Vacuum filtration on a thin vertical filtering baffle

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Abstract. The article considers the design issue of vacuum filtering apparatuses from the point of view of minimizing filtering costs, provided that the maximum performance of vacuum filtration apparatuses is ensured. In the paper, the Darcy equation was considered. Based on it, the equations of filtration apparatus productivity were determined by filtrate and by dry sediment. It was determined that the maximum productivity of both filtrate and dry sludge in vacuum filtration apparatuses is observed with a maximum difference in free surfaces on the vertical filter baffle.

1. Introduction
Various devices and mechanisms are used to compact and dehydrate sludge in the practice of water treatment. Some devices work by using the force of gravity (devices with bag filter elements [1]). More devices create pressure higher (for example, filter presses) or lower (for example, vacuum filters) than atmospheric pressure, increasing the productivity of the apparatus [2].

Analysis of scientific literature has shown that despite the variety of applied designs of vacuum filters with different geometric shapes and sizes of filter surfaces, there are no recommendations regulating the calculation of a vacuum filtration installation with vertical filtering baffles.

For example, work [3] considers the process of vacuum filtration and the choice of the optimal filtering surface, taking into account the capital costs of filtering equipment. But when determining the volume of the filtrate for one minute, it was not taken into account that in the process of filtration, the filtration rate (and hence the volume of the filtrate per unit area) does not change linearly, but rather according to the logarithmic dependence [4].

2. Materials and methods
The mathematical description of the filtration process through a horizontal baffle is known [5]. Simulation of the operation of technological equipment is performed according to well-known methods [2, 6]. Consider the process of vacuum filtration through a vertical baffle, the hydrostatic pressure on which increases from top to bottom (Figure 1), while it is different on the free surfaces of the liquid on different sides of the filter baffle. Theoretical and experimental studies of the filtration process made it possible to derive some filtration equations for vertical filter surfaces [7] operating at pressures above atmospheric pressure.

A mathematical model of vacuum filtration of incompressible sediment is considered. The following assumptions are applied:
the initial suspension does not stratify;
- sediment does not slide along the partition;
- the process takes place at constant pressures $P_1$ and $P_2$;
- the resistance of the filtration baffle is low compared to the resistance of the sediment;
- a flat rectangular vertical filtering baffle is considered (Figure 1).

\[ F \Delta P \mu \rho = \frac{dV}{dt} V \frac{F}{F} \]

where $V$ – filtrate volume, m$^3$;
$F$ – filtration surface, m$^2$;
$t$ – filtration duration, s;
$\Delta P$ – pressure difference across the filtering partition, Pa;
$\mu$ – viscosity of the filtrate, Pa s;
$\rho$ – density of the filtrate, kg/m$^3$;
$\rho_0$ – volume resistivity of the sediment, m/kg;
$x_0$ – proportionality factor in the equation
$h_{oc} = x_0 \cdot \frac{V}{F}$,
where $h_{oc}$ is the thickness of the sediment layer on the filtering partition, m.

Filtration constants $\rho_0$ and $x_0$ should be determined experimentally for specific sediment by laboratory experiments [8].

By integrating equation (1) in the range from 0 to $V$ and from 0 to $t$, as well as performing transformations, we obtain dependence for determining the volume of the resulting filtrate (5):

\[ V dV = [\Delta PF / (\rho_0 x_0)] dt \]  
\[ \int_0^V V dV = \int_0^t \frac{\Delta PF}{\rho_0 x_0} dt \]
\[
\frac{V^2}{2} = \frac{\Delta P F^2}{\mu r_0 x_0} t 
\] (4)

\[
V = \sqrt{\frac{2 \Delta P F^2}{\mu r_0 x_0} t} 
\] (5)

The value of pressure \(\Delta P\) under the influence of which filtration is carried out is the total value of the hydrostatic pressure \(\rho gh\) and the pressure difference \(\Delta p\) on both sides of the filtering baffle on the free surfaces of the liquid, i.e. \(\Delta P = 0.5 \rho gh + \Delta p\).

For an infinitesimal increase in the area \(df\) of the filtering baffle, the increase in the filtrate volume will be expressed:

\[
dV = \sqrt{\frac{2(0.5 \rho gh + \Delta p) - t}{\mu r_0 x_0}} df 
\] (6)

\[
df = a \cdot dh
\] (7)

where \(a\) – width of the filtering baffle, m;
\(h\) – coordinate, for the top of the partition \(h = 0\), for the bottom of the partition \(h = b\);
\(\rho\) – density of the suspension, kg/m\(^3\);
\(g\) – acceleration of gravity, m/s\(^2\).

Since the value \([2/(\mu r_0 x_0)]^{0.5}\) for the incompressible sediment is constant, we denote it by the symbol \(A_1\).

Hence:

\[
dV = A_1 \sqrt{\Delta P t a} \cdot dh = A_1 a \sqrt{t} \sqrt{(0.5 \rho gh + \Delta p)} \cdot dh
\] (8)

By integrating and simplifying equation (8), we obtain equation (11), which allows us to determine the filtrate performance of the vacuum filter:

\[
\int_0^V dV = A_1 a \sqrt{\Delta P t} \left[ \frac{1}{0.5 \rho g} \left( \frac{1}{2} \right) \right]_0^b dh
\] (9)

\[
V = A_1 a \sqrt{\Delta P t} \left[ \frac{1}{0.5 \rho g} \left( \frac{1}{2} \right) \right]_0^b dh
\] (10)

\[
V = \frac{A_1 a \sqrt{\Delta P t}}{0.75 \rho g} \left[ \frac{1}{2} \right]
\] (11)

Almost any sediment is compressible. In this case, the dependence of the resistivity of the sediment on pressure can be expressed by the empirical Lewis equation:

\[
r_0 = r_1 \cdot s \Delta P
\] (12)

where \(r_1\) and \(s\) are empirical constants determined empirically for each sediment.

For a real compressible sludge, after appropriate transformations and integration, we get:
\[ V = \frac{A_r}{\sqrt{0.25\rho g}} \left[ \left( \Delta p + 0.5 \rho g h \right)^{\frac{3-s}{2}} \right] \]

where

\[
A_r = \sqrt{\frac{2}{\mu_0 r_0 x_0}}
\]

3. Results

Equations (11) and (13) show that if the filtration process takes place without the use of external pressure \( \Delta p \), then the specific productivity is proportional to the hydrostatic pressure in the power \((3-s)/2\). In this case, flat elements of minimum thickness, vertically lowered down, have the highest specific productivity with an equal filtration area, since with an equal area of all types of surfaces at flat filtering partitions, the value of \( h \) is maximum. Thus, the spherical shape, which is quite common in the process of vertical filtration, is the least effective.

As the thickness of the sediment layer on the surface of the filtering baffle increases, the overall resistance to filtration increases. If we assume that at some point in time, for technological reasons, the filtration process stopped, and at this moment on the filter baffle there is a sediment with a volume separated from the suspension with an efficiency of \( E \), (unit fraction), having a moisture content \( W_{sed} \), then, in this case, the dry sludge mass will be:

\[ m_{dc} = \rho V(1-W_{sed})E \]

Specific productivity \( G \), [kg/(m\(^2\)·h)], of the filtering partition on dry matter can be determined by the equation (16):

\[ G = \frac{m_{dc}}{(Ft)} \]

Taking into account equation (15), we get:

\[ G = \frac{\rho V(1-W_{sed})E}{(Ft)} \]

After substitution of the filtrate volume \( V \) from equation (11) and simplification, we obtain:

\[
G = \frac{A_r\left(\Delta p + 0.5 \rho g h\right)^{\frac{3-s}{2}}(1-W_{sed})E}{0.75gh\sqrt{t}}
\]

4. Conclusion

It can be summarized that in order to ensure maximum performance of vacuum filtration devices, it is necessary:

- Make the most of the filter cloth for filtering the suspension, and for this the apparatus must be immersed in the suspension, and, if possible, only the unit for regenerating the filter material must remain above the liquid surface;
- For maximum utilization of hydrostatic pressure, the filter housing must be submerged to the maximum permissible depth.

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