
The suspension loses part of the liquid phase as filtrate, when it moves through the channel under pressure. At the same time it condenses, and then continuously removed from the filter. A thin layer of sediment is stored directly at the partition; it ensures the absence of solid particles in the filtrate.

The same filters have found their application in the chemical and food industries. Unfortunately, flow-through filters have not yet received a wide industrial application, which is primarily due to the insufficient knowledge of the basic laws of their work and the lack of engineering methods of calculation.

Flow-through filters are characterized by a constant external pressure, and the pressure along the central channel can vary significantly. It results in a significant uneven distribution of the radial filtration rate throughout the space.

The study of the hydrodynamics of flow filtration is an urgent problem. To date, there are no reliable sources for calculating an industrial flow filter. Existing filter designs to study the process are laboratory or semi-industrial. The necessity of elaborating of recommendations for writing a reliable methodology for performing of calculations for a pre-project study is the urgency of research of hydrodynamics in a perforated channel.

2. Mathematical description of the hydrodynamics of the flow filter

Laminar flow in a circular channel with fluid outflow through a permeable wall, in the general case, is described by the Navier-Stokes equations, taking into account the corresponding boundary conditions. In a cylindrical coordinate system for axisymmetric flow establishment, these equations are written in the form:

\[
\begin{align*}
U \frac{\partial u}{\partial x} + \varrho \frac{\partial u}{\partial r} &= -\frac{1}{\rho} \frac{\partial p}{\partial x} + \frac{\mu}{\rho} \left( \frac{\partial^2 u}{\partial x^2} + \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} \right), \\
U \frac{\partial u}{\partial x} + \varrho \frac{\partial u}{\partial r} &= -\frac{1}{\rho} \frac{\partial p}{\partial r} + \frac{\mu}{\rho} \left( \frac{\partial^2 u}{\partial x^2} + \frac{1}{r} \frac{\partial u}{\partial r} + \frac{\partial^2 u}{\partial r^2} - \frac{\varrho}{r^2} \right),
\end{align*}
\]

if \( U, \varrho \) are axial and radial components of the velocity vector in the channel; \( x, r \) are longitudinal and radial coordinates.

The system of equations (1) is closed by the continuity equation:

\[
\frac{\partial u}{\partial x} + \frac{1}{\varrho} \frac{\partial (r \cdot \varrho)}{\partial r} = 0
\]

After a series of transformations of this system of equations, we get the equation describing the flow in a channel with permeable walls in the one-dimensional approximation in the form

\[
\frac{dp}{\varrho} + \beta \cdot U_{ave} \cdot dU_{ave} + U_{ave}^2 \cdot d\beta + \beta \cdot (U_{ave} - \theta) \cdot \frac{dG}{G} + \lambda \frac{U_{ave}^2}{2} \cdot \frac{dx}{D} = 0,
\]

if \( \beta = \frac{\int_0^R U^2 \cdot r \cdot dr}{(U_{ave}^2 \cdot R^2)} \) is the coefficient of momentum, takes into account the non-uniformity of the velocity distribution in the channel cross section;

\( \lambda = \left[ 8\mu \frac{\partial U}{\partial r} \right]_r = R \left/ (\varrho \cdot U_{ave}^2) \right. \) is the coefficient of resistance of flow;
\[ U_{ave} = \frac{2}{R^2} \int_{0}^{R} U \cdot r \cdot dr \]  

average flow rate across the channel;

\[ \theta \]  

is the projection of the velocity vector for the fluid taken from the channel or flowing into it, on the direction of movement of the main flow; \( p \) is pressure in the channel;

\( \mu, \rho \) are viscosity and density of liquid; \( G \) is fluid flow in the cross section of the channel; \( D \) is diameter of the channel.

Solving equation (3), we can determine the distribution of the average velocity of the fluid flow along the channel, \( U_{ave} = f(x) \), and calculate the pressure distribution in the channel along the fluid flow, \( p = f(x) \). However, equation (3) can be solved only if the values of the coefficients \( \beta, \lambda \) and the values of \( \theta \) are known. In the general case, the coefficients are functions of the local radial \( Re_r \) and axial \( Re \) numbers of the Reynolds. In addition, as it was evidenced by numerous experimental studies [3], the values of the coefficient and value of \( \theta \) are determined by the individual properties of the permeable wall, such as the structure and surface state of the permeable wall. In [4], the results of approximate solutions of equations (1) and (3) for the values of \( \beta, \lambda, \) and \( \theta \) which were specified or obtained in experiments, are given.

In [4], equation (3), obtained as a result of a series of transformations, is presented in the form of a differential equation that describes the distribution of the average longitudinal velocity along the length of the perforated channel:

\[
\frac{d^2 U_{ave}}{dx^2} - a \cdot U_{ave} \cdot \frac{dU_{ave}}{dx} - b \cdot U_{ave}^2 = 0
\]  

To solve this equation it is necessary to know the values of the coefficients \( a \) and \( b \). The coefficients \( a \) and \( b \) take into account in complex the influence of those factors that determine the values of the coefficients \( \beta, \lambda \) and the value of \( \theta \) on the hydrodynamics of the flow in the perforated channel. For example, for a tubular channel made of a material used for the manufacture of filter walls and laminar filtration flow through the channel wall, the values of the coefficients \( a \) and \( b \) are defined as

\[
a = \frac{k \cdot \rho \cdot s}{2 \cdot D_{in} \cdot \mu \cdot \delta}, \quad b = \frac{2 \cdot k \cdot \rho \cdot \lambda_0}{D_{in}^2 \cdot \mu \cdot \delta},
\]  

if \( s = 8(2-c)-m \); \( D_{in} \) is internal diameter of the channel; \( \delta \) is channel wall thickness; \( k \) is channel wall permeability; \( \mu \) and \( \rho \) are viscosity and density of fluid; \( c \) – correction coefficient that takes into account the curvature of the fluid flow line as it flows into the filter septum; \( m \) – correction coefficient that takes into account increase in hydraulic resistance due to the roughness of the surface of the septum of filter relative to smooth surface; the linear loss coefficient is equal to \( \lambda_0 \) for smooth surface.

The values of the coefficients \( a \) and \( b \) are related by the ratio:

\[
a = \frac{D_{in} \cdot s}{4 \cdot \lambda_0} \cdot b.
\]

All values that are included in the expressions for the coefficients \( a \) and \( b \) can be calculated or assigned, except for the parameter \( s \) which is included in the coefficient \( a \). It determines the conditions for coupling the fluid flow along the channel with the filtration flow through its permeable walls. The lack of methods and techniques for determining the values of \( c \) and \( m \), which are the part of this parameter, is the main difficulty in solving equation (4).

The analytical solution of equation (4) in its entire composition is difficult, and it has to be solved by numerical methods. For short channels with a high intensity of liquid withdrawal through their permeable walls, it is approximately possible to take \( b = 0 \). When \( b = 0 \), equation (4) is solved analytically for the values of the parameter \( s \) taken in this case. Graphic representations of the curves of the dependences of the average liquid flow velocity and hydraulic non-uniformity along the flow in the
channels with permeable walls [5] are identical in shape, and they differ quantitatively only. They are characterized by their own values of the structural content of the coefficients $a$. The structure of the coefficients $a$ in each work was determined by the individual characteristics of the problem being solved.

To summarize the experimental data and analyze the obtained results, it is more convenient to represent equation (4) in a dimensionless form [5]:

$$\bar{U}'' - a \cdot \bar{U} \cdot \bar{U}' - b \cdot \bar{U}^2 = 0,$$

if $\bar{U}(X) = \frac{U_{ave}}{U_{ave}} \cdot X = \frac{x}{l}$ is dimensionless average velocity and dimensionless coordinate;

$U_{ave}$ is average flow rate at the entrance to the channel;

$l$ is the length of the channel.

In this case, the values of the coefficients $a$ and $b$ are defined as

$$a = \text{Re} \cdot G_1 \cdot G_2^2 \cdot \frac{s}{\ln G_3}, \quad b = 4a \cdot \lambda_0 \cdot \frac{G_i}{s},$$

if $\text{Re} = \frac{U_{ave} \cdot D_{in}}{\mu}, \quad G_1 = \frac{l}{D_{in}}, \quad G_2 = \frac{k}{D_{in}}, \quad G_3 = \frac{D_{ex}}{D_{in}}$;

$D_{ex}, D_{in}$ are external and internal diameters of the channel;

$l$ is the length of the channel.

The general solution of this equation can be used to calculate the flow in any cylindrical channel, characterized by the eigenvalues of the coefficients $a$ and $b$.

In [5], analytical dependencies are proposed for determining the pressure distribution and flow rate of the suspension in a flow filter. However, the proposed model of the work of the flow filter does not take into account the influence of the conditions of conjugation of transit and filtration flows. This influence is an important factor in determining the hydrodynamic pattern of flow-through filtration. In addition, proposed analytical dependencies are applicable only in the conditions of the laminar mode of the transit flow and they do not take into account changes in the viscosity of the suspension along the filter channel.

3. Flow filter calculation

The following calculation of the flow filter design is proposed.

1. Calculation of material balance

Express the rate of flow of a fluid from the formula for calculating Reynolds:

$$\text{Re} = \frac{\vartheta \cdot D_{in} \cdot \rho}{\mu},$$

if $\mu$ is viscosity of the liquid, Pa·s; $D_{in}$ is internal diameter of the channel; $\rho$ is density of the liquid, kg/m³.

Initial consumption:

$$q_{in} = \frac{\pi \cdot D_{in}^2}{4} \cdot \vartheta,$$

if $\vartheta$ is fluid flow rate, m/s.

Final consumption:

$$q_f = 0.8 \cdot q_{in}.$$
The flow of the filtered liquid:

\[ q_{filtr} = q_{in} - q_f \tag{11} \]

2. Determination of pressure differential \( \Delta p \) and \( \vartheta^* \):

if \( l \) is the length of the channel, m; \( d \) is the diameter of the channel, mm.

If \( Re = 1200 \) and \( \lambda = 0.03 \) the expression is valid for smooth pipes on the Murin schedule.

\[ p_{in} = p_f + \Delta p \tag{12} \]

\[ \tau_w = \frac{\Delta p \cdot D_{in}}{4 \cdot l}, \tag{13} \]

if \( \tau_w \) is shear stresses, Pa.

\[ \vartheta^* = \sqrt[1/2]{\frac{\tau_w}{\rho c}} \tag{14} \]

3. Determination of sedimentation rate:

\[ \vartheta_h = \frac{d^2 \cdot (\rho_f - \rho_s) \cdot g}{18 \cdot \mu c}, \tag{15} \]

the following condition must be met: \( \vartheta_h / \vartheta^* < 0.2 \)

4. Determination of permeability, which provides a given degree of flow:

\[ \vartheta_{filtr} = \frac{k \cdot \Delta p_{filtr}}{\mu \cdot \delta} \tag{16} \]

if \( \delta \) is the wall thickness equal to 3 ÷ 5mm; \( \Delta p_{filtr} \) is hydraulic resistance of the partition; \( k \) is permeability of the filter septum.

The average diameter is:

\[ D_{ave} = \frac{D_{ex} - D_{in}}{2}, \tag{17} \]

if \( D_{in} \) is internal diameter, mm; \( D_{ex} \) is external diameter, mm

4. Determining the parameters of the filtering surface flow filter

The following calculation of the flow filter design is proposed.

We obtain conversion formulas that allow us to determine the permeability of the filter partition of the flow filter on the basis of model experiments. In this case, the distribution of the average velocity of the liquid flow along the flow in the flow filter will be close to its distribution model.

The problem of equivalence of a flow filter model is considered under the following conditions: the internal diameters and lengths of the channels of model and the flow filter are the same, the flow rates of the fluid supplied to the channels are the same, the model and the flow filter work at the same flow coefficient values. Under these conditions, the following factors, such as channel sizes initial flow rate and flow rate, did not affect the intensity of fluid withdrawal within a certain section of the model and a flow filter with length \( \Delta x \), within which the change in the velocity of the fluid flow and the pressure change along the channel can be neglected because of their smallness.

For the conditions under consideration, the intensity of fluid withdrawal within the channel section \( \Delta x \)
will be determined only by the peculiarities of the filtration flow through the thin-walled cylindrical filter partition, and for the model it will be determined by the regularities of the outflow of liquid from a single nozzle. And then the volumetric flow rate for a flow-through filter for the section $\Delta x$ will be determined as

$$q_{filtr} = \frac{k}{\mu} \frac{\Delta p_{filtr}}{\delta} \cdot \pi \cdot D_{in} \cdot \Delta x,$$

if $k$ is the permeability of the filtering partition; $\delta$ is thickness of the filtering partition; $\Delta p_{filtr}$ is hydraulic resistance of the partition; $D_{in}$ is internal diameter of the channel; $\rho$ is fluid viscosity.

For the following model:

$$q_{in} = \zeta \cdot f_{hole} \cdot \sqrt{\frac{\Delta p_{0}}{\rho \cdot g}} \cdot n \cdot \Delta x,$$

if $\zeta$ is the coefficient of fluid flow; $\Delta p_{0}$ is hydraulic resistance of baked liquid; $\rho$ is the density of the liquid; $n$ is the linear density of the nozzles.

The unknown parameters that enter into equation (19) are the values that form the complex $\frac{k \cdot \Delta p_{filtr}}{\delta}$. From the joint solution of equations (19) and (20) it follows that

$$\frac{k \cdot \Delta p_{filtr}}{\delta} = \zeta \cdot f_{hole} \cdot \sqrt{\frac{\Delta p_{0}}{\rho \cdot g}} \cdot \frac{n \cdot \mu}{\pi \cdot D_{in}}.$$

Only when the values of the complex $\frac{k \cdot \Delta p_{filtr}}{\delta}$ are constant along the entire flow, is it possible that the distribution of the average velocity of the fluid flow in the channels of flow filter and of the model completely coincides. If we specify the thickness of the filter partition $\delta$, then this coincidence will be possible if the constant flow in the flow filter of the complex, defined as constancy of the flow in the flow filter of the complex, defined as

$$k \cdot \Delta p_{filtr} = \zeta \cdot f_{hole} \cdot \sqrt{\frac{\Delta p_{0}}{\rho \cdot g}} \cdot \frac{n \cdot \mu}{\pi \cdot D_{in}}.$$

It is necessary to take into account the value of hydraulic resistance $\Delta p_{filtr}$, because the coefficient of linear losses in the model differs from that one for the flow filter, and the linear loss of pressure in the flow filter will be higher than in the model. For calculations of the first approximation for relatively short channels and small values of the coefficient of linear loss, assuming the equality of the distribution along the flow of intra-channel pressure in the flow filter and the model, we get

$$k = \zeta \cdot f_{hole} \cdot \sqrt{\frac{1}{\rho \cdot g \cdot \Delta p}} \cdot \frac{n \cdot \mu \cdot \delta}{\pi \cdot D_{in}},$$

if $\Delta p_{0}$ is hydraulic resistance equal to outflow of liquid from nozzles and filtration.

5. Experimental part

A series of experiments was carried out to assess the performance of the model channel at different initial flow rates of the fluid supplied to the channel. In the model channel there were 15 nozzles, uniformly distributed along the channel, to take water from the channel. The channel porosity in this case was $\zeta_f = 0.001$. The number of control points was 5. They were used to construct graphical dependences of the change in the rate of water flow along the channel. The coordinates of the sections for which the flow rates
of the fluid were determined, as well as the sections of the nozzles for which the flow of the fluid flowing out of the channels was determined, were assigned according to shown in Figure 2.

![Figure 2. A schematic diagram of the flow-through filter](image)

1 is distance from the beginning of the fluid supply to the control point; 2 is number of sections; 3 is the number of perforated holes

Experiments for three different initial water consumption were conducted. The values of the parameters which characterized the conditions of the experiments are presented in table 1.

| No of experiment | $q_{in}, q_{f}, \text{sm}^3/\text{s}$ | $U_{in}, \text{m/s}$ | φ | Coordinates of control points (cross sections $x_i, \text{mm}$) | Additional information |
|------------------|-------------------------------|----------------|---|-------------------|-----------------------|
|                  | $q_i, \text{sm}^3/\text{s}$   | $U_i, \text{m/s}$ | $\xi_f$ | $Re_{in}$ | $\beta_i$ | $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ |
| 1                | 11.5 9.0 0.0547 0.77         | 0.0605 0.0586 0.0508 0.0530 0.0508 | 0.91 0.088 0.763 0.795 0.763 | 1.12 1.07 0.93 0.965 0.93 |
|                  |                              | 0.158 0.139 0.127 0.119 0.113 | 0.825 0.77 0.705 0.66 0.628 | 1.17 1.03 0.94 0.88 0.84 |
| 2                | 63.7 35 0.245 0.556          | 0.310 0.275 0.241 0.218 0.197 | 0.86 0.765 0.67 0.607 0.546 | 1.27 1.13 0.99 0.89 0.805 |
| 3                |                              | 0.158 0.139 0.127 0.119 0.113 | 0.825 0.77 0.705 0.66 0.628 | 1.17 1.03 0.94 0.88 0.84 |

Figure 3 shows the graphical dependences of the distribution of the average velocity of the flow of fluid in a model channel with permeability $\xi = 0.001$. The dependences were obtained for three different flow rates. They are smoothly varying curves; the shapes of them are determined by the value of the initial rate of the flow of fluid and the amount of its withdrawal from the channel.
Figure 3. The distribution of the average rate of flow of fluid in the channel at different values of the initial flow of fluid along the length of the channel

1 is experiment No. 1; 2 is experiment No. 2; 3 is experience No. 3

An important characteristic of the running flow filter is the flow coefficient $\phi$, determined by the ratio of flow rates of fluid at the inlet and outlet of the channel. Figure 4 shows the graphical dependences obtained on the model channel. They show the influence of the flow coefficient on the distribution of the dimensionless average velocity in the channel, regardless of the initial flow rate. Graphic dependences are outgoing from one point, smoothly changed curves; the degree of curvature of them decreases with increasing of flow coefficient.

Figure 4. The distribution of the dimensionless average rate of flow of fluid in the channel

1 is experiment No. 1; 2 is experiment No. 2; 3 is experience No. 3

One of the hydraulic characteristics of the flow filter is the uneven distribution of the average flow rate of fluid in the channel. If the other conditions are equal, the hydraulic uneven distribution of the average flow velocity in the channel depends on the flow ratio. It is clearly represented in the form of graphical dependencies of the ratio of local and average speed along the stream. This dependence for the model
channel when it is working in the range of the flow ratio within $\phi = 0.6 \div 0.8$ is presented in Figure 5.

![Figure 5](image_url)

**Figure 5.** Graphic dependence of the ratio of local and average velocity along the stream

1 is experiment No. 1; 2 is experiment No. 2; 3 is experience No. 3

6. Results and discussion

Graphic dependences of the change in the average flow velocity as a function of the initial flow rate and the flow coefficient were obtained in experiments on the model channel and considered in the paper. They are similar to the data obtained for filtering the selection of liquid from flow channels and given in [5-7] in their shape and nature of mutual position when the initial performance and flow ratio are varied. So these dependences in both cases can be described by the same form of mathematical dependencies, differing only in the set of constants included in them. This allows us to use the proposed simulation technique for studying the hydrodynamics of flow filters. A model of flow of a fluid with a variable mass in the channel, whose mathematical model in the general case is the equation

$$\frac{U^2}{2} - a \cdot U \cdot U' - b \cdot U'^2 = 0,$$

can be used for analytical research of the distribution of pressure, flow rate and hydraulic irregularity along the channel of flow filter.

7. Conclusions

It is necessary to develop a low-cost, time-consuming, and material-consuming methodology for pre-project experimental studies to assess the qualitative influence of structural elements and performance parameters on the efficiency of operation of flow filter. It allows developing of new high-performance designs of flow filter.

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