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Solve Membrane Fouling Problems with High-Shear Filtration

High-shear advancements are allowing membrane separation systems to displace some conventional separation methods such as centrifuging, evaporation, and clarifying. Applications range from wastewater treatment to biological separations.

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Over the last few decades, membrane-based separation methods have enjoyed considerable use in the chemical process industries (CPI). This increased interest has been driven by advantages membrane systems have over many separation systems such as centrifuges, bioreactors, vacuum filters, and evaporators. Some of the advantages include a crystal-clear filtrate, flexibility in separation quality based on filter media, and materials compatibility due to a wide range of membranes available.

Much of this technology was developed after World War II, yet, several factors delayed an upswing in the popularity of membrane separations until the 1970s. The challenges that limited the use of membrane filtration as a viable, production-scale separations alternative were unreliability, high cost, and slow fluxes which ranged from 34 to 102 L/m^2/h.

Fouling problems

By far, the largest contributor to these limitations was — and still is — fouling, in which solids in the feed accumulate on the membrane and, over time, clog the pores and gaps in it. Fouling creates several problems:

Throughput is reduced and flux through the membrane slows. As a result, the membrane's performance never stabilizes, but continuously deteriorates, making the process extremely unreliable. Moreover, because the membrane degrades with required cleanings, fouling leads to frequent membrane replacement. This drives up overall system costs to uneconomical levels.

Tangential flow

By the late 1960s, tangential or cross-flow filtration systems were developed to combat membrane fouling. These systems consisted of membrane elements placed in a plate-and-frame, tubular, or spiral-wound cartridge assembly through which the feed stream was pumped at a high velocity. The net flow of the feed was, therefore, parallel to the membrane, as opposed to the old dead-end filtration. Forces produced by these feed systems sheared liquid near the surface of the membrane and, thus, removed trapped particles, which tended to keep the membranes clean for some period of time. The new technology was able to delay fouling sufficiently to make chemical cleaning necessary every few days, rather than hours or minutes in the absence of tangential flow.

Nevertheless, several years ago there were many CPI applications still requiring higher performance and lower operating costs from membrane technology. For example, in biotechnological applications where proteins and enzymes were being isolated from lysed cells, high concentrations of organic materials would collect on the membrane surface and act as an additional filter.

This layer of material would be held to the membrane by a stagnant boundary layer and the affinity of the feed material for the membrane. This process

of accumulation would restrict the flow of valuable protein through the membrane.

Cross flow, while adequate in other situations, was simply not effective enough for many applications where the product was extracted and sold by the milligram. Even some less exacting industries such as wastewater treatment found the flux rates of conventional tangential membrane separators to be too low for high-yield industrial processing. What they needed was volume of product, but the high fluxes required could only be achieved with tangential flow at such high velocities that the cost of separation became dominated by the cost of energy. Thus, despite all the improvements that had occurred in membrane separation technology, some industries still found traditional separation methods more economical.

The designers of cross-flow systems were on the right track: Hydrodynamic shear can be used to effectively prevent membrane fouling. The trick was to focus the fluid turbulence and shear at the membrane's surface, which would disperse foulants much more effectively and lessen the need for large cross flows that consumed high amounts of energy.

High-shear filtration systems

This resulted in the development of high-shear membrane separation technologies. These systems, which have only been around for about the last decade, employ mechanisms to make the amount of shear independent of the cross-flow rate. This advantage has made these modules capable of more efficient operation or more intense shear than cross-flow designs.

Whereas traditional cross-flow membrane systems produce shear at a rate of 30,000–50,000 s^{-1}, the rate of these new systems was greater than 100,000 s^{-1}. In addition, this shear rate was not wasted in the feed liquid, but rather generated at the membrane's surface where fouling was the greatest.

High-shear systems employ three different technologies: vibration, spinning disc, and spinning cylinder. All use high shear to keep membranes clean, but they do it in different ways. These new systems enable membranes to be used in applications ranging from the treatment of wastewater to delicate biotech separations.

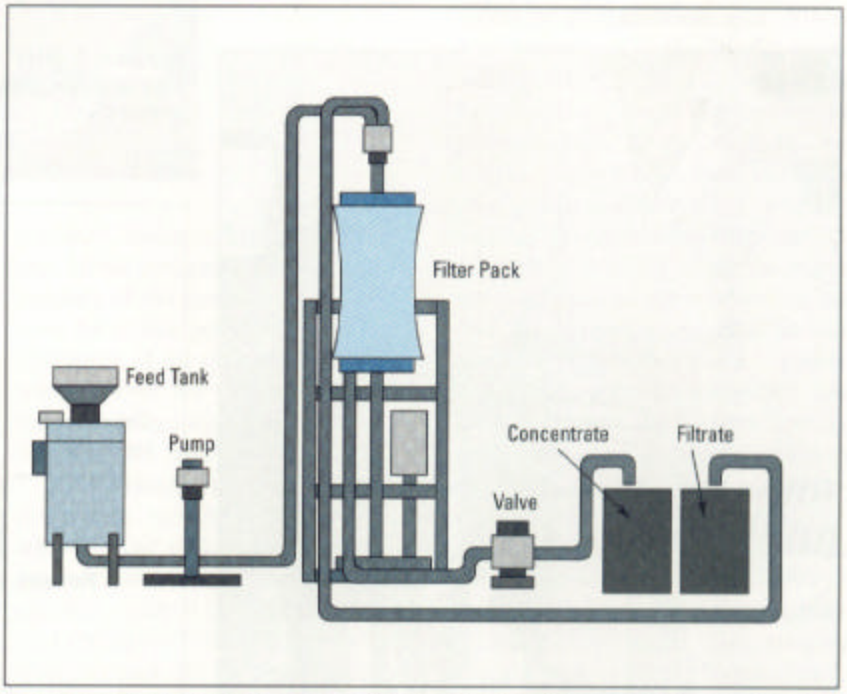
Vibration antifouling technology

Instead of pumping water across the membrane to produce shear, the vibratory shear enhanced process (VSEP) system moves the membrane itself. In a VSEP machine, the membrane or filter module is cylindrical and vibrates in a twisting motion (Figure 1). This produces shear waves that propagate sinusoidally from the surface of the membrane leaf elements stacked inside the cylinder, so that solids and foulants do not have the chance to adhere to the membrane's surfaces. Meanwhile, the feed slurry flows at about 1.5–2 gpm across the gaps formed by 10–500 parallel membrane leaf elements.

VSEP concentrates the shear right at the membrane's surface. The problem with cross-flow antifouling techniques is that the bulk of the energy fed into the system is used to maintain the flow. Up to 90% of the energy never actually reaches the membrane. Vibratory modules, however, concentrate 99% of the supplied energy at the surface of the membrane. Therefore, the first advantage of vibratory systems is their increased energy efficiency.

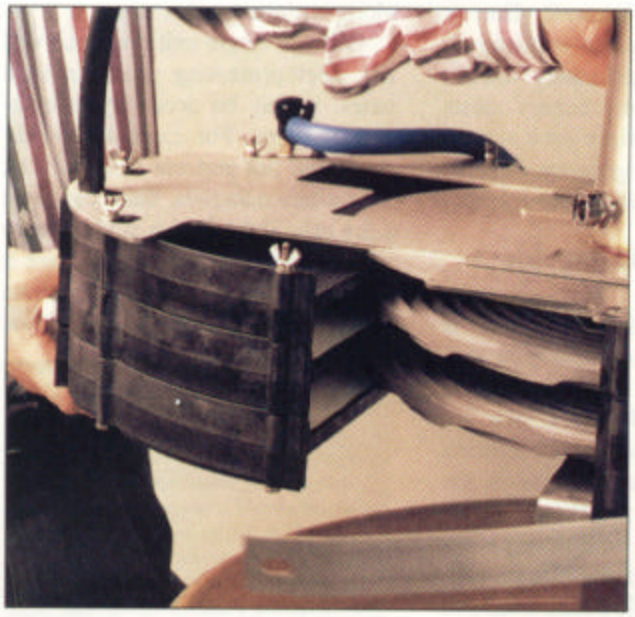
A VSEP machine vibrating at a nominal 1-in. peak-to-peak displacement at 60 Hz produces a shear rate of about 150,000 s^{-1}. This is about 3–5 times the shear rate attainable in cross-flow systems, which results in a more thorough dispersal of foulants. This energy efficiency allows higher shearing stresses without incurring prohibitive operating costs.

VSEP is suitable for the concentration of submicron particles and colloids, and treatment of industrial



■ *Figure 1. Setup of VSEP machine. The membrane or filter module is cylindrical and vibrates in a twisting motion. (Courtesy of New Logic International)*

A smaller unit (mini DMF) might have a couple of square feet of membrane area, while a full-scale system contains 10–30 ft². The smaller unit is for biotech applications such as cell lysate recovery. As explained above, an unwanted gel layer can form on the membrane and act as an extremely fine filter, resulting in a loss of protein macromolecules. With DMF technology, the gel layer is dispersed and the protein recovery rate becomes higher. Because product quality is so important in biological separations, the mini unit handles very small amounts of medium and can contain as little as 0.33 ft² of membrane. The process environment is entirely isolated, since the disc in the unit is spun via a magnetic coupling. The unit can be sterilized, so there is no risk of contamination. The mini DMF can consistently achieve protein recovery rates over 95%. This has put DMF in a niche once dominated by centrifuges, depth filters, and liquid/liquid extraction methods.



■ *Figure 3. VFP generates toroidal vortices all over the surface of the active membrane by a spinning, cylindrical rotor mounted in a tubular casing. (Courtesy of Membrex)*

Spinning cylinder

Vortex flow perfusion (VFP) is similar to DMF in function, but differs from both DMF and VSEP in execution (Figure 3). Like DMF, the VFP system separates out valuable substances in small volumes of liquid, and improves the thoroughness of separation and the flux by dispersing the gel layer.

However, instead of using parallel shear to prevent fouling, VFP generates toroidal vortices all over the surface of the active membrane by a spinning, cylindrical rotor mounted in a tubular casing. The membrane lies on the inside of the casing and, as the rotor spins, the vortices formed between the rotor and the membrane transport away potential foulants. The cleaning action of the vortices reduces the consistency of the fouling layer and allows for stable permeate flow rates. The speed of the rotor can be varied, which allows the operator to select the level of gel dispersal and, therefore, the flux rate.

VFP systems are most suitable for protein recovery in bioreactors, where living cells such as bacteria are introduced into a culture medium. The medium is continuously cycled through a VFP module to selectively extract the proteins produced by the cells. The VFP system's design is conducive to cell fermentation, since living cells that are exposed to the gentle cleaning action of the vortices remain viable for over three months. In addition, the rotor itself is entirely isolated from the motor, which turns it via a magnetic coupling. This ensures the sterility of the main cylindrical unit, since no parts subject to leakage (such as rotary seals) ever come into contact with the cell medium.

System differences

Although high-shear membrane separators perform well as a whole, each particular technology has conditions and applications in which it works best. The main difference between spinning disc and cylinder, and vibratory modules is the amount of energy required to run each one. For example, in spinning discs, a motor can drive only a few of the discs, each of which keeps only two membranes clear. At the same time, a slightly stronger motor can be used in a vibratory module to keep hundreds of membrane surfaces clean. As a result, vibratory machines are more energy efficient, using only 10 hp to vibrate over 1,000 ft² of membrane area. Vibratory machines can also handle more-viscous feed streams efficiently. The exact viscosity level is based on the process fluid. As the material becomes more viscous, more energy is required to maintain the 1-in. peak-to-peak displacement. Once the vibrational system is using the maximum energy and not operating at the 1-in. design amplitude, then the flux rate will lessen. There is a trade-off, however, since a rotating disc can be spun at extremely high speeds, resulting in a shear rate which is many times as intense as in vibratory machines.

In addition, vibratory machines are not cost-effective for low-volume (less than 5 gpm) applications. VSEP, for example, uses roughly the same drive mechanisms regardless of the size of the filter pack. The result is that, while VSEP ma-

wastewater. Other applications include latex concentrating, acid clarification, pigment washing and concentrating, process water/wastewater filtration, mineral clay dewatering, and catalyst washing and concentrating.

One of the applications of larger VSEP machines has been in inorganic/organic pigment washing. Typically, pigments that need to be washed before they reach product quality are diluted with a solvent and then concentrated. This process is often repeated several times. With VSEP, however, the washing can be done in a continuous cycle in which the concentrated pigment solution is directed back into the feed tank. This saves labor, since VSEP cycling eliminates numerous procedural in-betweens that require operator supervision. In addition, regulations restricting organic solvent emissions are not a problem, since the closed system prevents almost all vapor leakage.

Another use for the VSEP system is in industrial wastewater treatment. Conventional treatment of wastewater often is a multistep process: A typical process might include chemical addition, then a clarifier, then a filter press, and finally ion exchange. VSEP rolls the whole operation into one machine equipped with nanoporous membranes which remove everything from large particles to dissolved molecules on the order of nanometers, without creating any gel layer or fouling layer.

Often, a single unit operation will not meet processing goals. In such cases, it may be necessary to combine systems.

Spinning disc

Dynamic membrane filtration (DMF) prevents fouling through the creation of intense shear forces which lift away foulants. Unlike VSEP, DMF generates its shear forces in the gaps between rotating solid discs and stationary membrane surfaces that flank them on either side (Figure 2). The resulting turbulence develops a significant shear at the boundary layer formed on the membrane surface. As with VSEP, the induced shear minimizes concentration polarization and the buildup of a gel layer which causes the rapid decrease in the permeate flux characteristic of conventional cross-flow filters. In DMF, the rotating disc offers the additional advantage of variable shear, which is controlled through the speed of the disc making precise adjustments possible.

DMF systems are suited for concentrating high-value materials such as those found in the pharmaceutical industry. An example is the separation of two nearly identical proteins which requires high shear rates to let one protein pass through the membrane while the other is retained.

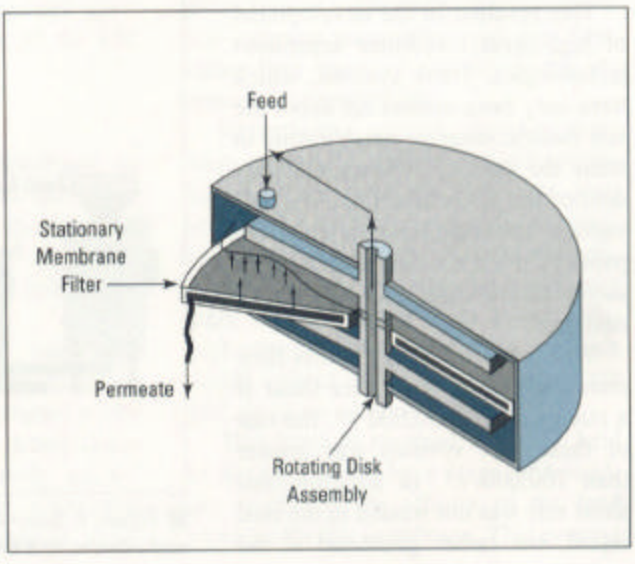


Figure 2. DMF system. Rotor assembly, stationary membrane filter, and flow paths to feed, retentate, and permeate. (Courtesy of Pall Corp.)

chines become more cost-effective as their output increases, both rotating disc and VFP modules are more cost-effective at low volumes of less than 1 gpm.

There are differences between spinning disc and spinning cylinder technologies as well. As noted above, a spinning cylinder module is gentler on the feed stream than a grooved, winged, and machined rotating disc, and so it is better suited to cell fermentation. At the same time, the design of cylinder modules is such that it is difficult to scale them up for larger applications, while spinning discs can be stacked and, thus, augmented for higher volume feed streams.

Limitations

In all cases, membranes have limits in terms of pH, temperature, and pressure, which make them unsuitable for certain feed applications. Most membranes do not perform well or cannot operate in extreme pH ranges: less than 1 and greater than 12.5. Temperature limitations vary depending on the membrane material and the backing. However, temperatures greater than 150°C, although generally beneficial to the flux, can damage membranes.

VFP and DMF systems are not as economical for large flow rates such as those found in wastewater applications. These systems tend to be suited for biotech applications where the product has a high value, but a low processing volume. As mentioned previously, the VFP system tends to be gentler on the processing material as compared with the DMF and VSEP.

In the low-volume range, VSEP systems are not as economical as the others are, with the smallest industrial system processing 3–10 gpm. The VSEP systems are also not suitable for pressures above 600 psi, which limits some of the separations in the reverse osmosis region.

Costs

Installed costs based on $/ft^2$ favor the vibrational membrane system. These systems have a small footprint, 4×5 ft for a unit with up to 1,600 ft^2 of membrane area. For VFP and DMF systems, costs are higher because the larger systems contain only about 100 ft^2 of area. These two systems are priced to process high-margin, low-flow materials.

All three units are fully automated with the primary maintenance being that for the drive systems. Another maintenance cost is that of the membranes, which varies depending upon the type that is used and the frequency of replacement. Energy costs vary with each application, being highest for extremely viscous materials. However, energy costs are relatively low since each system uses the energy to generate shear to improve the processing throughput.

Selecting a solids/liquids separator

For every application, there is usually a choice of separation systems which makes selecting the best system difficult. However, there are some guidelines to determine whether high-shear filtration is the right choice. As mentioned previously, membranes do not or cannot perform under extreme pHs or temperatures. For such conditions, you will need to use another solids/liquids separator such as a filter press or a rotary vacuum drum filter.

The choice is based on well defined process goals. For example, if you need a system that can process 500–1,000 gpm without a perfect separation, then you would use a centrifuge. However, a high-shear system would be preferred if you need a clear filtrate. A filter press or evaporator is appropriate when a dry cake is needed since a high-shear membrane system will only produce a thick sludge. Finally, traditional cross-flow membranes perform well on streams containing less than 1% suspended solids which do not need to be concentrated to a thick slurry. The exact maximum concentration depends on the feed solids. A high-shear setup usually yields a product that is 3–4 times more concentrated, along with better flux rates.

Often, a single unit operation will not meet processing goals. In such cases, it may be necessary to combine systems. For example, a filter press will not perform efficiently on very dilute materials, but it can form a dry cake if the feed is slightly more concentrated. Here, you could use a high-shear filter to pre-concentrate the stream to the press. CEP

Further Reading

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