ISSN: 0975-8585

Research Journal of Pharmaceutical, Biological and Chemical Sciences

Preliminary Purification of Suspension-Carrying Liquids by Cross-Flow Filtration.

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ABSTRACT

This paper is devoted to the study of possibility of using cross-flow (dynamic) filtration that takes place on a flat filtering surface depending on hydrodynamic conditions in a filter (velocity of oncoming flow, filtration rate), properties of a dispersion medium, sizes and density of the particles to be removed. It has been found out by the calculation-analytical method that this technique has a limitation in terms of minimal size of the particles, which are thrown back to the flow without clogging the filtering surface. For the studied specific suspensions this size depended on a cross-flow velocity on a filtering surface and a normal rate of filtration (suction). The minimal size of the particles being thrown back to the flow at the actually achievable rates of cross-flow filtration is about 50 µm at the rate of oncoming flow of about 5 m/sec. As the normal rate of filtration rises, the minimal size of the particles that are thrown back increases. Taking into account properties of uranium-containing solutions it seems perspective to use this method as a preliminary phase of purification from suspended impurities of various origin.

Keywords: uranium-containing solution, purification, cross-flow filtration, suspension, self-cleaning filter, dispersion.

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INTRODUCTION

When liquids are purified mechanically the application of traditional frontal filtration (when total flow being purified is perpendicular to filtering surface) is not the optimal technical approach because holes of a filtering surface can be clogged with particles rather quickly, and, as a result, it becomes necessary to regenerate the filtering element frequently and/or to replace the spent filtering element with a new one. Hence, the filter's service life and its capacity to retain suspended impurities are limited.

In particular, the said problem arises in case of bore-hole recovery of uranium at a section for reprocessing uranium-containing pregnant solutions. The present technology provides pumping these solutions out of operational units (by air lifts, submersible pumps) to a sand trap. A liquid is clarified in the trap, and suspended particulates – sludge and sand – are removed. However, the sedimentation phase is long (~ 2-3 days), and it rises costs of the whole uranium recovery process.

At the next phase of bore-hole recovery of uranium – a phase of desorption (or regeneration) of ion-exchange resin – bag-type filters are currently used for the purification of washing solutions. Due to high dispersion and an increased concentration of suspensions in the solutions bag-type filters are clogged with impurities rather quickly; it results in the necessity to wash them frequently, to replace them, and corresponding hand work is required [1].

Each of the abovementioned purification phases has its own specific features that are determined, first of all, by concentrations and sizes of impurity particles being trapped. Thus, due to the actual problem that had arisen at the phase of acidification of operational units, it became necessary to find an alternative approach which would base on the application of non-regenerative separation purification of solutions with solid suspended particulates (particle size - $d \geq 50$ μm) instead of preliminary sedimentation. It will be demonstrated during complex research of the said problem that cross-flow (dynamic) filtration can be successfully applied for solving it [5].

A classic version of cross-flow (dynamic) filtration

In case of cross-flow of a dispersion medium, that is being purified, along a filtering surface under the conditions when a laminar sub-layer appears at the "wall-liquid" boundary the surface can be cleaned from relatively large suspended particles. Indeed, the flow rate at the wall is equal to zero but it rises drastically at an insignificant distance from it, and this rise provides that those particles, which size is commensurable with the laminar sub-layer's thickness, can be driven away back to the flow, see Figure 1.

In case of the classic cross-flow method of purification (Figure 2) the total flow being filtered goes from the pump by the input loop and enters first a sedimentation tank. An independent loop is formed using another pump that creates cross-flow along the whole length of filtering element of the filter (a steel grid or a grid made of another fine mesh material). In this case necessary conditions are created due to pressure difference on the filter membrane for implementing the normal toward the surface component of the flow rate (filtration rate).

The basic diagram of the filtration of this type is given in Figures 1 and 2 [8]. A filtrate is obtained as a result of passing through the filter membrane, and this filtrate is a final product of the process. Due to the operation of an additional pump in the mode of continuing recirculation the contaminated part of the flow goes first to a sedimentation tank in which suspension is concentrated, i.e. a sediment forms, and then it returns to the input of the purification unit (Figure 2). This approach creates good conditions for providing tangential direction of the flow along the whole length of the filtering element. However, the filtration procedure is rather complicated in this case because additional equipment (a tank, a pump, fittings, pipelines, etc.) of the recirculation system must be used, and it is unacceptable sometimes by technical and economic reasons [3].

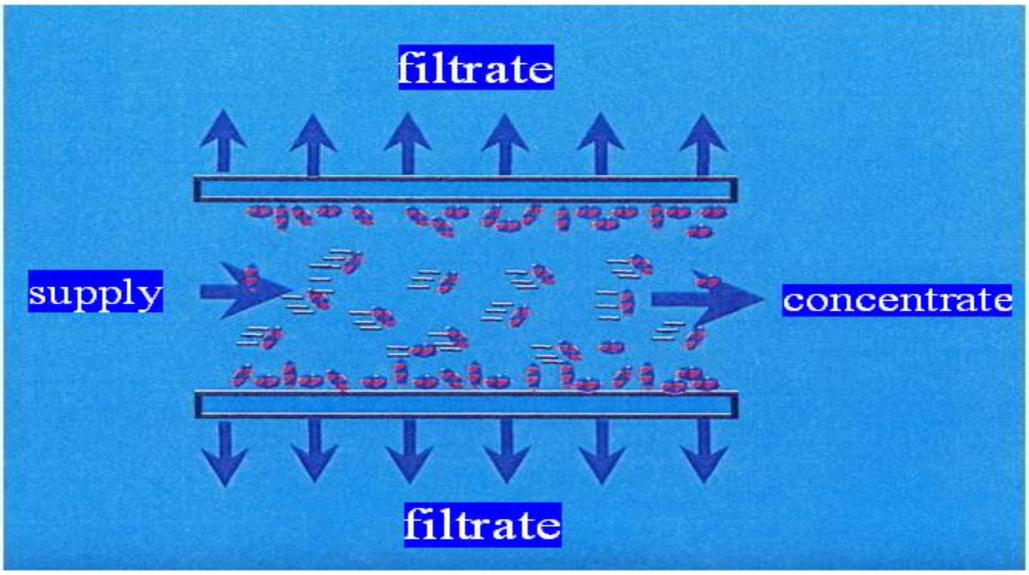

Figure 1: A basic diagram of cross-flow filtration

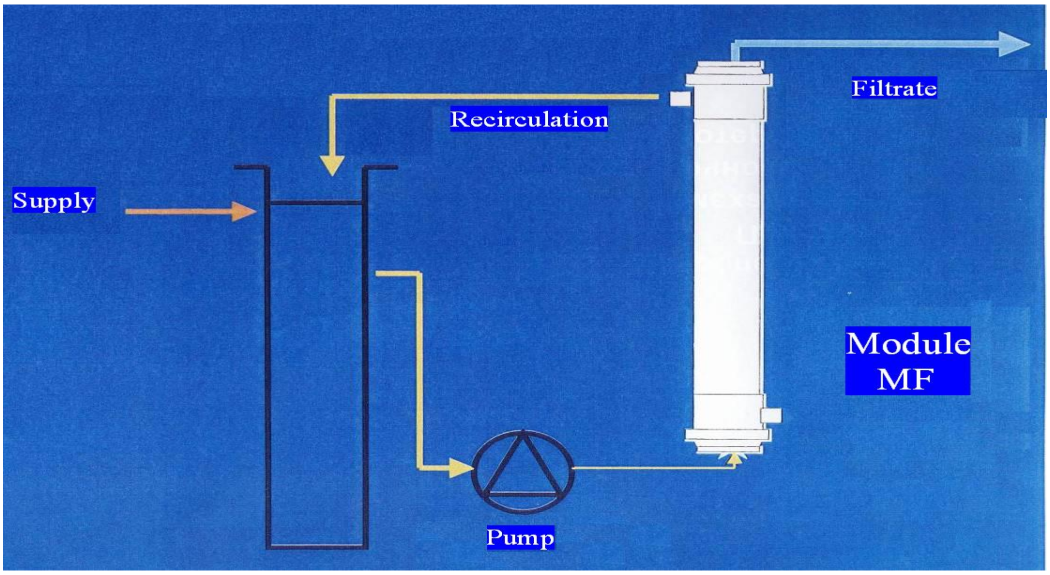

Figure 2: Main components of the equipment for classic cross-flow filtration

An alternative version of cross-flow filtration

A less expensive one-loop version of cross-flow filtration (just one pump works) has been proposed instead of the above described basic two-loop design of cross-flow filtration. This version is implemented as a partial tangential flow at a filtering surface that is mostly created at the input section of the flow of a liquid and is shaped this way or another. Thus, in case of vertical direction of the flow in relation to the filtering surface a special sprinkler can be installed on this surface, which is oriented to the flow center, Figure 3.

In the given design the impurities are thrown away by the flow to peripheral sections of the filter and retained in dead-end recesses; at the same time the stagnated liquid partially flows back to the filter's central zone followed by its filtration in the normal mode.

Other designs for the implementation of one-loop cross-flow filtration are also possible. And a ratio between the flows of a liquid being purified that are tangential and normal toward the surface depends on specific hydrodynamic conditions of the flow inside the apparatus. They include channel geometry, a velocity of the oncoming flow and its initial orientation relative to the filtering surface (vertical, horizontal, angle-wise), pressure of a liquid being purified, filtering membrane properties (porosity, mesh size).

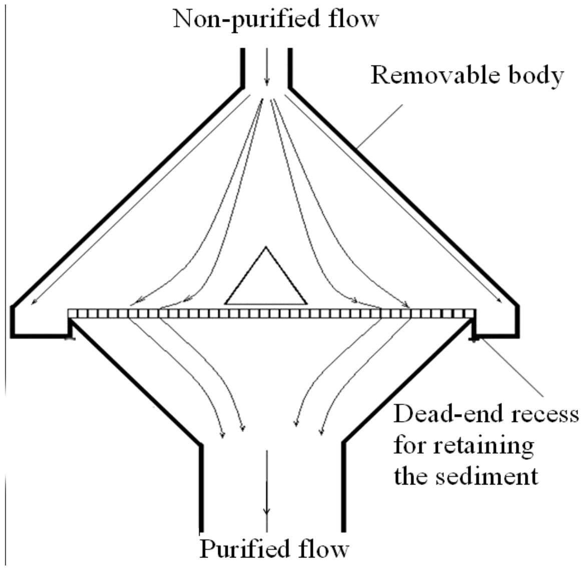

Figure 3: A cross-flow filter with a peripheral recess for retaining suspended impurities

Mathematical solution of the task

For any design of cross-flow filtration an important component of substantiation of its efficiency is mathematical solution of the task of how a particle of a specific size behaves nearby the filtering surface. When solving this task all forces that influence the particle are taken into account and hydrodynamic conditions are determined under which the particle is not retained on the wall but is thrown back to the flow.

Numerical methods of solving hydrodynamic tasks for the calculation of liquid or gas flows in structural elements of various apparatuses are now continued to be successfully developed. Solutions on the interaction of solid particles with a liquid (gas) and a wall (filtering element) in the course of particles motion along the surface have been developed in a number of studies [4], [11].

In this study we used the codes [7] developed at SSC RF – IPPE and their modifications as applied to the task to solve, namely: determination of carry-over of particles as a factor of the assumed specific values of the parameters (particle diameter and density, liquid density, suction velocity and flow rate through the filtering membrane).

The diagram of the apparatus shown in Figure 3 was used for calculating a trajectory of a particle motion. The flow to be purified with suspended particles goes top down through the input nozzle to a dish-type cross-flow filter, which consists of a filtering membrane with small holes for passing liquids through and a dead-end recess for retaining (concentrating) the particles that have been thrown back by the flow.

The numerical solution of full Navier-Stokes equations describing a liquid flow in structural units requires significant computational costs. Therefore different approaches to the computation of a velocity field were developed with different degrees of assumptions and simplifications. The liquid motion was simulated numerically for solving the task of liquid flow in the immediate proximity to the surface in the laminar sub-layer. For simplicity, a horizontal motion of the flow was considered; it is shown in Figure 4 and is described by the equations:

The equation of continuity:

$$\frac{du}{dx} + \frac{d\upsilon}{dy} = 0 \qquad (1)$$

The Navier-Stokes equation:

$$u\frac{du}{dx}+v\frac{du}{dy}=-\frac{1}{\rho}\frac{dp}{dx}+v(\frac{d^2u}{dx^2}+\frac{d^2u}{dy^2}) \quad ,$$

$$u\frac{d\upsilon}{dx}+v\frac{d\upsilon}{dy}=-\frac{1}{\rho}\frac{dp}{dy}+v(\frac{d^2\upsilon}{dx^2}+\frac{d^2\upsilon}{dy^2}) \ , \qquad (2)$$

where u, υ - horizontal and vertical components of velocity, respectively;
ρ - medium density;
p - medium pressure;
ν - medium kinematic viscosity.

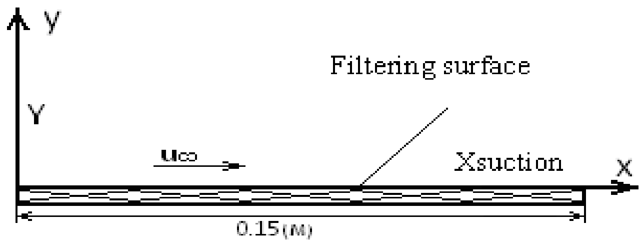

Figure 4: A diagram, which explains the boundary conditions in the formula (1)

The boundary conditions:

$u=u_\infty$, $\frac{d\nu}{dy}=0$ when x = 0, 0 < y < Y,

where Y- height of the laminar sub-layer;

u_∞ - horizontal component of velocity, far from the laminar sub-layer;

$u=0, \upsilon=\upsilon_0(y)$ when $y=0,\ 0<x<X$, where

$X_{suction}$ – horizontal coordinate (length) of the filtering element through which a liquid is filtrated (sucked off);

υ_0 - flow vertical velocity at the boundary (suction rate);

$$\upsilon_0(y)=\begin{cases}\upsilon_0 \text{ when } x<X_{suction}\\ 0 \text{ when } x>X_{suction}\end{cases} \qquad (3)$$

$\frac{du}{dx}=\frac{d\upsilon}{dx}$ – when $x=X$, $0\le y\le Y$ – a condition for stabilization.

“SUCT” code [10] was applied for solving the key task of determination of the velocity field using the formulae (1)-(3). This code is based on monotone balance difference scheme. The incomplete factorization method was applied for solving the finite-difference simultaneous equations. For describing the boundary layer in more detail the calculations were done for the non-uniform mesh that thickens closer to the filtering surface. The results that have been obtained for different υ_0/u_∞ ratios showed that for $x<X_{suction}$ values the velocity was described well by the ratio related to plate longitudinal flow-over with the uniformly distributed suction (or filtration rate) [6]:

$$u(y)=u_\infty\left(1-e^{\upsilon_0 y/\nu}\right) \qquad (4)$$

And in this case the value of $\upsilon(y)=\upsilon_0$ is always negative.

If we assume that the boundary layer thickness is equal to y* value, on which $u(y^*)=0.99u_\infty$, then the boundary layer thickness is determined by the ratio:

$$y^* = \delta = \mu \frac{\ln 0.01}{\rho \upsilon_0}, \tag{5}$$

where μ- dynamic viscosity.

It follows from the formula (5) that the boundary layer thickness reduces as the suction rate rises.

One should expect that the abovementioned approach to the determination of the velocity field describes well enough a particle behavior in the immediate proximity to the place where it enters in the filtering surface.

A physical model and a problem statement given in [12] were used for calculating motion paths of particles after they have entered in the filtering surface. The motion of particles, which size was less than or comparable to that of the laminar sub-layer, was analyzed. The essence of this model is as follows: following the particle's entry in the filtering surface, provided that the pore size is less than or comparable to the particle size, the particle starts to move along the surface in the laminar sub-layer area in the so-called "dragging" mode, i.e. at certain moments it can "catch" on asperities, and its velocity decreases almost to zero. If we consider the forces that influence the particle immediately after it has torn off one of the obstacles, they are similar to the forces that were taken into account when the first task was solved. It should be mentioned however that in this case the transverse lift force (Magnus, Saffman, Zhukovsky's force) starts to play the noticeable role because at the moment of tearing off an obstacle this force can be considerable due to large difference between velocities of the gradient liquid flow, which flows over the particle from the wall side and from the external side far away from the wall [8].

Figure 5 explains this effect. At the moment when a particle stops at one of the obstacles the flow-over velocity is $u_1 > u_2$ because u_2 on the wall is about zero. It causes a considerable pressure gradient and, correspondingly, the transverse lift force directed from the wall. This force becomes equal to zero when the particle moves away from the wall and escapes the laminar sub-layer. The ability of the particle of a certain size and weight and in case of certain thicknesses of the laminar-sub-layer to escape from it depends on a ratio of the main forces that influence the particle. Of course, this reasoning is correct for that particle only, which size is less than or comparable to the laminar sub-layer thickness. Its value and the velocity gradient in it at each point of the filtering surface are found by solving the liquid flow equation.

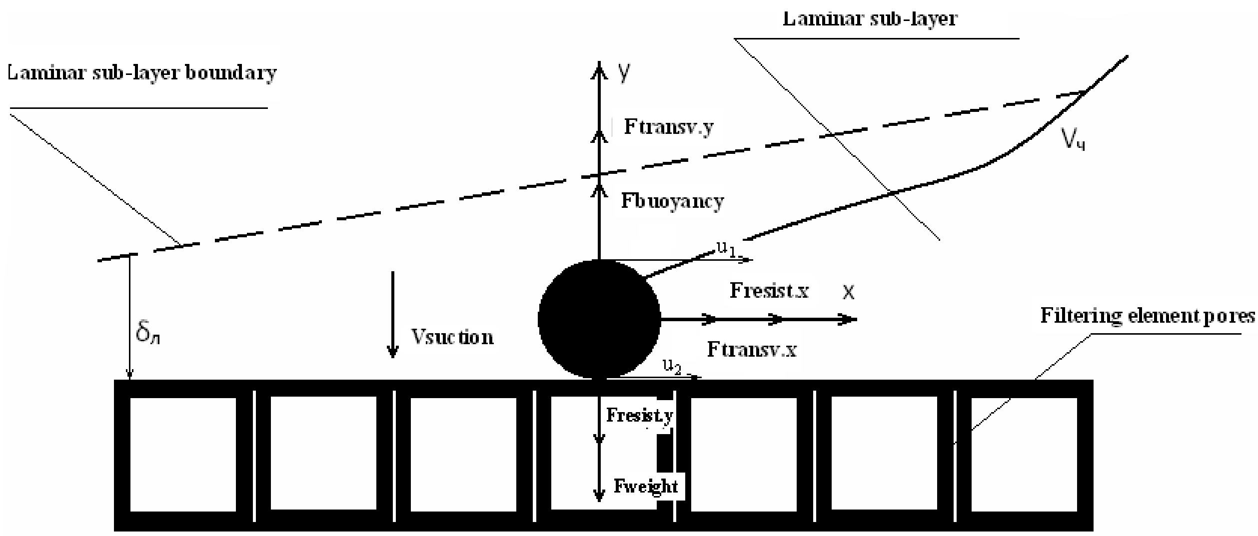

Figure 5: The forces influencing an impurity particle near the filtering surface

The simultaneous equations of particles motion in the laminar sub-layer in the Cartesian coordinate system have the following form:

$$\rho_ч \frac{4}{3}\pi \frac{d_ч^3}{8}\frac{d^2x}{dt^2} = \frac{\pi^2}{2}\frac{d_ч^3}{8}\rho_{ж}\frac{d\upsilon_{xж}}{dy}\left(\frac{dy}{dt}-\upsilon_{yж}\right)-\pi\mu_{ж}\frac{d_ч}{2}\left(\frac{dx}{dt}-\upsilon_{xж}\right), \quad (6)$$

$$\rho_ч \frac{4}{3}\pi \frac{d_ч^3}{8}\frac{d^2y}{dt^2} = -\frac{\pi^2}{2}\frac{d_ч^3}{8}\rho_{ж}\frac{d\upsilon_{xж}}{dy}\left(\frac{dx}{dt}-\upsilon_{xж}\right)-6\pi\mu_{ж}\frac{d_ч}{2}\left(\frac{dy}{dt}-\upsilon_{yж}\right)-\left(\rho_ч-\rho_{ж}\right)\frac{4}{3}\frac{\pi d_ч^3}{8}g, \quad (7)$$

where dx/dt, dy/dt – a liquid low rate along the axes, respectively; X axis is directed lengthwise and Y axis – crosswise the particle motion. The positive direction is from the wall into the flow.

The procedure of solving these simultaneous equations is not described here. It should just be mentioned that the task has a numerical solution as well as an analytical one. Particle motion paths within the laminar sub-layer have become the results of solving these simultaneous equations. And depending on geometrical and mode parameters of the flow and particles, the particle behavior can be divided into two categories, which differ in essence. It is either motion after tearing off the surface and escape, or jumping motion within the sub-layer with return to the surface.

The main parameter causing various paths of the particles is their diameter. The described particle behavior enables one to make quantitative assessment of a portion of the particles that escape from the total flow if we assume that it is highly probable that the particles with jumping paths, after they have been caught on an obstacle, are retained on the filtering surface and go through it. The particles with the tendency to escape from the sub-layer will most probably be carried away into the flow[2].

A large portion of small particles (less than 10 μm) almost exactly follows the liquid flow line, and they are either carried away by the flow without having reached the filtering surface or move along the liquid flow line as a result of liquid suction through the filtering surface. In the case under consideration when specific weights of the carrying medium and particles do not differ drastically, the flow hydrodynamics for such particles coincides with hydrodynamics of the carrying medium.

In this case the suction rate is determined by a pressure drop on the filtering surface and by geometrical parameters of the filter.

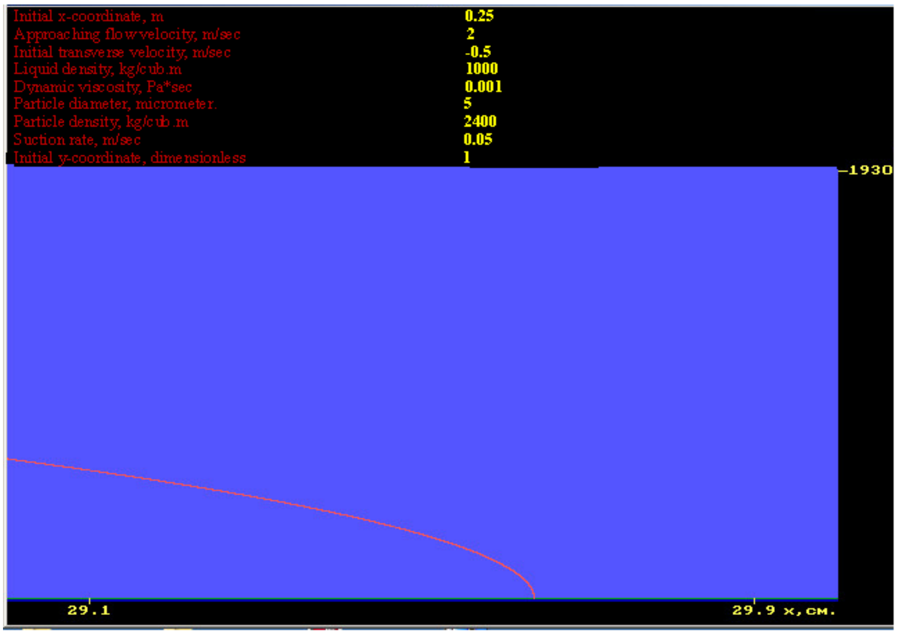

Figure 6: An example of motion of small particles in the laminar sub-layer

Figure 6 shows an example of the calculation of a motion path of a particle of 5 μm in diameter, which is at the boundary of the laminar sub-layer at the initial moment and gets the transverse velocity of 0.5 m/sec in the direction to the wall (for example, as a result of the liquid turbulent pulsing). The suction rate in this case is 0.05 m/sec. The particle enters into the filtering surface in about 5 cm of its length. Figure 6 shows that the effect of cross-flow filtration does not affect the particles of ~5 μm in size at the velocity of the oncoming flow of ~2 m/sec and the suction rate of 0.05 m/sec (the particle "falls" on the surface).

Figure 7 shows an example of the calculation of a motion path of a larger particle (70 μm in diameter), which is at the boundary of the laminar sub-layer at the initial moment and gets the transverse velocity of 1.8 m/sec in the direction to the wall (for example, as a result of the liquid turbulent pulsing). The suction rate in this case is 0.1 m/sec. It follows from the Figure that the particle enters into the filtering surface in about 1 cm [13].

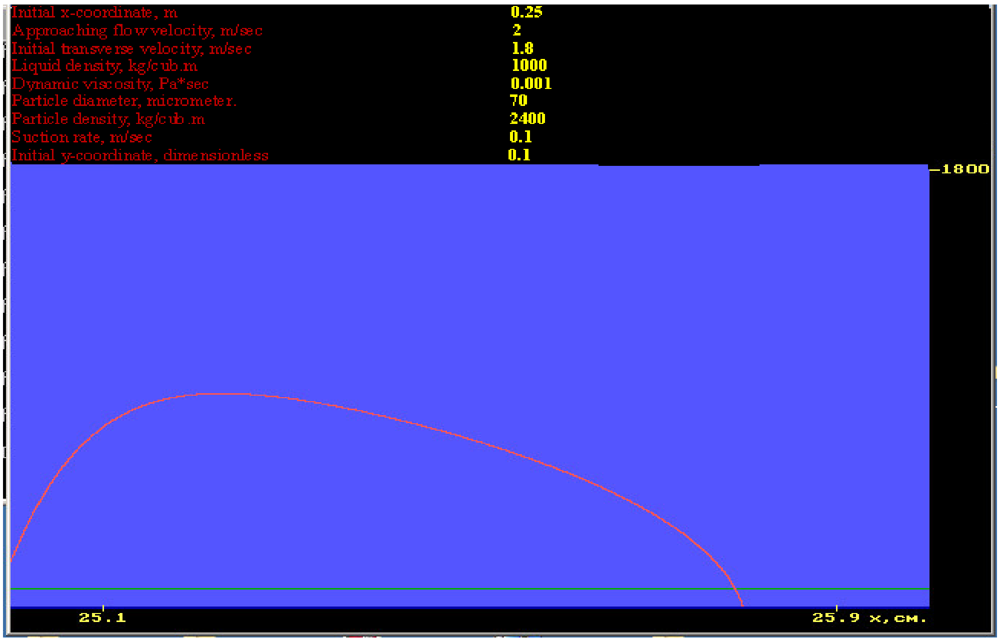

Figure 7: An example of motion of a large particle after it has torn off an obstacle provided that the suction is available

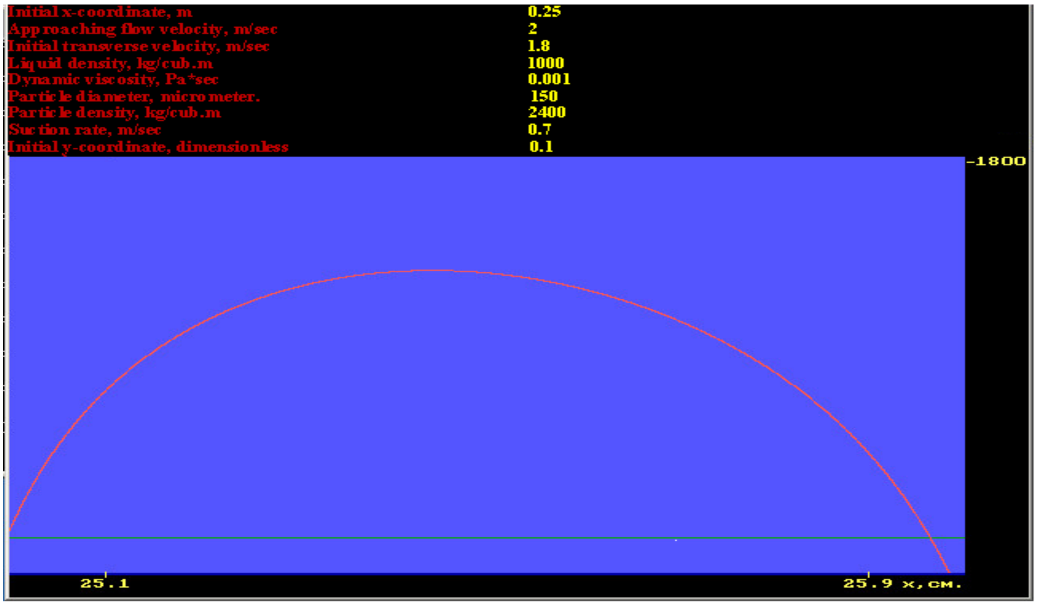

Figure 8: An example of motion of large particles (150 μm) at a considerable filtration rate (0.7 m/sec)

Figure 8 shows an example of the calculation of a motion path of a particle of 150 μm in diameter, which is at the boundary of the laminar sub-layer at the initial moment and gets the transverse velocity of 1.8 m/sec in the direction to the wall (for example, as a result of the liquid turbulent pulsing). The suction rate in this case is 0.7 m/sec. It follows from the Figure that the particle enters into the filtering surface in about 1 cm.

Figures 9 and 10 show the results of the studied mathematical simulation of filtration in case of the tangential (film) flow of a liquid – a boundary size of the particles that are thrown back from the laminar sub-layer as a factor of the oncoming flow velocity and filtration rates at different densities of particles.

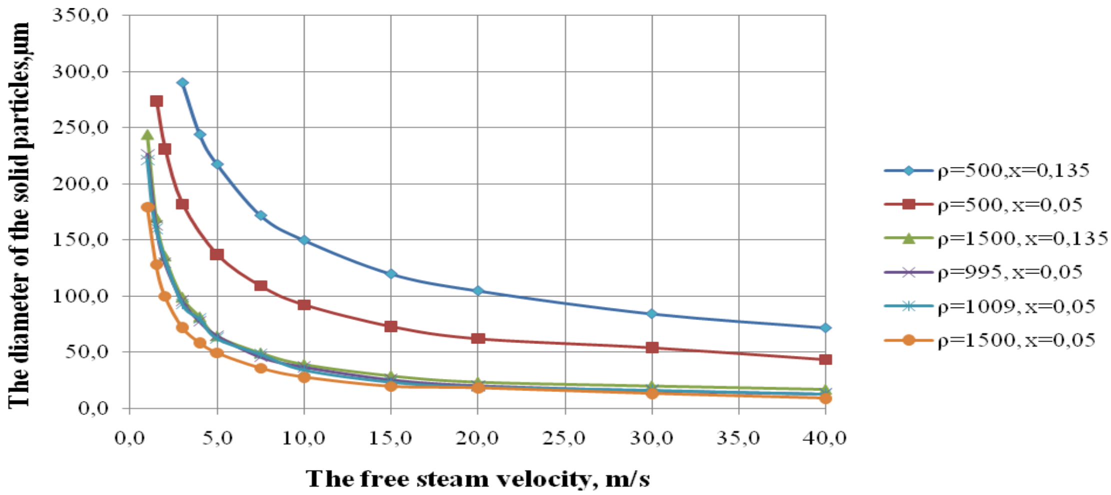

Figure 9: The calculation of a boundary size of the particles that are thrown back from the laminar sub-layer as a factor of the oncoming flow velocity at different densities of particles

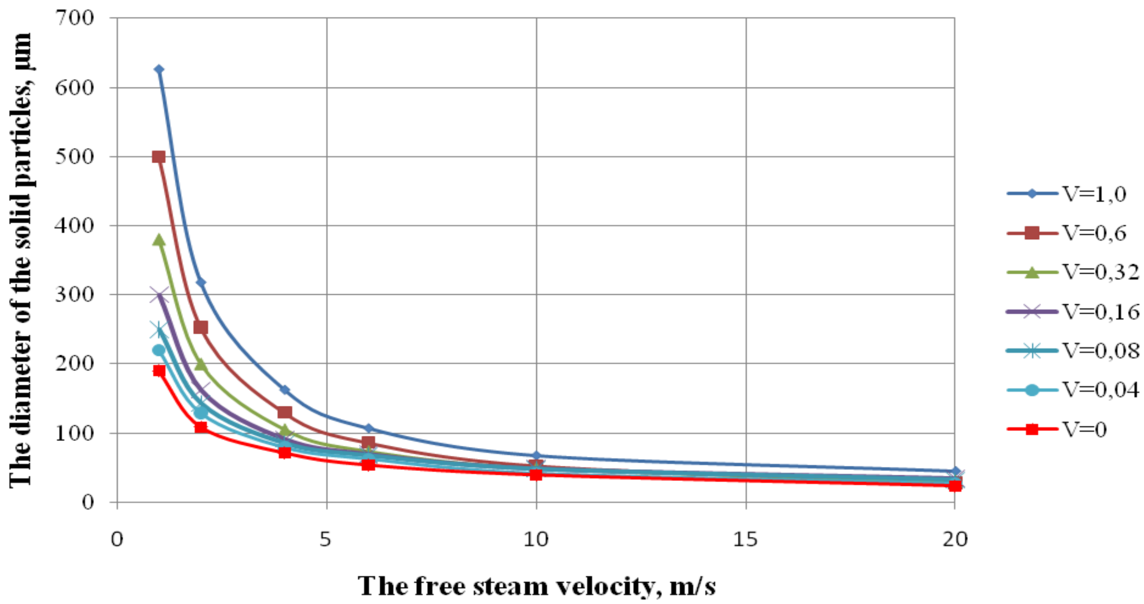

Figure 10: The calculation of a boundary size of the particles that are thrown back from the laminar sub-layer as a factor of the oncoming flow velocity at different filtration rates

As it follows from the Figures above the size of the particles that are thrown back to the flow decreases significantly as the velocity of the oncoming flow rises. And a degree of this decrease depends on a density of the particles and a rate of suction (filtration): as density decreases a lower velocity of the oncoming flow is required for the particles of the same size to be thrown away from the boundaries of the laminar sub-layer. The similar result is obtained in case of a lower rate of suction (filtration).

A corresponding hydrodynamic mode in the system is essential for organizing the filtration process with tangential direction of the flow. The arrangement of this mode also depends on parameters of the pumping equipment applied.

Possible versions of the arrangement of the filtration process are shown in Figures 11 and 12. A low flow rate and a high trans-membrane differential pressure almost result in the frontal mode of filtration. On the other hand, a high flow rate and a low trans-membrane differential pressure do not provide the required filtration rate.

In practice, the pumping equipment applied for microfiltration must provide tangential linear rate of the flow (above the filtering surface) of more than 1.5 m/sec and pressure within the limits of 0.1-0.2 MPa [9], for ultrafiltration – the flow linear rate of more than 1.5 m/sec and pressure up to 0.5 MPa [9].

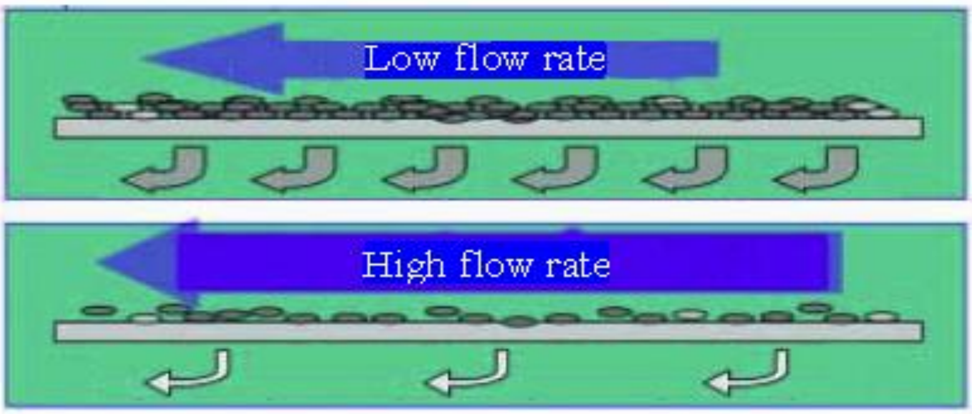

Figure 11: The effect of flow rate

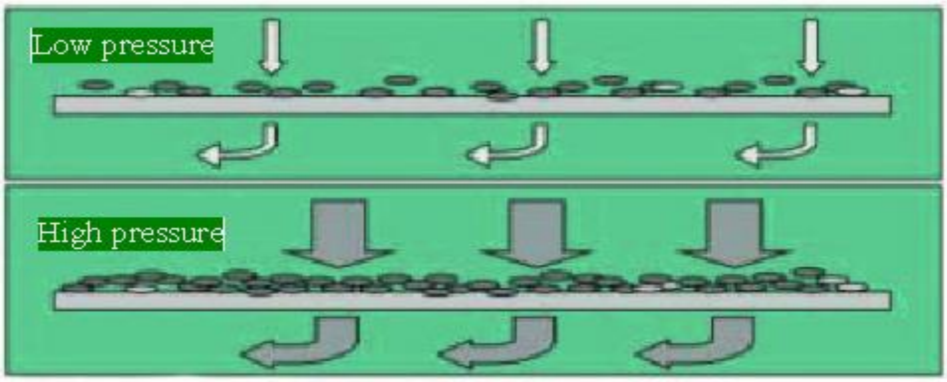

Figure 12: The effect of trans-membrane differential pressure

These recommendations must be taken in account when developing a preliminary purification system with tangential direction of the flow.

One may conclude from the above given results of the calculation of cross-flow filtration that the efficiency of purification of suspension-carrying flows by this method depends, in general, on a size and density of the particles to be retained, properties of a liquid being filtered (viscosity), and hydrodynamic conditions (velocity of the oncoming flow of a liquid to be purified, filtration rate) [15]. It has been found reasonable to apply the cross-flow filtration method for removing coarsely dispersed fractions of suspended particles (d≥70 μm), and the filtration rate in this case must not exceed ~0.1 m/sec.

Taking the above mentioned into account the pumping equipment must provide the optimal conditions for the creation of a necessary tangential flow along the filtering surface with the view of carrying the particles away as well as a required rate of filtration – the parameters, which, in a sense, contradict one another. The approximate values of these parameters are as follows: the flow liner rate above the filtering surface is more than 1.5 m/sec; pressure is 0.1-0.2 MPa. It is reasonable to apply the cross-flow filtration method for the purification of uranium-containing solutions at the phases of preliminary as well as fine purification of solutions from suspensions[14].

CONCLUSIONS

The following can be concluded from the abovementioned calculations of cross-flow filtration:

- Small particles of less than 10 μm in diameter are almost not prone to "hydrodynamic filtration" and move along flow lines of the carrying medium.
- The motion of large particles of more than 50 μm in diameter complies with the abovementioned patterns. In this case the filtration efficiency depends on a particle size and a rate of the suction achieved.
- The developed code makes it possible to determine trends in geometrical dimensions of the filter, medium motion velocity (oncoming flow velocity), and suction rate (filtration rate).
- When developing a filtration system with cross-flow it is necessary to take into account pumping equipment specifications. They must provide the optimal conditions for creating a cross-flow along the filtering surface for carrying the particles away and, at the same time, a required filtration rate, which, in a sense, contradict one another. The approximate values of these parameters are as follows: the flow linear rate above the filtering surface is more than 1.5 m/sec; pressure is 0.1-0.2 MPa.
- It is reasonable to apply the cross-flow filtration method for the purification of uranium-containing solutions at the phases of preliminary as well as fine purification of solutions from suspensions.

Acknowledgment

The research was done in the framework of the Contract No.14.625.21.0001 of 21.08.2014 signed by and between Ministry of Education and Science of the Russian Federation and JSC ñSSC RF ï IPPEò(unique identifier - RFMEFI62514X0001).

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