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Jakob Murkes

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FUNDAMENTALS OF CROSSFLOW FILTRATION

Jakob Murkes
Stockholm
Linnegatan 48B
Sweden

Traditional Crossflow Filtration and its Bottlenecks

Crossflow filtration is a method applied mainly to hyper- and ultrafiltration as well as, to some extent, microfiltration. In crossflow filtration the solution or suspension fed to the filter flows parallel to the filter medium or membrane. Perhaps the name "parallel" or "tangential" filtration would be more illustrative than "crossflow." The filtration product, i.e., the filtrate or permeate (depending on whether a suspension or solution is separated) leaves the filter channel at right angles to the medium. The crossflow method is just the opposite of the so called "dead-end" filtration used in almost all traditional filtering processes. In "dead-end" filtration the flow of suspension is directed at right angles to the medium and the filtrate leaves the medium in the same direction (Fig. 1.) This difference between parallel and perpendicular flow is significant because perpendicular flow entails cake formation, whereas crossflow is intended to prevent such cake build-up. Dead-end filtration is thus applied when the cake is to be collected, when the main purpose is the recuperation of

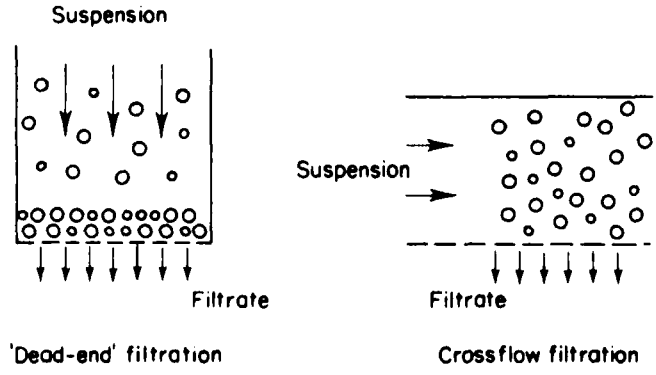


Figure 1. Dead-end filtration with cake formation and crossflow cake-free filtration. Reprinted with permission from Murkes and Carlsson,[14] Copyright 1988, John Wiley & Sons.

suspended solids, or when relatively rapid cake formation cannot be avoided. The crossflow method is applied, on the other hand, when formation of the deposit on the medium is to be prevented as far as possible. This is the case for solutions and suspensions with very low solids content, such as liquids treated by reverse osmosis, ultra- and microfiltration. For these three kinds of processes there is the same flow pattern as well as very similar hardware.

In Figure 2 are shown typical membrane geometries used for crossflow ultra-and microfiltration. The difference is mainly the nature of the medium and the applied pressure. Also, the drawbacks and limitations are similar. Especially important is the limitation of the applicability of these related technologies due to what is called "concentration polarization"[1, 2, 3] and/or to the unwanted formation of deposits on the membrane surface. When the liquid flows parallel to the medium its velocity v generates a shear force τ at the surface of the medium

$$\tau = 8v/D \qquad (1)$$

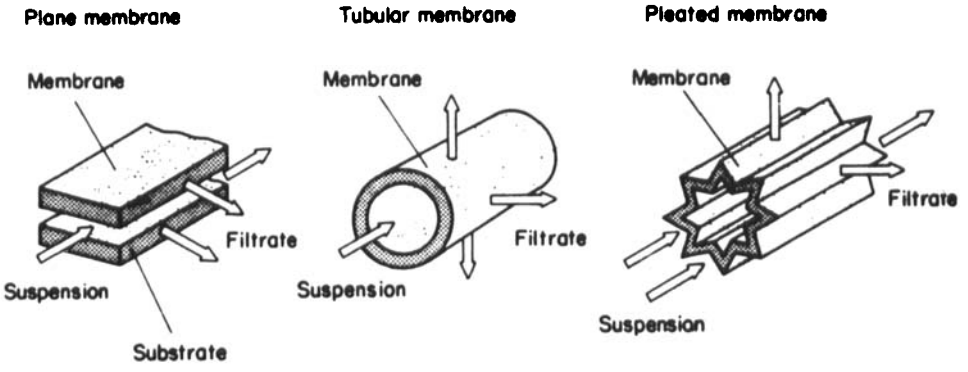


Figure 2. Different geometries of crossflow filter membranes. Reprinted with permission from Murkes and Carlsson.[14] Copyright 1988, John Wiley & Sons.

where D is the diameter of the filter channel. Owing to this shear force, the deposits on the surface are swept away and the filter remains clean and unobstructed during the whole operation. Thus, its flux capacity does not decline. This ideal result is unfortunately never achieved completely. Since the generated shear force is not high enough, some particulate deposits remain on the surface along with a layer of concentrated solution or even a gel (when there are macromolecules in solution.) Owing to the convective flow, the concentration of the solution C_w at the membrane surface increases with operation time and eventually reaches a gel formation concentration C_g which is much higher than the bulk concentration C_b (see Fig. 3.)

The filtrate flux through the membrane J is a function of both of these values

$$J = k \ln(C_w/C_b) \qquad (2)$$

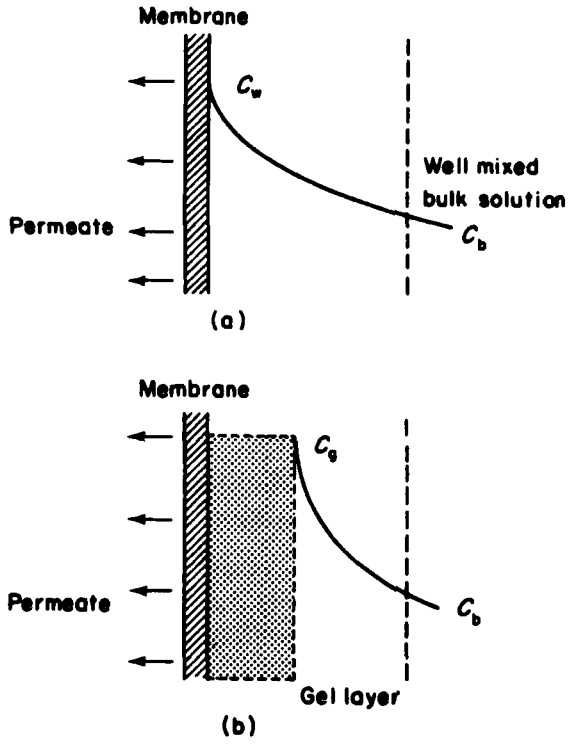


Figure 3. Concentration polarization. Reprinted with permission from Murkes and Carlsson,[14] Copyright 1988, John Wiley & Sons.

On the other hand, the flux is also related to the pressure drop Δp over the membrane and to the hydraulic resistance of the membrane R_m and of the polarization layer R_p:

$$J = \Delta p/(R_m + R_p) \tag{3}$$

Combining these two equations gives:

$$\ln(C_w/C_b) = \Delta p/(k(R_m+R_p)) \tag{4}$$

As long as $C_w < C_g$ the flux increases with the increase of pressure drop, but when $C_w = C_g$ any further increase of Δp entails a compaction of the polarization layer and an increase of its thickness. Thus, the resistance R_p increases simultaneously with pressure and no further flux increase is obtained.

Concentration polarization brings about a flux decline with operation time and makes the intrinsic properties of the membrane in terms of flux and retention not really relevant. The flux of an unclogged membrane can never be achieved in practical operation. As a rule, the flux declines very rapidly at the beginning, and thereafter, when equilibrium conditions are reached, it almost levels out with only a very slow decline. The reason for this slow decline in spite of equilibrium conditions can be explained by the fact that equilibrium is very seldom really attained as far as the granulometry of the deposit layer is concerned: this layer is more and more enriched with finer and colloidal fractions.[4]

It is true that the concentration polarization problem is somewhat less serious in microfiltration of particulate material as compared to solute polarization. This can be seen from the expression[5] of the hydraulic resistance α of a deposit layer having porosity ε and consisting of particles with diameter d

$$\alpha = 162(1-\varepsilon)^2/d^2\varepsilon^3 \qquad (5)$$

It is obvious that coarser particles forming the deposit layer entail a lower hydraulic resistance. That is why the biggest difficulties are encountered when colloidal suspensions are filtered.

The problem of flux decline caused by concentration polarization as well as by plugging of the medium by particle penetration is perhaps the most serious bottleneck as far as the practical applicability of crossflow ultra- and microfiltration is concerned. Many investigations have been carried out in order to find an efficient method for dealing with these difficulties.

The methods investigated were the use of foam balls to clean tubular membranes, vibrations, flow pulsations, rubbing the surface by adding particulate material to the washing liquid, washing the different detergents, backwashing with pure water or with filtrate and osmotic backwashing.[6]

All these depolarization and cleaning procedures complicate the plant lay-out, and bring about a higher consumption of water, energy and chemicals. They also significantly reduce the net operation time. Worst of all, they seldom are sufficiently efficient.

It is thus easily understood that developing more productive membranes with inherently higher fluxes is of little practical importance as long as the fouling problem cannot be solved adequately.[7] A real break-through of membrane technology can occur only after the problem of keeping the membrane clean has been solved. No development of "better" membranes can change this fact.

It appears that the most efficient and natural way to combat deposits and concentration polarization is to increase the flow velocity in order to enhance the shear force. In practice, however, the velocity increase is limited to a value which is not big enough. Higher flow velocities bring about higher pressure drops through the module, which in turn entails lower pressure available for filtration and often makes it impossible to connect modules in series. Furthermore, higher flow velocities necessitate bigger and more expensive circulation pumps, higher energy consumption and lower recovery of filtrate (ratio filtrate flow/feed flow.)

In large tubular modules this practical velocity limit is about 5 m/s. It is often much lower because of the smaller tube diameter or higher pressure drop in non-tubular modules. At the same time a velocity of 5 m/s is not high enough to keep the membrane surface sufficiently clean and, thus, to keep the flux on a high level. Deposits on the membrane surface may seem to be absent, but even a deposit of the order of

magnitude of 1 mg submicron particles per cm^2 membrane area, invisible to the naked eye, considerably increases the hydraulic resistance of the membrane. Changing the nature of the membrane can, in some cases, slightly improve the results. For instance, the use of hydrophilic material (such as cellulose acetate) for filtering oil emulsions is better than using polymers with a stronger affinity to oil. Yet, in all cases, oil will eventually adhere to the membrane surface and make it almost impermeable. Washing off oil-coated membranes is very difficult if not impossible. Flow velocities up to 5 m/s have been shown to be totally inadequate for preventing membrane coating with oil. The velocities needed in this case are about 15 to 20 m/s. This explains why the use of membranes for dewatering of oily effluents was never a satisfactory practical solution to the problem, in spite of encouraging laboratory results.

There are basically three methods that can be applied separately or, if feasible, jointly to solve these serious problems:

(1) Prevention of deposit formation by carrying out filtration in electrical field.
(2) Using the so-called dynamic or secondary membranes.
(3) Generating sufficiently high-shear forces.

Electrokinetic Crossflow Filtration

Theoretically, electrokinetic crossflow filtration provides an elegant solution to the fouling problem in some cases. This method has undergone preliminary tests[8,9] and been found to be very interesting. The advantage of this process is that the electrically charged particles are attracted towards, and deposited on, an oppositely charged electrode (usually the anode). The filtering medium placed on top of the other electrode (often the cathode) thus remains free from any deposit. The particles are collected on the anode and swept away by the flowing liquid. The filtrate flux through the

unclogged medium is still further enhanced by the electroosmotic flow of water towards the cathode. In electrokinetic filtration the flux can be increased several times as compared to conventional crossflow filtration. There are, however, serious drawbacks. Even small concentrations of various salts increase the conductivity of the filtered suspension and the process turns into electrolysis with gas generation. Furthermore, the piping, tanks etc., cannot be made of any metal (with the possible exception of some stainless steel varieties); even very small amounts of metals in aqueous solution result in the deposition of corresponding salts on the filter medium, causing a continuously progressive fouling of the filter medium.

Secondary Membranes

The previously mentioned colloid or gel layer, which is deposited on the surface of the medium, actually constitutes a kind of secondary membrane since it is usually semipermeable and has solute rejecting properties. The point is that these harmful, unwanted deposits, formed of the constituents in the feed, should be substituted by "tailored" secondary membranes made on purpose and having such properties that the membrane performance would be improved. There is a certain similarity between these tailored dynamic membranes and the well-known precoat of filter media with filter aids in traditional dead-end filtration. In both cases the surface of the medium is pretreated with a suspension of a suitable particulate material, and in both cases this pre-treatment brings about a protecting layer which improves the flux and the rejection; this layer enhances the longevity of the media. Whereas in dead-end filtration this particulate material in suspension is microscopic, in crossflow applications this material is in most cases colloidal.

Figures 4 and 5 show what happens when a secondary membrane is deposited on a microporous and on an

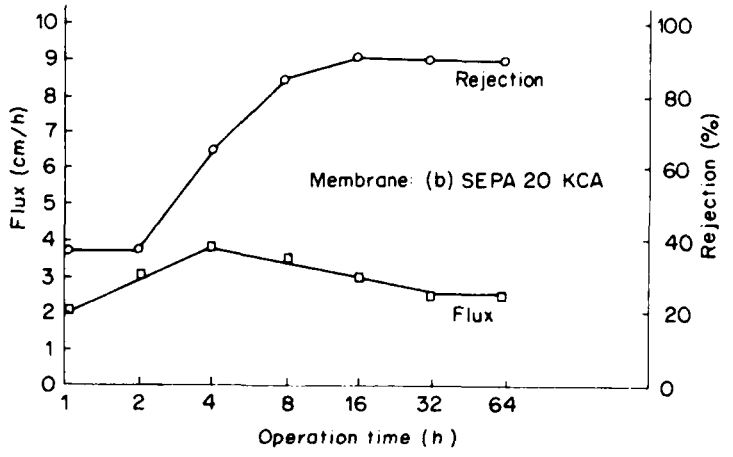


Figure 4 Flux and rejection versus operation time. Ultrafiltration of 0.2 g/litre egg albumin + 0.1 M NaCl + 0.01 M Na_2PO_4. Pressure 2 bar, temperature 20°C, flow velocity 2.2 m/s. Reprinted with permission from Murkes and Carlsson,[14] Copyright 1988, John Wiley & Sons.

ultrafiltration membrane. The conclusions that can be drawn from the corresponding experiments are as follows:

- The original, intrinsic properties of the membrane are of little relevance for its performance during the operation;
- With time the rejection generally improves as the flux becomes stabilized;
- A secondary membrane obviously forms, with properties comparable to a skinned ultrafiltration membrane. In the experiment illustrated in the Figure 5, the microporous medium with a pore size of 0.2 μm,

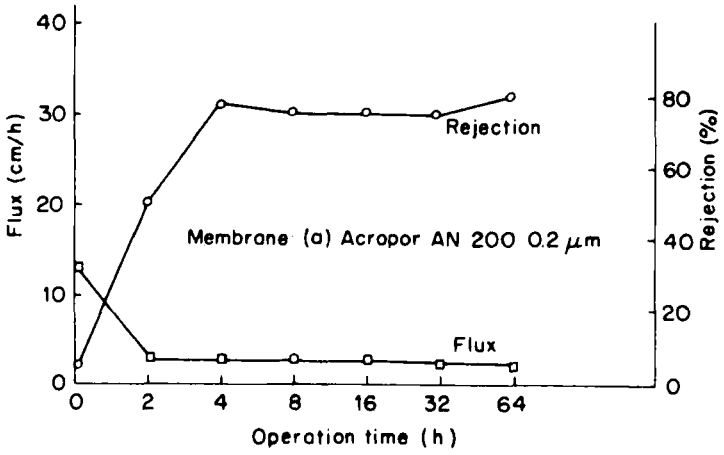


Figure 5 Flux and rejection versus operation time. Ultrafiltration of the same solution as in Figure 4. Microporous membrane. Pressure 2 bar, temperature 20°C, flow velocity 2.2 m/s. Reprinted with permission from Murkes and Carlsson,[14] Copyright 1988, John Wiley & Sons.

has acquired solute rejection properties comparable to those of a skinned ultrafiltration membrane.

Dynamic membranes have been investigated mainly in connection with reverse osmosis operation. These membranes, developed at Oak Ridge National Laboratory, consist of colloidal Zr(IV) hydroxide deposited under closely controlled pH-conditions.[10] Very little has been done in the field of dynamic membranes for ultrafiltration.[11] An example of such membranes developed especially for the separation of oily emulsions can be found in Ref. 12. Figure 6 shows an electron micrograph of colloidal silica particles deposited on a microporous support. These colloids form a kind of secondary solute-rejecting membrane. The development of adequate

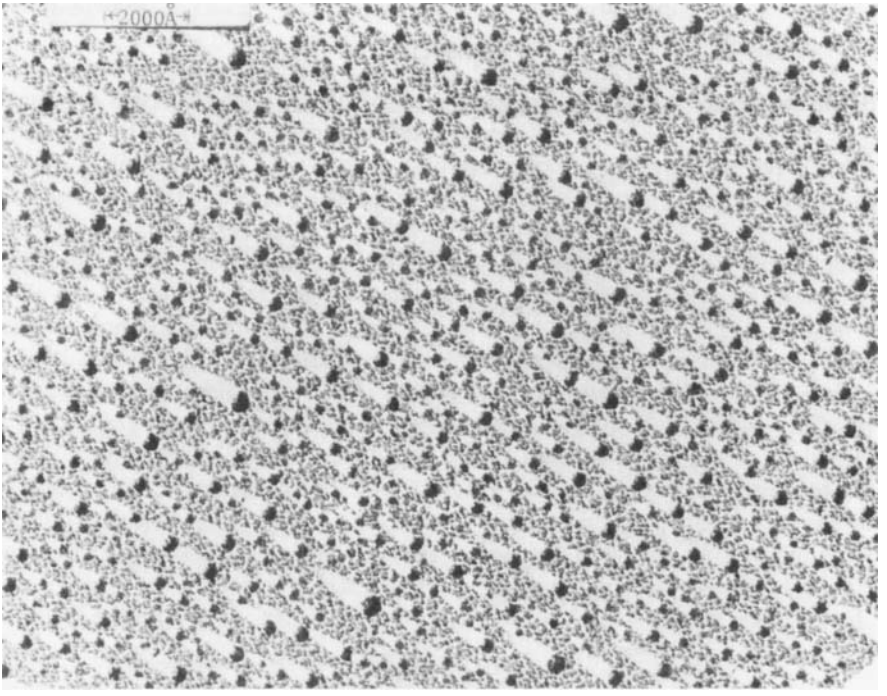
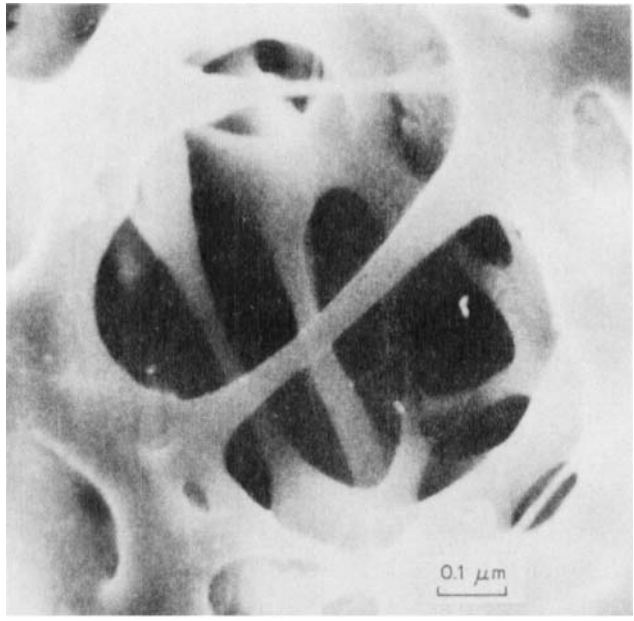
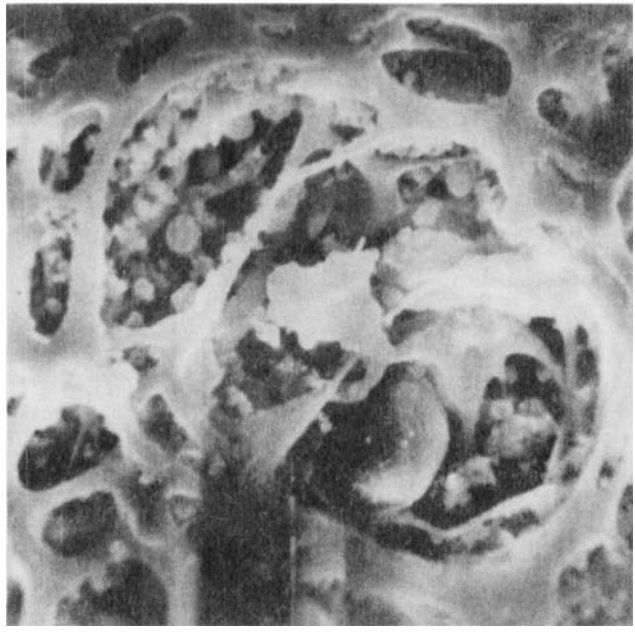


Figure 6 Formation of dynamic membrane. Electron micrograph of silica colloidal particles dispersed with ultrasonic sound. Particles shadowed with Pt. Reprinted with permission from Murkes and Carlsson.[14] Copyright 1988, John Wiley & Sons.

secondary membranes can significantly influence the performance of high-shear filters in terms of flux, flux stability and membrane longevity.

We spoke of the fundamental importance of generating sufficiently high-shear forces to maintain the membrane surface free from deposits. But media can become clogged not only on the surface but also internally, inside the pores (Fig. 7.)





This applies especially to microporous media. Logically we would expect that larger pores are more easily entered by particles than small ones, which means that more open media become clogged faster. That is, in fact, what actually happens. Experimentally there is no point in using media with pores larger than 1 micron. The initially high filtrate flux of large-pore media drops rapidly and eventually becomes lower than the flux of small-pore media.

In crossflow microfiltration the fundamental filtration law is just the opposite of the traditionally accepted law: in all "normal" filtration the flux is inversely proportional to the hydraulic resistance of the medium, whereas here we can rather speak of a direct proportionality. Therefore, for crossflow microfiltration either ultrafiltration membranes or microporous media with pore sizes not larger than 1 micron are used. Very often the flux of a 0.2 μm membrane, after a certain time, is higher than the flux of a 1.2 μm medium. In many instances a higher flux was obtained with an ultrafiltration membrane than with a microporous one, which otherwise would be quite sufficient for the task in question and might be expected to yield higher fluxes. These are paradoxical results, explained by the fact that microporous media are much more easily clogged internally than skinned membranes.

It is important to note that some observations point to the fact that colloidal secondary membranes are much more easily formed on a microporous support with pore openings not larger than 1 micron. Considering what has been said above concerning a better flux preservation of submicron media, it appears that such media are advantageous for crossflow microfiltration.

Figure 7 Microporous membranes, pore size 0.45 micron. Beginning internal clogging. Reprinted with permission from Murkes and Carlsson.[14] Copyright 1988, John Wiley & Sons.

High-Shear Force Approach

The methods discussed above improve crossflow filtration per se, but the most significant improvement in terms of filtrate flux is obtained by keeping the medium as free from deposits as possible by means of sufficiently high-shear force. Then, the high-shear method can be still more improved by using suitable dynamic membranes and/or by superposing an electrical field. [13]

Another more practical solution to the fouling problem was tried. The basic idea was very simple: to replace the linear velocity of the liquid along the filter medium by a movement imparted to the liquid by means of a rotating body in a circular filter channel. We discovered that this idea was not a new one. In an American patent from 1927[15] the author wrote that "the main purpose and accomplishment of the apparatus is to maintain an indefinitely unclogged filtering medium with a constant rate of filtering flow," which could be accomplished by means of a rotary filter with a "continuously rotating filter medium." This patent remained unnoticed for half a century.

What is important is the generation of a relative velocity between the liquid and the filter medium. The easiest way to generate a sufficiently high relative velocity is to rotate either the medium relative to the liquid or vice versa. A sufficiently high-shear force is created by the velocity at the medium surface to keep it clean from deposits. If a rotary movement replaces a linear movement of the liquid (which means that a rotor replaces the feeding pump), three important advantages are achieved:

- The relative velocity can be easily made very high;
- The feed pump does not need to have a larger capacity than the filtrate flow;
- The recovery in terms of filtrate flow/feed flow can theoretically be very high (nearly 100%).

Owing to the efficient cleaning of the filter medium, the filtrate flux declines much more slowly and sometimes can

even be kept almost constant. This fact brings about the most important practical advantage of the high-shear crossflow technique: high product capacity and almost continuous operation with very infrequent stops for cleaning the medium.

The basic relationships in this case are qualitatively the same as in the case of traditional low-shear crossflow filtration. The difference is quantitative as the fluxes in a high-shear process are one order of magnitude higher than in the low-shear process. The most important relationships are illustrated in Figures 8 and 9.

The formulas in the figures are limiting expressions of the following equation:[14]

$$J = -\frac{B\Delta p}{\mu}\left(\frac{C^2\Delta p}{(av^3 + bv^{3.5} + 0.28v^4)^{1/2}} + L_o\right)^{-1}$$

where $a = 21\,\mu/D_p\rho_L$

$b = 6(a/21)^{1/2}$

B - Darcy's permeability coefficient

C - volumetric concentration

L_o - equivalent cake thickness

D_p - particle diameter

Δp - pressure drop over bed

ρ_L - density of liquid

v - tangential velocity

μ - dynamic viscosity of the liquid

The graphs in Figs. 8, 9, and 10 illustrate the most significant importance of the flow velocity. High velocity means high-shear force which in turn brings about small deposit thickness (reduced concentration polarization) and therefore high flux. The main topic of this article is the question of how to enhance the shear force in a crossflow filter.

Specific Properties of the High-shear Crossflow Filtration

Let us analyze in more detail the specific properties of

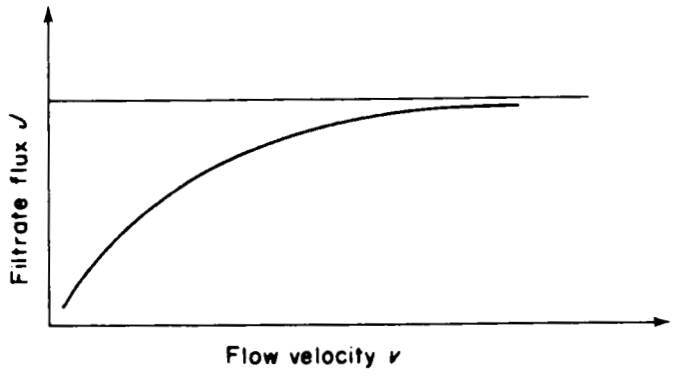


Figure 8 Filtrate flux versus flow velocity in crossflow filtration (low- and high-shear.)

$$J = \text{const. } v^{3/2} \text{ for } v \to 0 \text{ and } J = \frac{B\Delta P}{\mu\, l_o} \text{ for } v \to \infty$$

where l_o is cake thickness having resistance equal to the resistance of filter medium, B is permeability of equivalent cake, Δp is pressure drop across cake, μ is liquid viscosity. Reprinted with permission from Murkes and Carlsson.[14] Copyright 1988, John Wiley & Sons.

the high-shear process. Since in this process, just as in traditional hyper- and ultrafiltration, the flow is parallel to the medium surface, we can speak of high-shear crossflow filtration.

It should first be pointed out that this process applies equally to hyper-, ultra-, and microfiltration and can also be used for dewatering (thickening) of suspensions. (In practice it is difficult to apply the technique to high-pressure reverse

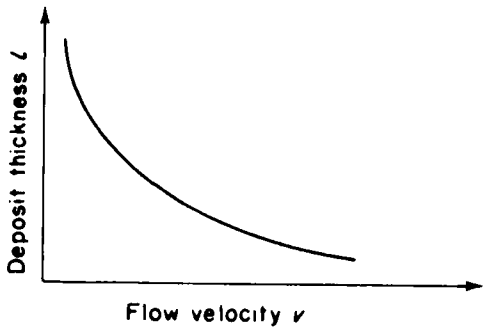


Figure 9 Deposit thickness versus flow velocity in crossflow filtration (low- and high-shear.)
$1 = \text{const. } \Delta p/v^{3/2}$ for $v \rightarrow 0$
$1 = \text{const. } \Delta p/v^{2}$ for $v \rightarrow \infty$
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osmosis.) It is important to emphasize that this is a multipurpose process and that the corresponding hardware can be made as a multipurpose, universal filter. The only things that differ are the media (ultrafiltration or microporous membranes, tightly woven or sintered media.) Otherwise the rotor speed may differ and the filter cells may be arranged serially or in parallel.

To sum up, the basic elements of fundamental importance to the high-shear crossflow process are the following:

1) A sufficiently elevated relative velocity between the filter medium and the liquid to be filtered. This velocity can easily be obtained by a rotary movement and should preferably be between 10 and 20 m/s peripheral velocity.
2) The use of either skinned ultrafiltration membranes or very fine porous (less than 1 micron) microfiltration media.

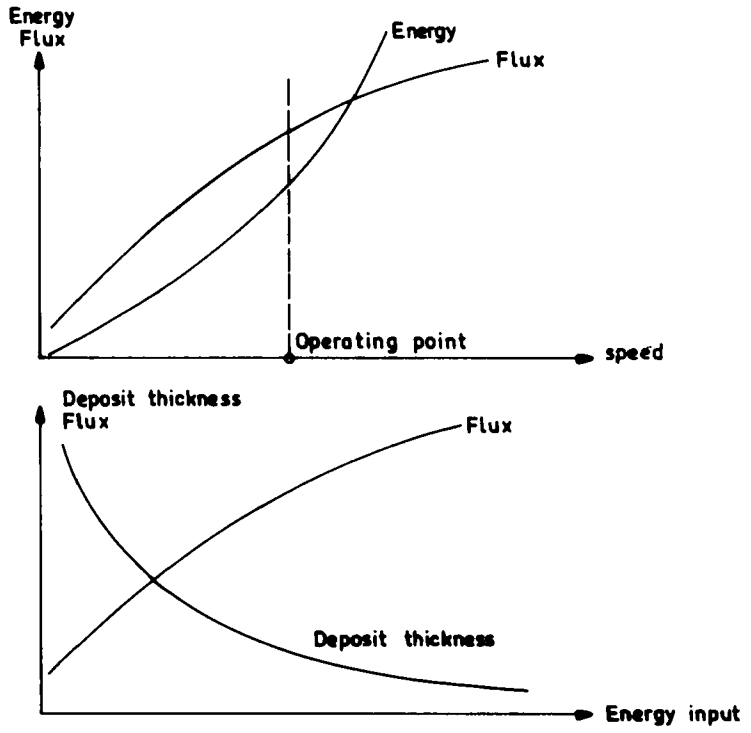

Figure 10 Relationships between energy input, flux, deposit thickness and speed. Choice of operating point.

3) The use, as far as possible, of tailored material to be deposited on the surface of the media used.

Filters operating according to these principles have important practical advantages over other more traditional filtration or ultrafiltration methods. In many cases these advantages, as listed below, can easily make the traditional methods obsolete.

1) The filtrate (permeate) fluxes are in general one order of magnitude higher (they are mostly between 100 and 1000 L/m^{2}h.)
2) The flux decline with time is very slow, sometimes

almost zero. This makes the necessary interruptions for washing or exchanging the membranes very infrequent and increases the life span of the membranes.

3) The filtrate is virtually always totally free from any particulate matter, including colloids, viruses etc. In many cases some high-molecular weight solutes are also retained, even if microporous media are used. In some cases this can be an advantage; in others a disadvantage.
4) The filter is not very sensitive to the content of solid inclusions in the feed. Thus only very coarse preseparation is required to protect the filter medium.
5) There is no longer any need to use flocculating or demulsifing agents, nor are filter aids needed, even for the finest filtration.
6) Suspensions and emulsions with very difficult filtration properties can be easily filtered without any pretreatment (Example: dyestuff suspensions, metal hydroxide suspensions, solubilized oil emulsions.)
7) The capacity of feed pumps is of little importance and in principle is nearly equal to the filtrate flow.
8) The recovery of the product is very high and the recirculation of the feed very reduced.
9) In one and the same filter different types of operations can be performed: ultrafiltration, microfiltration, clarification, and thickening of suspensions.
10) Since the separation takes place in a closed space the process is environmentally clean.
11) Many applications, which until now were not technically or economically feasible, can be approached with a good possibility of success.

Along with the clear advantages there are some drawbacks. The hardware is of course more complicated and

expensive than that used for traditional "low shear" filtration and ultrafiltration. But because of significantly higher fluxes and other factors, the cost of one volume of the product is usually lower. Another drawback is the heat generated by friction. Even if this heat can be minimized by parallel coupling of the filter cells, it may not be advisable to filter heat sensitive and mechanically sensitive suspensions and solutions (for example, enzymes.) Finally, high-shear filtration requires relatively high power of the driving motor, around 7 kW/m^2 filter area, though the pumping power is much smaller than in conventional plants and energy consumption per unit volume of the product is competitive.

The design of the rotating body inside the filter conveying the energy for generation of the shear force is very important. The more energy that is supplied to the liquid, the thinner is the deposit and, thus, the higher is the product flux. The energy conveyed increases with the speed of the rotor (see Fig. 10.) The operation speed of the rotor must be optimized, since too high a speed brings about a very high energy consumption without increasing the flux correspondingly. This operation speed is different for different applications and must be found by experiment.

The Hardware for High-shear Crossflow Filtration

The basic American patent[15] was forgotten for many years, but in the 1960's the idea was taken up again by Kaspar[16] and Malinowskaja[17,18] which resulted in the first industrial rotary filter made by W. Bachofen[19] and a few years later by the Japanese company Kotobuki[20] and the American company Artisan.[21] All these filters consist of several rotating filter discs connected in series (Fig. 11.) In these filters the feed flows outwards and inwards between the discs from the inlet to the concentrate discharge point. The slurry is more and more concentrated as it flows along its zig-zag path until such a maximum concentration is reached that the concentrate is

barely able to flow. The concentrate is discharged by means of an automatically opening constant pressure valve. All these filters cannot, however, be regarded as high-shear filters of the kind discussed in this article, since they are intended solely for thickening particulate suspensions, especially thixotropic ones (including washing of the concentrate); they are designed for high suspension concentrations and work with very moderate shear forces. The flow velocity in the Kotobuki thickener is about 10m/s and in the Artisan unit around 5m/s. Strictly speaking, the Artisan filter works according to another principle, the so-called "delayed cake filtration," where the cake of constant and very limited thickness is allowed to build up on the filter media, thus necessitating high filtration pressures.

Another type of high-shear filter has a cylindrical filter medium. It was described by Oak Ridge National Laboratory,[22] (see Fig. 12) and called "Axial filter," by Margaritis and Wilke[23] and "Rotorfermentor" and by Bhagat and Wilke.[24] The industrial development of this type of filter was carried out recently by Escher-Wyss and by Sulzer.[25,26] In these filters the filter medium can either be carried by the rotor in a cylindrical shell or be stationary while the rotor is shaped to impart rotary movement to the liquid. Both rotary and stationary cylindrical filter media also occur. In the case of a rotary medium, filtration is assisted to a certain degree by centrifugal force which prevents sufficiently large particles (or rather solids with sufficiently big mass) to touch the membrane and to enter the pores or to form a cake. The theory of filtration in a cylindrical axial filter is presented by Margaritis and Wilke[23] and Lieberherr.[26]

The properties and applications of the axial filter are similar to those of the circular disc filter although the axial filter has some interesting specific properties. One such property is the above mentioned centrifugally assisted filtration, another is a possibility of backflushing the media by

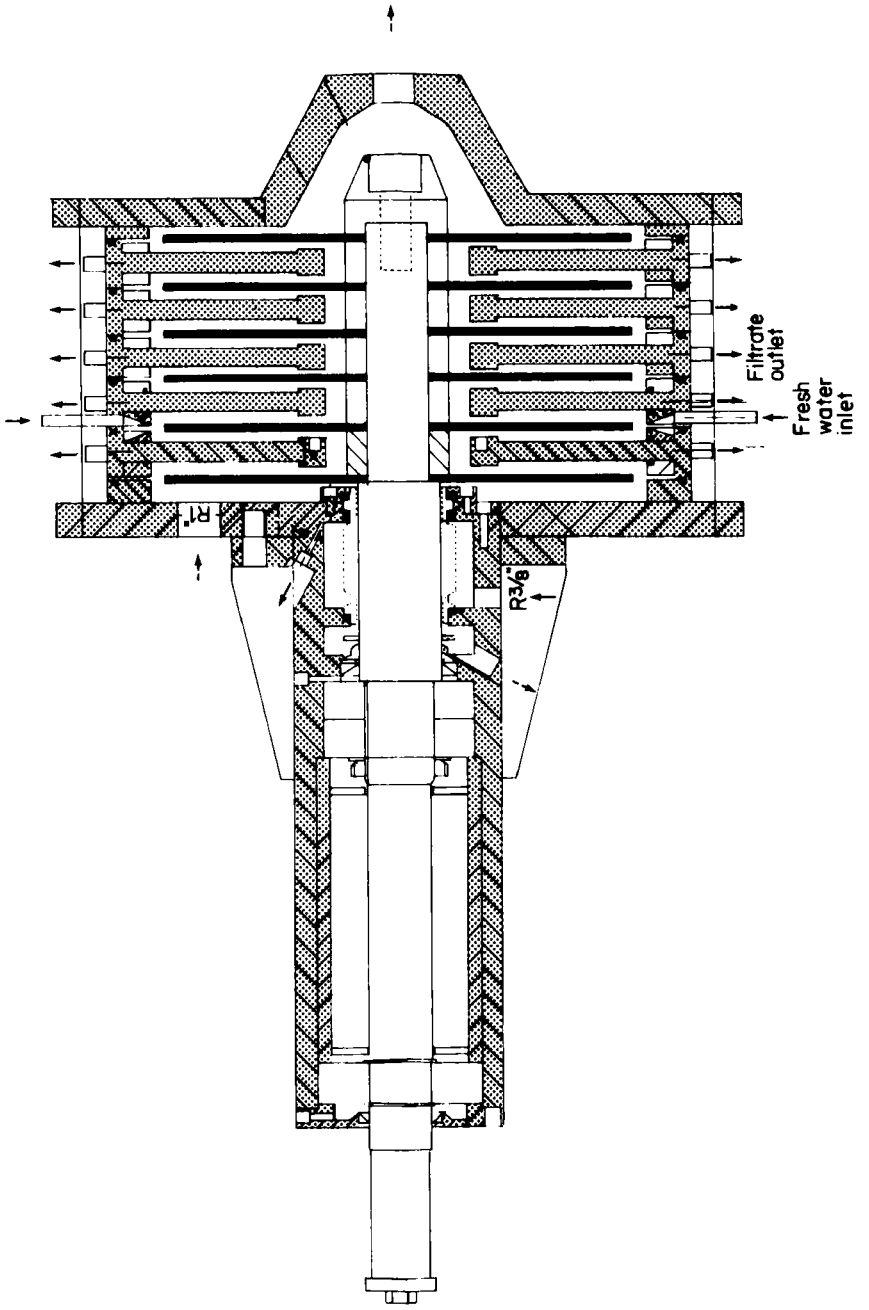

Figure 11 The principle of the multipurpose rotary highshear filter. The number of cells is arbitrary (here 6) especially if cells are connected in parallel. Feed inlet is either to the end plate (if cells are connected serially) or to each cell separately (if cells are connected in parallel.) Concentrate outlet to the right. Concentrate discharge and constant pressure valve directly after the concentrate outlet are not shown here. Reprinted with permission from Murkes and Carlsson.[14] Copyright 1988, John Wiley & Sons.

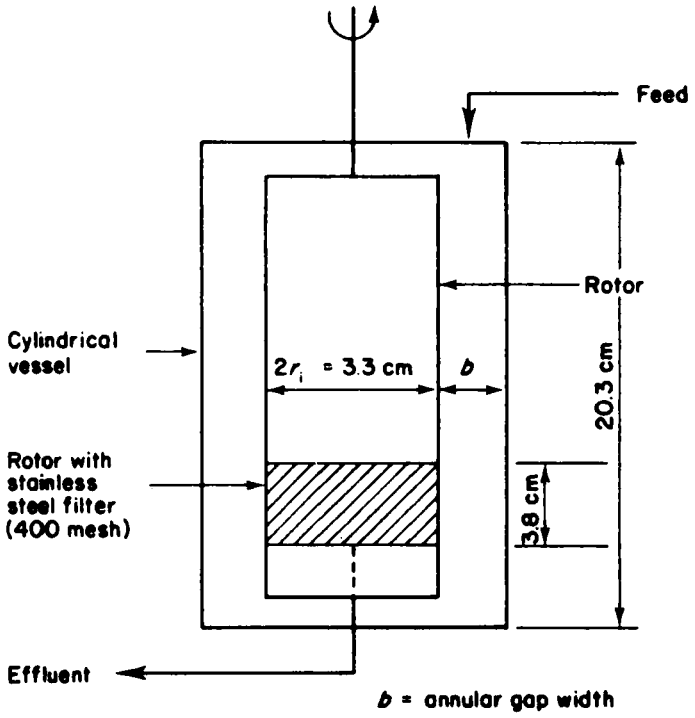

Figure 12 Axial filter with rotating filter medium. Reprinted with permission from Murkes and Carlsson.[14] Copyright 1988, John Wiley & Sons.

simple methods.[14] Still another specific property of this filter is its suitability for various laboratory investigations, its applicability as a chemical reactor[22] and as a fermentor.[23] This suitability is due to the possibility of keeping the reacting suspension in a closed space and at the same time removing the reaction products through the membrane. If the possibility of adequate aeration is added, this filter is very suitable for concentration of bacterial suspensions.

The industrial applicability of the axial filter has not been, as yet, assessed as deeply as the applicability of the

circular disc filter for ultra- and microfiltration and for thickening. Very interesting industrial applications of the cylindrical filter can certainly be anticipated.

The first and probably the only filter designed for multipurpose operation according to the principles described above for high-shear crossflow filtration is the rotary CROT filter made by ASEA Brown Bovery (ABB.)[27] Because of the novelty of the hardware there are, as yet, no reports of industrial applications of this filter in the literature, although it has been in operation since 1987.

The CROT filters of ASEA (see Fig. 13) are built of an arbitrary number of circular cells from 1 to 40, of 500 and 1000 mm diameter, which gives a total filter area between 0.5 and 60m^2. The corresponding capacities can be determined in each particular case when the flux is known. This determination is usually made in a small scale laboratory filter. As mentioned above, this figure is in most cases between 100 and 1000 L/m^2h. The CROT filters can be used as either microfilter-clarifiers or ultrafilters.

Industrial Applications of the High-shear Crossflow Filter

The only reports available to date have been released by ASEA. One plant is reported to have been operating as a microfilter with satisfactory results since July 1987 in a nuclear fuel factory in Sweden where grinding material (uranium dioxide) is removed from the grinding process and concentrated; the filtrate is recycled to the grinding process. Four filters arranged as ultrafilters have been in operation since August 1988 in a bleached pulp plant. The chloroorganics here are removed by ultrafiltration from the effluent coming from the oxygen-enhanced alkaline bleaching step. Other plants are about to be installed in Sweden in the lumber industry for treatment of white water. The filter type in question is very suitable for dewatering of all kinds of oil-water emulsions, both

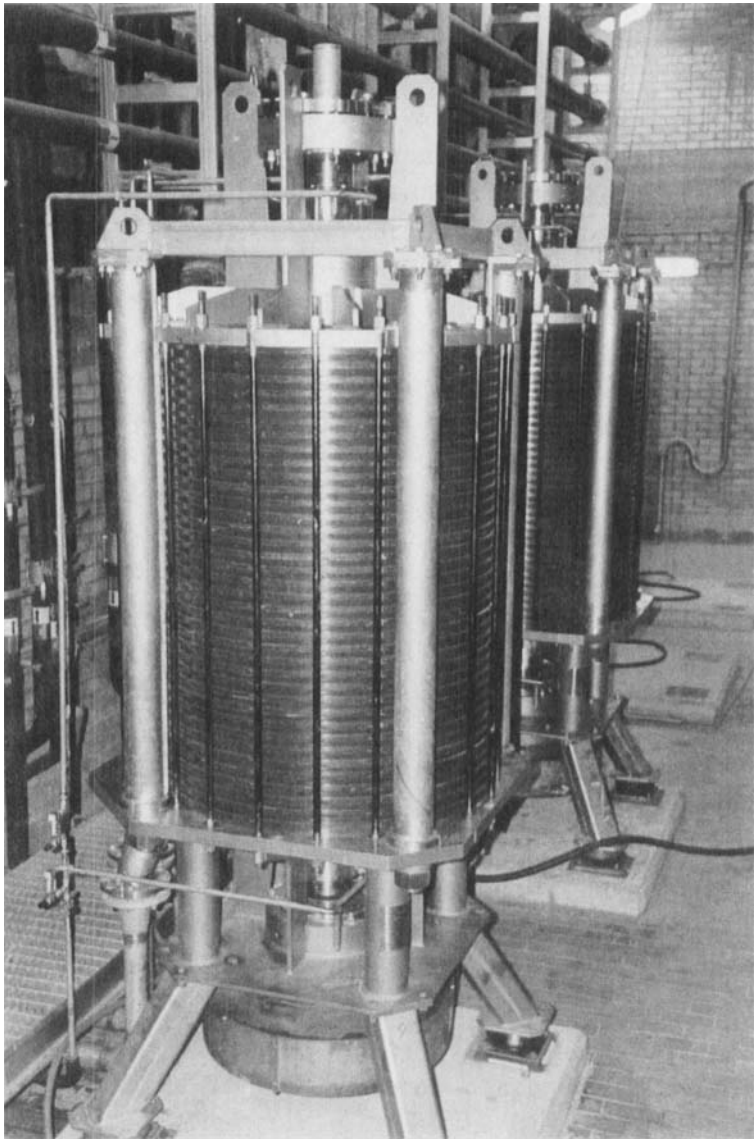

Figure 13 The ASEA BROWN BOVERI CROT high-shear filter in a cellulose plant in Sweden. With permission ASEA BROWN BOVERI.

heterogeneous and homogeneous (solubilized) such as bilge water on-board ships, spent workshop cooling emulsions, and oily water on off-shore drilling platforms. A commercial order for a plant for dewatering of cutting oil emulsions has been received. Several other examples of successful applications in laboratory conditions are reported in a recently published book,[14] where theory and practice of crossflow filtration, both traditional "low-shear" and the above described "high-shear" methods are discussed in detail.

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27. ASEA Brown Boveri, address ABB Water Filtration, Water Purification Systems, Box 53, S-72104 Vasteras, Sweden, telefax 46-21-148407. Representatives for US and Canada are FLAKT Canada Ltd., 1400 Merivale Road, Box 5050, Station "F", Ottawa, Ontario, K2C3P9, Canada, attn. Mr. Bob Melvylle, Telephone: 613-226-3300.