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Dynamic filtration with rotating disks, and rotating and vibrating membranes: an update

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The advantages and drawbacks of dynamic filtration are discussed and currently available industrial filtration modules are presented. Since membrane shear rates are the key factor governing their performance, three equations are given to calculate the shear rates of various modules, with disks rotating near fixed membranes, rotating membranes on a single shaft and vibrating membranes such as in the VSEP. Recent applications taken from the literature confirm the large gains relatively to crossflow filtration in permeate flux and membrane selectivity, owing to large reductions in cake formation and concentration polarization. One of the advantages of this technology is that, with rotating membranes, it gives a choice between increasing the flux by factor of 3–5 as compared to crossflow filtration by using high rotation speeds or obtaining the same flux at low speed, but with a large energy saving. The power consumed by vibrations in large industrial VSEP units is small, owing to the use of resonance frequency.

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Introduction

Crossflow filtration and dynamic filtration

The separation of molecules or particles from fluid by crossflow filtration through a membrane presents a permanent challenge because the filtration continuously builds-up a layer of rejected solutes that reduces the mass transport through the membrane. It is necessary to circulate the fluid at high velocities, from 4 to 6 m s^{-1}, in order to generate a high enough shear rate at the membrane to limit the growth of this layer and cake formation in the case of microfiltration (MF). Thus, the combination of high feed pressures and flow rates requires powerful and expensive pumps that consume much energy.

Dynamic or shear-enhanced filtration, which consists in creating the shear rate at the membrane by a moving part such as a disk rotating near a fixed membrane [1–4], rotating [5–7] or vibrating [8–13] membranes, permits to generate very high shear rates without large feed flow rates and pressure drops and could be a viable alternative to crossflow filtration, when membrane fouling is important, such as with highly charged fluids.

Advantages and drawbacks of dynamic filtration

Dynamic filtration not only increases substantially the permeate flux, but has a favorable effect on membrane selectivity. Clarification of a suspension by MF requires a high microsolute transmission, and dynamic filtration reduces cake formation by combining high shear rates and low TMP. Conversely, in waste water treatment by nanofiltration (NF) and reverse osmosis (RO), it is important to have the highest small solutes rejection by the membrane. Since high shear rates reduce concentration polarization, they also decrease the diffusive solute transfer through the membrane and therefore increase solutes rejection. Moreover, permeate fluxes are much higher than in crossflow filtration as they keep increasing until higher pressures and fouling resistance is reduced by high shear rates.

The drawbacks of dynamic filtration are its complexity and higher cost owing to moving parts and limitations in unit membrane area for some systems. But, the recent availability of large diameter ceramic disk membranes permits now the construction of modules with immersed rotating membranes on parallel shafts [14] of total area exceeding 120 m^2, which are easier to build and to service than multi-compartment modules with metal disks or membranes rotating between fixed plates as the Pall Corp DMF used in [1] or the Spintek used in [4,5]. Dynamic filtration would not be practical in large desalination or water production plants requiring huge membrane areas, generally equipped with spiral wound modules.

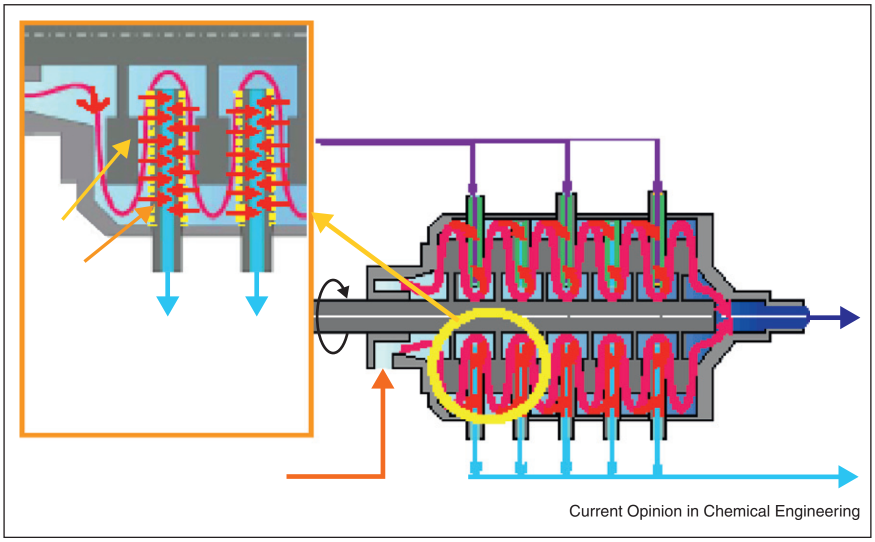
Industrial dynamic filtration modules

They consist of three types, disks or rotors rotating near fixed membranes or rotating organic/ceramic disk membranes and vibrating systems such as the VSEP (New Logic, CA, USA).

Rotating disks and membranes systems

A rotating disk module, the Dyno, is manufactured by Bokela GmbH (Karlsruhe, Germany) with membrane area from 0.13 m^2 to 12 m^2 and a maximum pressure of

Figure 1

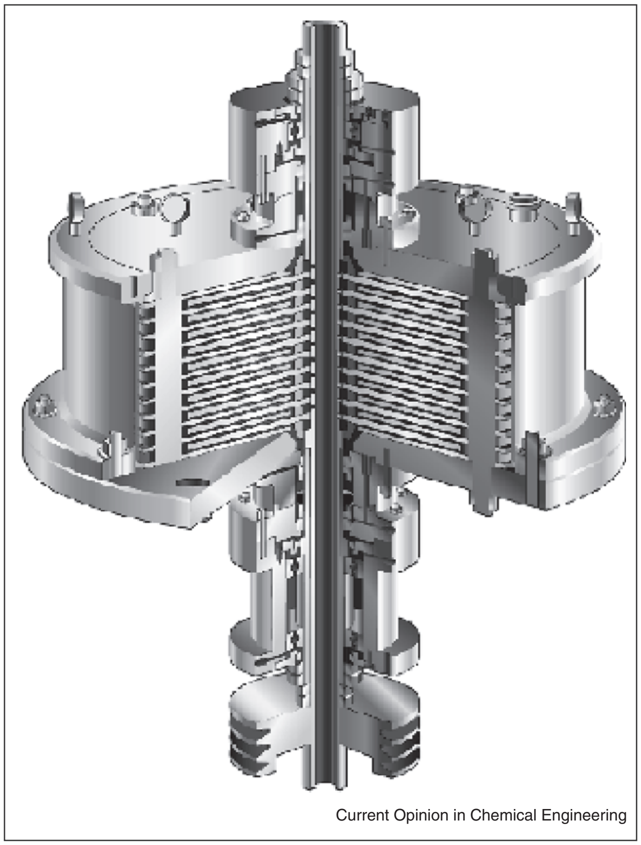


Dyno module with disks rotating between fixed circular membranes (Bokela, Germany).

600 kPa (Figure 1). It is available with polymeric or ceramic membranes. Another multi-disk system, but with rotating membranes, is produced by Spintek (Huntington, CA, USA) with a maximum membrane area of 2.3 m^2. Initially available with organic membranes, it can now receive mineral membranes (Figure 2).

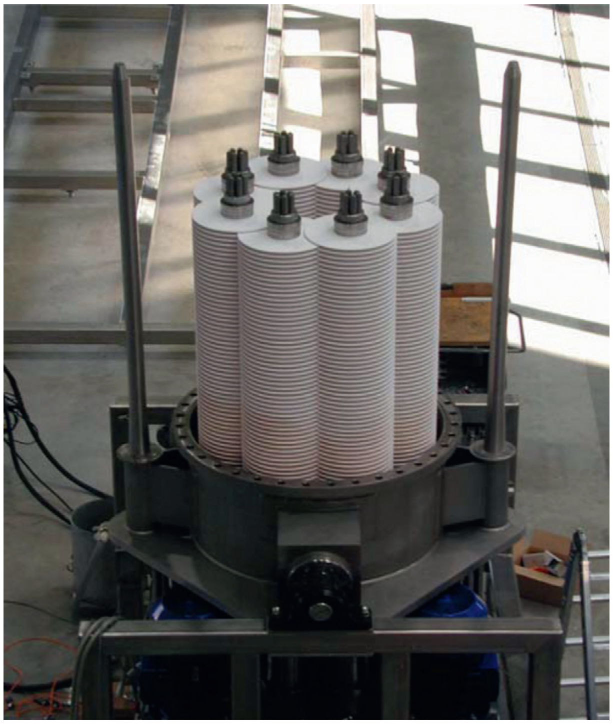
A variation of this concept, the Optifilter CR presently commercialized by Metso Paper (Raisio, Finland) features blades rotating between stationary flat circular membranes. The membrane diameter can reach 1 m and the total membrane area can exceed 140 m^2 [15]. Smaller units of 84 m^2 and 15 m^2 are available. They are used by more than 30 plants, mostly for treatment of pulp and paper effluents or pigment recovery [16]. The recent availability of ceramic membrane disks, especially in Germany, has spurned the commercialization of multi-shaft systems with overlapping rotating membranes. For instance the MSD system (Westfalia Separator, Aalen, Germany) features 31 cm diameter ceramic membranes on eight parallel shafts (Figure 3). The membrane shear rate is unsteady and maximum in the overlapping regions [6,7]. Other systems, the Rotostream (Canzler, Dueren, Germany) [17,18] and the Hitachi (Japan) [19], available up to respectively 150 and 100 m^2 membrane area have their parallel shafts in the same plane. KMPT company (Vierkirchen, Germany) offers a two-shaft module with rotating overlapping ceramic membranes of up to 16 m^2 area with pores size from 7 nm to 2 μm. The Novoflow company (Oberndorf, Germany) manufactures two types of single shaft rotating MF and UF ceramic membranes systems, the CRD (using 152 mm diameter ceramic disks, for a maximum membrane area of 5 m^2) and the SSDF using 312 mm ceramic disks for a membrane area of 15 m^2

Figure 2



Spintek module with rotating membranes.

Figure 3



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Industrial MSD module with 8 parallel shafts and 31 cm ceramic disks. Courtesy of Westfalia Separator.

per module. The SSDF is also available with composite MF-UF-NF membranes of 55 cm diameter with 25 m^2 of membrane per module.

Vibrating systems

An original concept, the vibratory shear-enhanced processing (VSEP), proposed in 1992 [20], consists of a stack of circular organic membranes separated by gaskets and permeate collectors (Figure 4), mounted on a vertical torsion shaft spun in azimuthal oscillations of 2–3 cm amplitude by a vibrating base, at its resonant frequency of 60.75 Hz. The shear rate at the membrane is produced by the inertia of the retentate and varies sinusoidally with time. The use of resonance permits to minimize the power necessary to produce the vibrations, which is only 9 kW (G. Johnson, New Logic Research, USA, Personal communication, 2008), even for large units of 150 m^2 membrane area. 376 VSEP systems have been installed worldwide since the beginning. These modules can sustain pressures of 40 bars and are suitable for NF and RO applications.

The principle of shear enhancement by vibrations has also been recently applied to hollow fiber cartridges by attaching it to a sliding rod connected to rotating disk that produces axial oscillations and generate the same Stokes boundary layers as in the VSEP [11,12], but with smaller shear rates. The performance increase owing to vibrations is smaller than with the VSEP and no industrial system seems to be yet available.

Figure 4

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Industrial VSEP vibrating modules (Courtesy of New Logic Research).

Calculations of shear rates in dynamic filtration modules

Membrane shear rates for different systems have been given in the literature and permit to predict performance. For a disk or a rotor of radius R rotating near a stationary membrane, the mean membrane shear rate in turbulent regime is given by [21,22]

$$\gamma_{\text{tm1}} = 0.0164(k\omega)^{1.8}R^{1.6}\nu^{-0.8} \tag{1}$$

where ω is the disk angular velocity, ν the kinematic viscosity and k a velocity coefficient such that $k\omega$ is the angular velocity of the inviscid core between disk and membrane. This coefficient was measured to be 0.42 for a smooth disk, and at least 0.82 when the disk is equipped with 8 radial vanes 6 mm high [23–24]. Shear rates at disk rim can easily reach $3–4 \times 10^5\ \text{s}^{-1}$ or higher.

In the case of rotating membranes mounted on a single shaft, as in the Spintek, the mean membrane shear rate is [25], for turbulent flows

$$\gamma_{\text{tm2}} = 0.0317(k\omega)^{1.8}R^{1.6}\nu^{-0.8} \tag{2}$$

higher than for a disk rotating near a fixed membrane.

The membrane shear rate in VSEP systems is both time and radius dependent, but its maximum with time at the disk periphery is given by Al-Akoum *et al.* [26] from the work of Rosenblat [27].

$$\gamma_{\text{max1}} = 2^{0.5}d_1(\pi F)^{1.5}\nu^{-0.5} \tag{3}$$

where d_1 is membrane displacement at periphery. It is smaller, at about $1.4 \times 10^5\ \text{s}^{-1}$ for water than membrane shear rates in a rotating disk of same diameter a high speed [28].

Review of recent applications

VSEP modules

Ahmed *et al.* [29] investigated arsenate and arsenite removal from drinking water using a small VSEP pilot with a Toray NF membranes, Arsenate removal was found to increase with increasing TMP, pH and shear rate and reached 99% above a pH of 7. Arsenite removal was 90% at pH of 11. At a low TMP of 550 kPa, the permeate flux stabilized to 50 L h^{-1} m^{-2} after two hours, 35% higher than without vibrations.

Hodur *et al.* [30] compared the concentrations of cheese whey with a 30 kDa regenerated cellulose membrane mounted in a VSEP pilot and in a crossflow plate and frame module under same TMP (400 kPa) and temperature (25 °C). Although initial permeate fluxes were similar for both modules at 80 L h^{-1} m^{-2}, they fell after 2 h of concentration to 33 L h^{-1} m^{-2} for the crossflow module against 50 L h^{-1} m^{-2} for the VSEP when the volume reduction ratio (VRR) reached 6. Protein rejection was 99.7% for the VSEP against only 74.5% for the crossflow module. The VSEP performance could have been even better if higher vibration amplitudes above 2 cm had been used.

Petala and Zouboulis [31] removed humic acid from contaminated surface waters with a VSEP pilot and 30 kDa, 100 kDa as well as NF membranes. The same authors [32] later treated with the same pilot landfill leachates waste waters using successively MF, UF (100 and 10 kDa) and NF membranes. Their data confirmed that VSEP high shear rates increased COD and small solutes removal as compared to crossflow filtration while maintaining large and stable permeate fluxes of 100 L h^{-1} m^{-2} at 10 kDa and 150 L h^{-1} m^{-2} at 100 kDa.

Shi and Benjamin [33•] investigated salt removal and membrane fouling in RO of model brackish water and brine using a VSEP pilot. The brine had the same ionic composition as brackish water, but with 10 times higher concentrations. They compared fluxes with and without vibrations and calculated fouling resistances. With brackish water, vibrations decreased fouling resistance at a VRR of 5 by a factor of 13. With brine, vibrations reduced fouling resistances by 60 at VRR = 2. Vibrations increased mean ionic rejection to 96% for brackish water and to 96% for brine. Moulai-Mostefa *et al.* [34] reported the separation of water from oil-in-water emulsions containing 4% of cutting oil, using 20 and 50 kDa membranes in a VSEP pilot. The permeate flux increased linearly with frequency until a maximum of 227 L h^{-1} m^{-2} at resonant frequency of 60.75 Hz for the 50 Da membrane at 25 °C and a TMP of 900 kPa. Permeate turbidity was 0.8 NTU, indicating good oil retention. At 20 kDa, fluxes were 50% lower, but oil rejection was complete.

In Europe, industrial VSEP installations include biogas effluents treatment, PVC latex concentration, polyethylene glycol and precious metal recovery. Main worldwide applications are treatment of landfill leachate that is very high in potential foulants, cooling blower blowdown and biogas effluent. The VSEP permitted, in NF, to concentrate the leachate by a factor of 10 while obtaining a clear permeate with permeate fluxes ranging from 225 to 170 L h^{-1} m^{-2}. Other promising fluids are oil and gas wastewaters and ethanol stillage, especially in Brazil. Large VSEP modules are used for removing solids after the fermentation process and before distillation in ethanol production from yeast. VSEP permeate was solid-free and the flux was around 65 L h^{-1} m^{-2} while fiber solid concentration rose from 3% to 18%.

Modules with longitudinal vibrations

Beier and Jonsson [35] oscillated a hollow fiber cartridge of 488 cm^2 membrane area in a cylindrical tank with a small amplitude, varying from 0.4 to 2.35 mm at a frequency up to 30 Hz and used it for enzyme recovery from aqueous solutions. The critical flux increased with shear rate, as $\gamma^{0.375}$ and reached 50 L h^{-1} m^{-2}. Genkin *et al.* [12] constructed a similar system of 57 cm^2 membrane area with 0.2 μm pores hollow fibers. The maximum amplitude was 4 cm at a maximum frequency of 10 Hz, giving a membrane shear rate of 2000 s^{-1} when tested with a 5 g L^{-1} yeast suspension. The maximum critical flux at 10 Hz was 75 L h^{-1} m^{-2}.

Gomaa *et al.* [36] built a module with a plane membrane oscillating vertically in a tank containing a 3 g L^{-1} yeast suspension. The permeate flux increased with increasing amplitude and frequency, but slowly above 15 Hz. Kim *et al.* [37] discussed the applicability of longitudinal or transverse vibrations to a hemodialyzer in order to enhance toxins removal. They concluded that the gain in toxin clearance could permit to miniaturize a wearable external artificial kidney, but did not provide any experimental data.

Applications of rotating disk systems

Sarkar and Bhattacharjee *et al.* [38•] described an original system consisting in a membrane disk rotating next to a contra-rotating rotor, used in UF at 5 kDa of a polyglycol solution in water. They varied separately angular speeds of membrane (ω_1) and stirrer (ω_2). Unfortunately the data presented do not permit to determine if it was more efficient to increase ω_1 or ω_2. It also seems complicated to build a system with stacked membranes on the same shaft rotating in opposite directions. In another paper, the same group [39] applied this technique to the recovery of proteins from casein whey, using successively a 30 kDa membrane to concentrate caseins and a 5 kDa membrane to recover lactose in permeate. With the stirrer at rest, they obtained at 50 kDa and a speed of 400 rpm stabilized fluxes of 230 L h^{-1} m^{-2} at a pH of 2.8. Fillaudeau *et al.* [40] used a RVF module (Profiltra, Boulogne Billancourt, France) with an impeller-shaped rotor, rotating between two membrane disks for clarification of rough beer. The impeller produced TMP variations that vibrated the membranes and possibly contributed to their cleaning. The permeate flux exceeded 250 L h^{-1} m^{-2} at 4 °C with a 1.1 μm pore membrane, much higher than with crossflow filtration.

Tamneh and Ripperger [41] compared the performance of a MSD lab pilot in single and double shaft configurations to quantify the gain in flux owing to overlapping membranes. From electrical power measurements, they concluded that the membrane shear stress in double shaft configuration was about twice that in single shaft one. This was confirmed by the absence of cake formation with 2 shafts and at a speed of 750 rpm, the flux remained steady at 1900 L h^{-1} m^{-2},while it dropped rapidly to 400 L h^{-1} m^{-2} with one shaft. Since ceramic membranes for the MSD were only available in limited pore size or cut-offs, Tu and Ding [42•] replaced them by disks equipped with two nylon membranes of same size and pore diameter (0.2 μm) as original ceramic membranes to concentrate $CaCO_3$ suspensions. Maximum permeate fluxes were higher at 300 kPa and 1930 rpm for nylon membranes, reaching 850 L h^{-1} m^{-2} versus 760 L h^{-1} m^{-2} for ceramic membranes, owing to their higher permeability and hydrophilicity.

Espina *et al.* [43••] described a two-stage MF-UF process for fractionation of milk proteins using a MSD pilot for extracting casein micelles in MF retentate and 80% of β-Lg proteins in permeate. This permeate was ultrafiltered at 50 kDa in a rotating disk module to recover α-La in permeate with a 90% transmission and a mean flux of 400 L h^{-1} m^{-2} up to VRR = 3. Luo *et al.* [44•] treated dairy waste waters using rotating disk pilot with a NF membrane, while measuring the power consumed. Since the permeate flux increased with increasing shear rate and TMP, the specific energy consumed per m^3 of permeate was minimal above a TMP of 30 bars and a shear rate of 2×10^5 s^{-1} and ranged from 12 kWh m^{-3} at VRR = 1 to 26 at VRR = 4. The same rotating disk system, together with a Rayflow flat system equipped with the same 40 kDa membrane, were used by Frappart *et al.* [45] to separate microalgae from sea water. In concentration tests, the rotating disk module yielded a flux of 80 L h^{-1} m^{-2} at VRR = 3 versus 35 for the Rayflow.

Discussion

It is clear that dynamic filtration systems cannot replace all cross flow filtration modules, as their cost per m^2 of membrane is higher, especially when compared with spiral wound modules and their maintenance may be expensive. If a waste water treatment can be achieved using spiral wound modules, this is clearly the best solution, but if their use require costly elaborate pretreatments or if further retentate concentration is not possible by crossflow filtration, then dynamic filtration may be a good alternative and used as final step after cross flow filtration. For instance Delgado [46] has successfully tested a VSEP at El Paso desalination plant for extracting fresh water from concentrated brackish water, a task that could not be achieved by crossflow filtration. In a potable water plant in California, the volume of RO concentrate needed to be reduced before disposal and the most economical solution was to further concentrate it using a VSEP by a factor of 6.6 and to discharge it in an evaporation pond [47]. Dynamic filtration systems can, often, directly treat effluents by NF or RO without pretreatment, which can reduce the cost of the whole process. At high shear rate, a dynamic NF module can sometimes yield the same microsolute rejection as a RO crossflow module with a much larger flux.

Conclusion

The interest in dynamic filtration has been growing in recent years. Its benefits in terms of permeate flux and membrane selectivity has been confirmed by many investigators and seems to be even more important in NF and RO than in MF and UF. Presently the most active company in this field seems to be New Logic Research which is the oldest and sells its VSEP worldwide for a large range of applications, biogas effluent and waste water treatment, landfilled leachates, ethanol process waters, processing of phosphate fertilizer, and so on. Several German companies have built industrial modules with ceramic membranes rotating on parallel shafts with membrane area of up to 150 m^2. However, information on their diffusion is hard to get. One of the main advantages of this technology is that it gives a choice between increasing the flux by factor of 3–5 relatively to crossflow filtration at high rotation speed or obtaining the same flux as crossflow filtration at low speed but, apparently, with a large energy saving.

Dynamic filtration can also be used in addition to crossflow filtration when treating highly concentrated fluids with high foulant content. It is then surprising that their acceptance by industry seems still to remain limited.

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