Technical Note

Performance of High-Area Millipore Express® Cartridge Filters

Scaling Considerations to Maximize the High-Area Advantage

Abstract

Sterilizing-grade membrane filters are formatted in a wide variety of pleat configurations. High-density pleat geometries provide increased productivity per device, a smaller filter footprint, and improved filtration economics. However, a high-density pleat arrangement can present unique challenges when scaling up from discs to cartridges.

An M-pleat pattern, as used in the Millipore Express® SHC and Millipore Express® SHR with Prefilter (SHRP) sterilizing-grade filters, was demonstrated to provide up to 100% more membrane area than a conventional pleat pattern. High-area filters were found be most advantageous for mid- to high-plugging streams in which the membrane is the dominant resistance to flow, so that the scalability from discs to devices is essentially linear.

There is a potential exception to the high-area advantage in plugging streams: when caking is the primary fouling mechanism, the particles may not be able to access the full surface area of the membrane. In this case, prefiltration should be considered. For non-plugging streams, a looser, conventional-pleat pattern may be preferred because, with this pattern, non-membrane flow resistances are minimized.

A model was developed to predict device productivity efficiency as a function of the filtration properties of the filtered stream. This model can be used to assess which applications can most benefit from high-area pleated devices and which applications should use conventional pleat configurations.

Introduction

For filters designed to minimize filter footprint and improve filtration economics, maximized filtration area density is a primary goal. For sterilizing-grade filters operated in dead-end mode (also known as normal flow filtration), a pleated membrane format has commonly been used to achieve this objective. Pleated formats, however, may impose flow resistances that impact the filtration efficiency of the device, particularly at high pleat density geometries [1, 2]. Factors that affect filtration efficiency include pleat length, membrane permeability, thicknesses, and flow characteristics of the upstream and downstream supports, as well as other aspects of the pleat configuration.

An M-pleat pattern (see **Figure 1**) has been developed that allows for a nearly 100% increase in membrane area compared to the area in conventional pleat patterns. Pleat design has been optimized for maximum area density, good device manufacturability, and a high level of device robustness. Improvements have been made in the ratio of long to short pleats, pleat compression, and upstream and downstream support materials. These improved designs still easily fit into existing cartridge sleeve and length dimensions.

A critically important filter design consideration is, of course, filtration efficiency—how well does the membrane perform when it is in the filtration device. One method of measuring device filtration efficiency is to compare the performance of the membrane in a filtration device to that of the membrane in a flat-sheet format in which the flow resistance is dominated by the membrane itself. The ratio of commercial-scale filter performance to small-scale, flat-sheet performance is often referred to as the scaling factor. Ideally, the scaling factor should be at or close to unity.

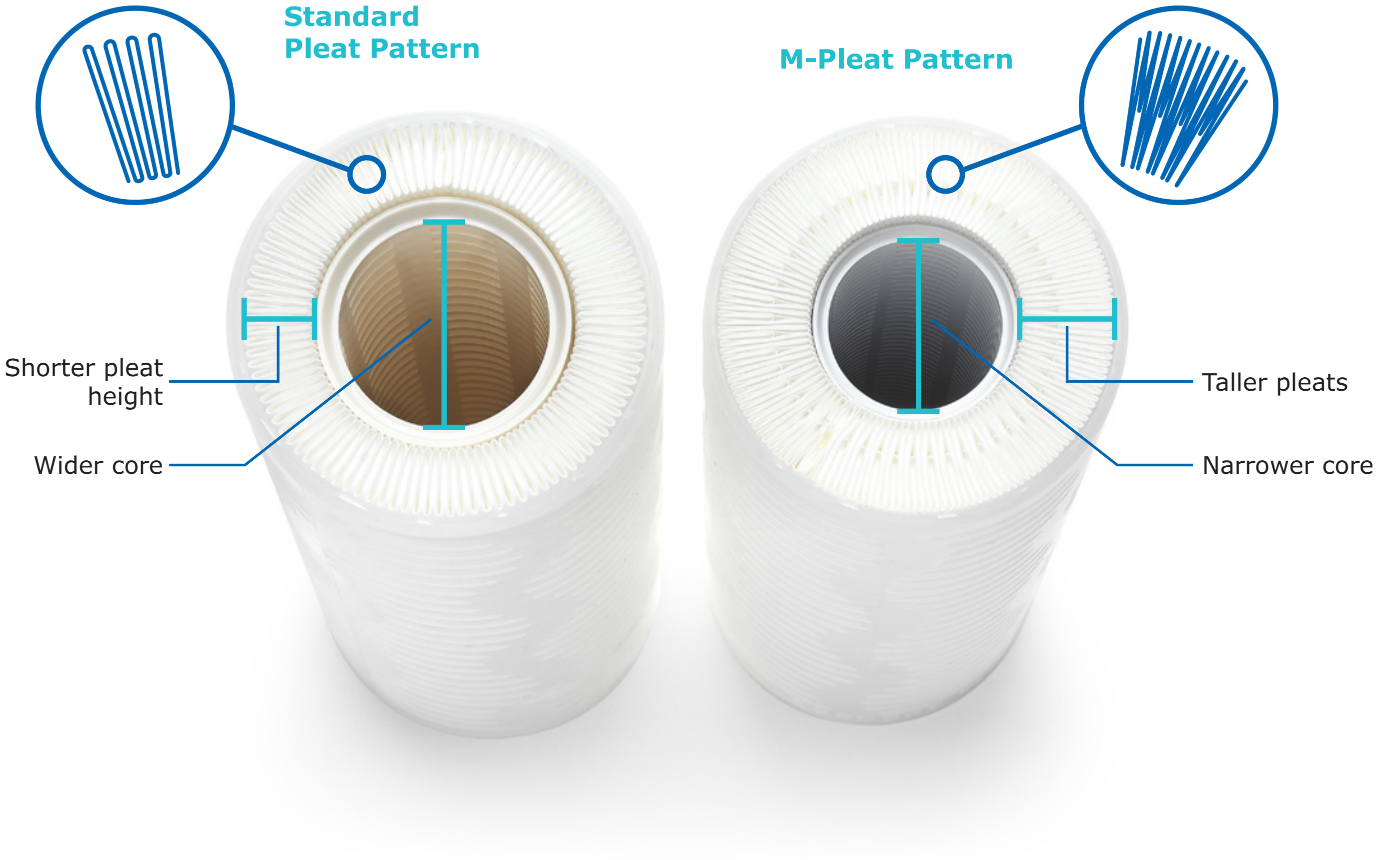

Figure 1. Conventional and M-pleat Pattern.

The scalability factor of a device cannot be defined as a single value under all conditions; rather, it must be defined with respect to a set of specified conditions. As a practical matter, there can be a compromise between other filter requirements (including high-area density) and good scalability. Scalability can also be sensitive to filter operating conditions, challenge stream characteristics, and the particulars of the selected filtration endpoint. Depending on the combination of these factors, a filter can exhibit a range of scaling factors.

In this work, high-area versions of Millipore Express® SHC and Millipore Express® SHRP devices were evaluated for scalability against a non-plugging stream (water) as well as three different plugging streams that represented a wide range of particle size distributions. Scalability was assessed as a function of particle size and degree of plugging. The filters were primarily tested for constant pressure operation, but constant flux operation was also measured.

Theoretical Background

Several factors must be considered when scaling from discs to pleated devices. These include flow resistance from the upstream and downstream supports, pressure losses from housings and plumbing, variability in filter properties, and variability in stream characteristics and operating conditions. Detailed descriptions of each of these have been given elsewhere, and each of these factors is generally applicable to any pleated filter device [3]. However, while theoretical treatments of flow restrictions in conventional pleat patterns are available, no known similar treatments have been published for the M-pleat pattern used in the devices evaluated in this work. Here we will focus on the effect of the M-pleat pattern on filter performance because factors such as membrane and process variability are not specific to high area devices.

Rather than develop a model that predicts the impact of the M-pleat pattern on filter efficiency from first principles, a semi-empirical approach is used here in which the flow resistance associated with the pleat pattern is inferred from the clean water scaling data, and then applied to a model that predicts filtration efficiency as a function of membrane plugging.

The flux through a filter can be describe using Darcy's law:

1.

$$J = \frac{\Delta P}{R_t}$$

Where J is the flux, ΔP is the pressure differential across the filter, and Rt is the total resistance to flow. Rt includes flow resistance from the membrane (Rm), the upstream and downstream supports (Rs), and the filter housing (Rh):

2.

$$R_t = R_m + R_s + R_h$$

Substitution of Equation 2 into Equation 1 gives:

3.

$$J = \frac{\Delta P}{R_m + R_s + R_h}$$

For a plugging stream, Rm will increase with throughput while Rs will be unchanged (assuming that the upstream and downstream supports do not plug). Rh will change with flow rate, but in a predictable manner.

As the membrane plugs, the resistance of the membrane becomes an increasingly larger fraction of the total resistance. This is illustrated generically in **Figure 2**. Since Rs and Rh become smaller relative to Rm as membrane plugging increases, the scaling factor increases with increasing filtrate volume (and degree of membrane plugging).

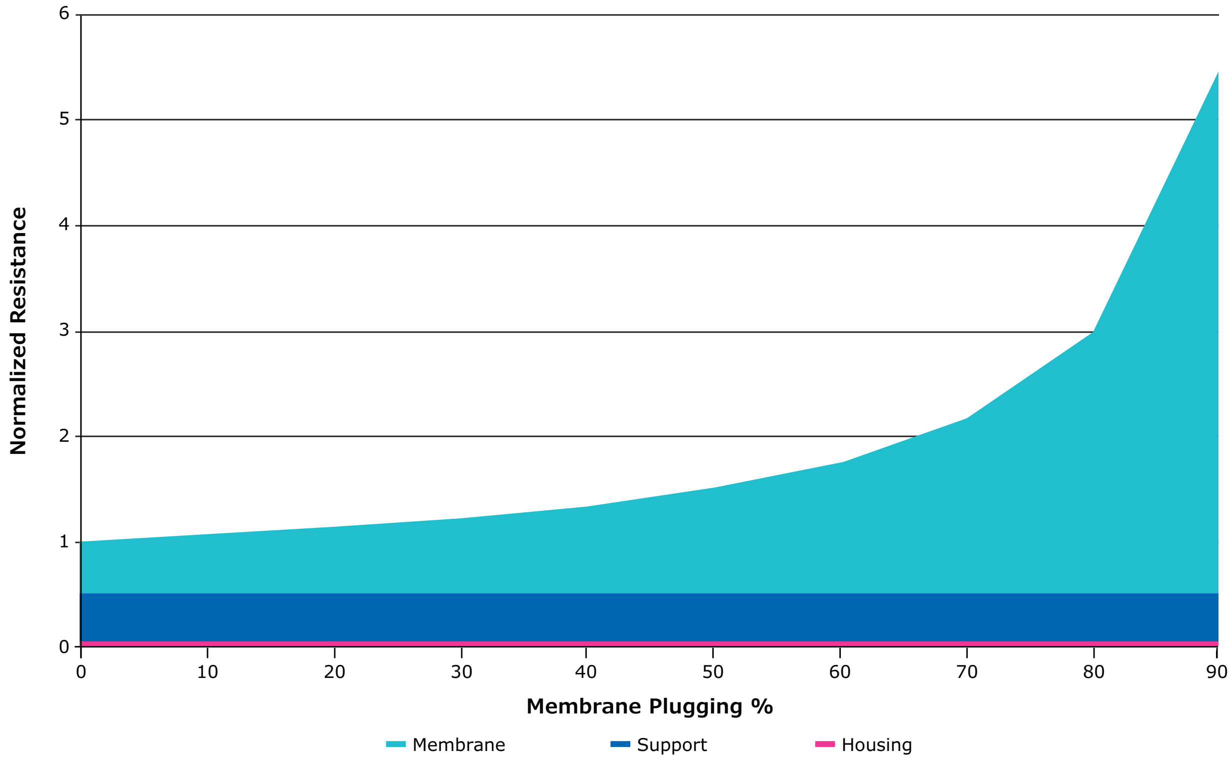

Figure 2. Components of total filtration resistance as a function of membrane plugging.

Materials and Methods

Membranes and Devices

Millipore Express® SHC high area (HA) cartridges and Millipore Express® SHC standard area (SA) products contain the same types of membranes: one layer each of 0.5 µm and 0.2 µm polyethersulfone (PES) asymmetric membrane. The Millipore Express® SHRP HA cartridges and Millipore Express® SHRP SA cartridges contain the same types of membrane: one layer each of 0.5 µm and 0.1 µm PES asymmetric membrane. Standard-area versions of these devices contain about 0.5 m^2 of effective filtration area.

In addition to these 10-inch cartridge filters, two competitor 10-inch cartridge filters were also evaluated. The cartridge types evaluated in this study are listed in **Table 1**. For the small-scale tests, 25 mm membrane discs were installed into OptiScale® 25 devices, which contain 3.5 cm^2 of effective filtration area.

Table 1. 10-inch cartridges evaluated in this study

Device code	Membrane description	Effective filtration area (m^2)
Millipore Express® SHC HA	0.5/0.2 µm PES	1.0
Millipore Express® SHRP HA	0.5/0.1 µm PES	1.0
Competitor A	0.5/0.2 µm PES	1.0
Competitor B	0.2/0.2 µm PES	1.0

Challenge Streams

Three challenge streams were used in this study; they are listed in **Table 2**. These streams represented small, mid, and large particle sizes and particle size distributions. The particle size distributions of these streams are plotted in **Figure 3**. The challenge streams were concentrated to achieve a high degree of plugging (> 90% flux decay at < 1000 L/m^2 of filtrate) within about 30 minutes at the process conditions.

Table 2. List of challenge streams for throughput tests.

Name	General description	Stream components
EMD Soy	Small particle size, narrow distribution	2.0 g/L EMD soy in DMEM with 3.7 g/L sodium bicarbonate and 1 g/L Pluronic® F-68 surfactant
Sigma Whey	Mid particle size, mid distribution	0.3 g/L Sigma Whey in PBS buffer
Soy T	Large particle size, wide distribution	0.1 g/L soy T in DMEM with 3.7 g/L sodium bicarbonate and 1g/L Pluronic® F-68 surfactant

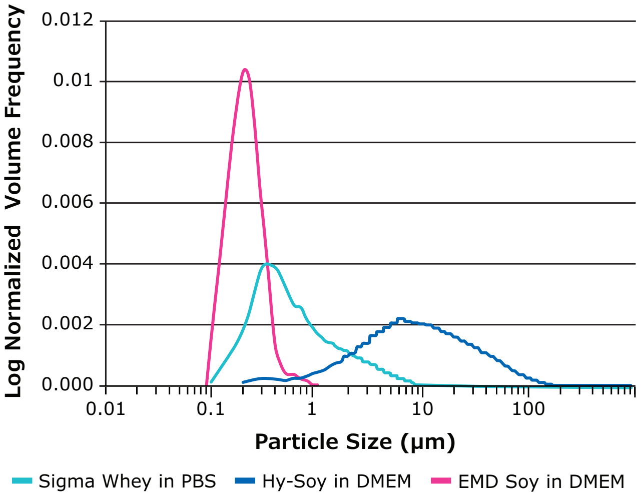

Figure 3. Particle size distributions of the challenge streams used in this study. Particle sizing data was gathered using a Malvern MasterSizer® particle sizer.

Test Method

Both OptiScale® 25 (OS25) devices and 10-inch cartridges were tested for clean water permeability at 10 psi (690 mbar) and 21–25 ºC. Following the water permeability test, throughput tests using one of the challenge streams were run at 10 psi (690 mbar). Throughput testing was run until the membrane permeability was reduced by at least 95% compared to the clean water permeability.

Results and Discussion

Water Permeability

Water permeability data for each of the membrane and device types are summarized in **Table 3**. For water, scalability factors for Millipore Express® SHC HA and the competitor devices were all approximately 0.5; the flow resistance due to the supports was about the same as that of the membrane, resulting in about a 50% loss in productivity compared to the productivity of the OptiScale® 25 device. For Millipore Express® SHRP HA, the membrane is responsible for a higher fraction of the total filter resistance, thereby resulting in a higher scaling factor.

Table 3. Cartridge-to-disc scaling factors for water permeability.

	Water permeability (LMH/psi)		
Device type	OptiScale® 25 Device	10-inch Cartridge	Scaling factor
Millipore Express® SHRP HA	411	293	0.71
Millipore Express® SHC HA	831	435	0.52
Competitor A	780	336	0.43
Competitor B	986	516	0.52

Throughput

As described in the materials and methods section, throughput performance was evaluated using multiple feed streams representing a wide range of particle size distributions. One of these streams, EMD Soy, has a relatively small median particle size (about 0.2 µm) and relatively narrow particle size distribution. Such a stream would be expected to foul the membrane through an internal pore-plugging mechanism. Constant pressure throughput versus time curves for EMD Soy comparing OptiScale® 25 capsule performance to 10-inch Millipore Express® SHC HA performance are shown in **Figure 4**.

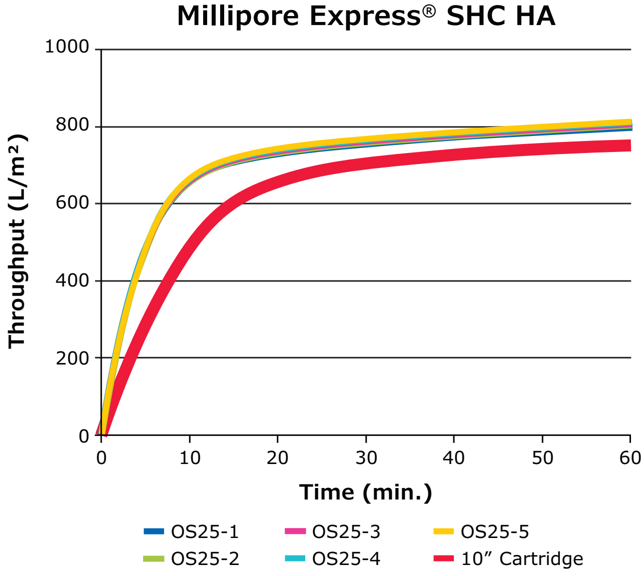

Figure 4. Throughput curves for Millipore Express® SHC HA challenged with EMD Soy.

For the EMD Soy stream, the initial flux-scaling factor is similar to that of water, but as the membrane plugs, the flux-scaling factor converges toward unity. This is because, as the membrane fouls, it becomes an increasingly larger fraction of the total filter resistance. Scaling factor is plotted as a function of filtration time in **Figure 5** for the SHC-HA cartridge. The model prediction is also plotted, which is in good agreement with the data. The throughput scaling factors for the cartridges tested in this study at 30 minutes filtration time (about 95-99% flux decay) are summarized in **Figure 6**. For this stream, scaling factors are all within about 15% (within the approximate measurement uncertainty) of 1.

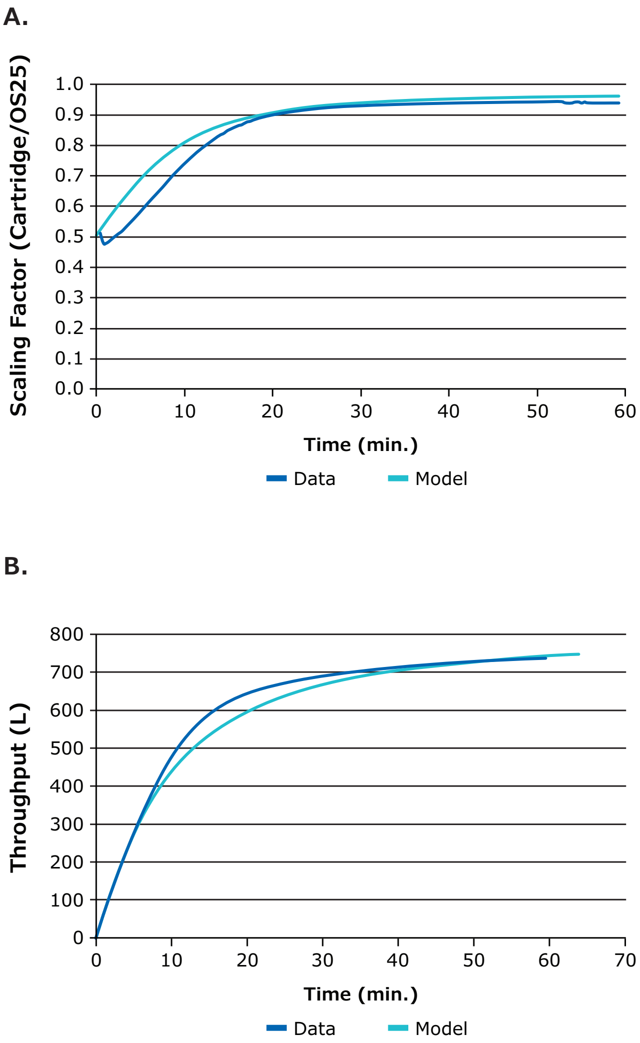

Figure 5. Comparison between data and model predictions for filtration of EMD Soy with Millipore Express® SHC HA; a) Scaling factor versus time; b) 10” cartridge throughput versus time.

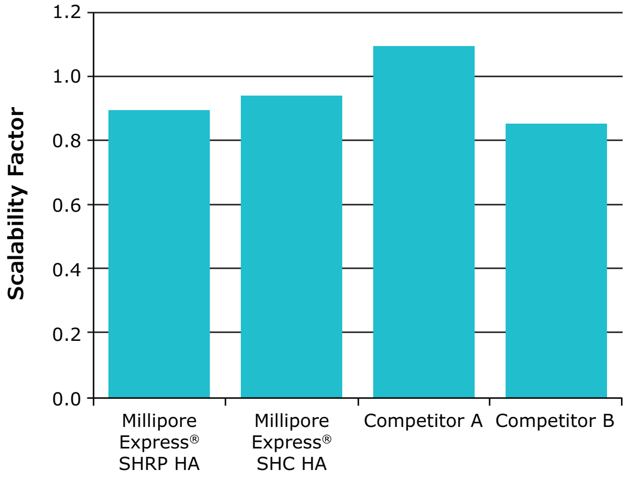

Figure 6. Scaling factors at 30 minutes filtration time using 2 g/l EMD Soy.

Throughput and flux decay curves for Soy-T (large particle size and wide distribution) are shown in **Figure 7**, and scaling factors at 30 minutes are summarized in **Figure 8**. For this stream, the initial flux scaling factors are as expected (similar to water), but as the filters plug, the scaling factors do not converge toward unity; in fact, they diverge away from unity. In contrast to the particle sizes in the EMD Soy stream, the particle sizes in the Soy-T stream are much larger than the pore sizes of the membrane. The Soy-T particles cannot enter the pore structure and therefore accumulate at the membrane surface, forming a cake.

In the OptiScale® 25 format, there is open space above the membrane surface. This facilitates unhindered cake buildup. In a densely pleated format, a nonwoven support is in contact with the membrane surface, bounded by an adjoining pleat. This limits the available space for a cake to form. Furthermore, in a densely pleated format, the particles must travel laterally through the nonwoven support before reaching the membrane. Any particle buildup at the entrance to the pleat pack prevents subsequent particles from accessing the membrane surface.

It has been previously shown that standard-area devices do not suffer nearly as much from large particle accessibility to the membrane surface[3]. Therefore, high-area devices may not be preferred to standard devices if challenged directly with a Soy-T–type stream. However, microfiltration devices exposed to supra-micron particles often benefit from prefiltration. An appropriately sized prefilter removes the large particles that would otherwise form a cake on the final filter membrane surface. With the large particles removed, the throughput advantage of high area devices can be restored.

An intermediate size particle stream, whey, was also tested. The throughput curves are shown in **Figure 9**. As with the EMD Soy stream, the flux scaling factors converge toward unity. **Figure 10** shows that the model prediction is again in close agreement with the data. It can be concluded that, for plugging streams where caking is not a predominant fouling mechanism, high area devices scale close to unity if a high level of plugging is achieved. If the level of plugging is low or intermediate, the scaling factor is also intermediate between that of what it is with water and one. In such a case, the model described in this report can be used to estimate scaling factor.

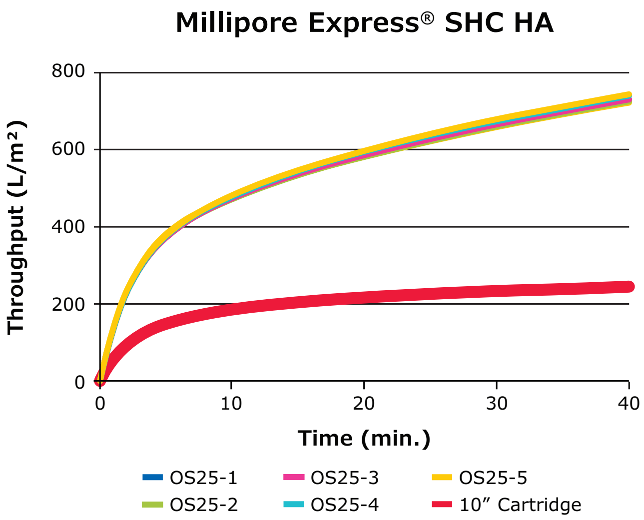
Millipore Express® SHC HA

Figure 7. Throughput curves for Millipore Express® SHC HA challenged with Soy-T.

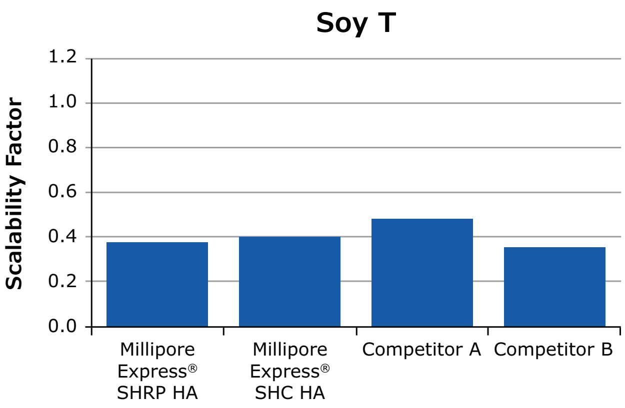
Soy T

Figure 8. Scaling factors at 30 minutes filtration time using 0.1 g/l Soy-T.

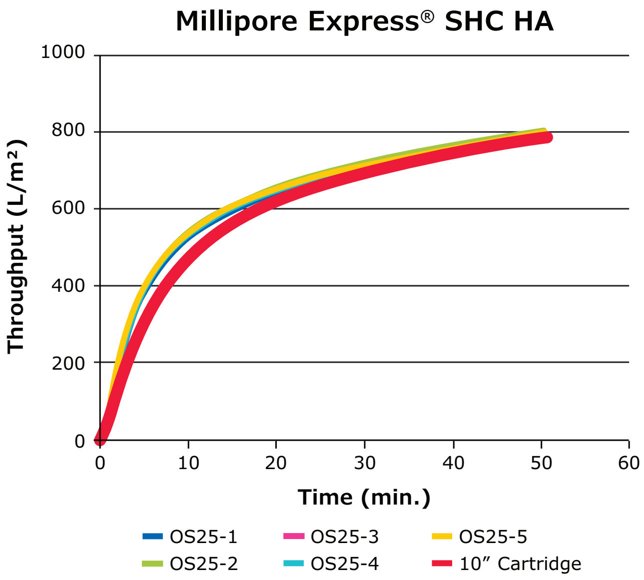
Millipore Express® SHC HA

Figure 9. Throughput curves for Millipore Express® SHC HA challenged with Whey.

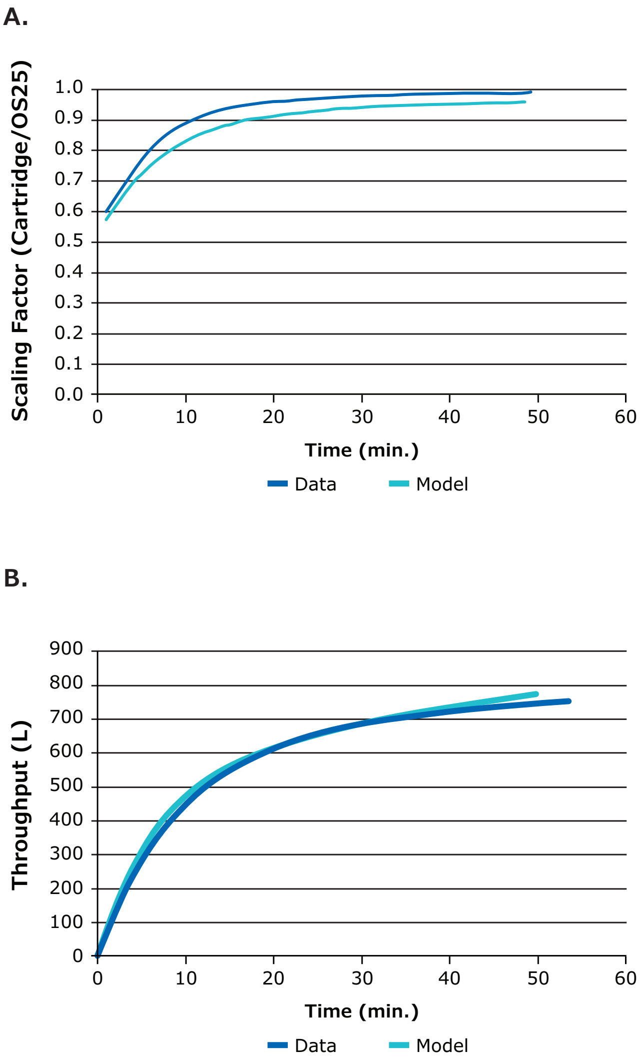

Figure 10. Comparison between data and model predictions for filtration of whey with Millipore Express® SHC HA; a) Scaling factor versus time; b) 10″ cartridge throughput versus time.

Normal flow filtration is often operated at constant pressure, but constant flow is another common mode of operation. To evaluate scalability for constant-flow operation, a Millipore Express® SHC HA cartridge was tested at a flux of 500 LMH using the whey stream. **Figure 11** shows that the initial ΔP for the cartridge was about double that of the OptiScale® 25 devices, but as the membrane plugged and reached the 20 psi (1400 mbar) filtration endpoint, the fluxes of the cartridge and OptiScale® 25 devices converged. This trend is similar to that in constant-pressure operation and demonstrates that the scalability principles demonstrated for constant pressure operation are applicable to constant flow operation as well.

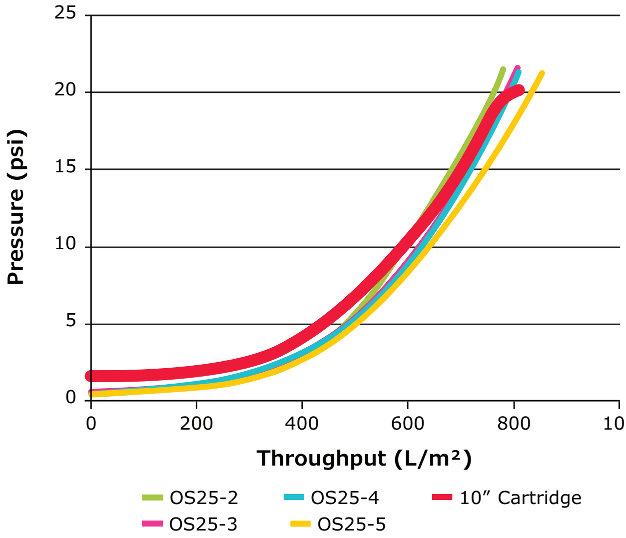

Figure 11. Scalability at constant flow operation for filtration of whey with Millipore Express® SHC HA.

While the focus of this work was on scaling from discs to high area pleated devices, including competitor devices, it is of interest to compare the absolute performance of Millipore Express® SHC HA to that of the competitor devices. Because of the high consumption of feed fluid of these cartridges, it was not possible to compare the throughput performance of these devices together in a simultaneous test. Instead, the membranes were compared together in the form of OptiScale® 25 devices. The throughput capacity test results for each of three streams are shown in **Figure 12**. For each stream, Millipore Express® SHC filters exhibited a clear throughput capacity advantage over the competitor membranes. Since both the effective filtration area and the scaling factors of all the devices are similar to each other, the Millipore Express® SHC HA 10-inch cartridge has an absolute throughput capacity advantage compared to competitor 10-inch cartridges.

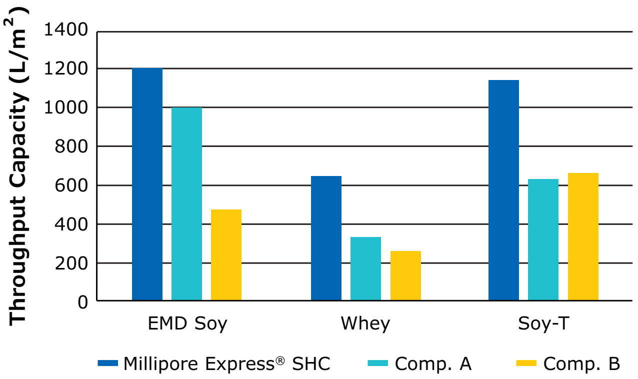

Figure 12. Comparison of membrane throughput capacities.

Conclusions

Nonconventional pleat configurations can increase filtration area in a cartridge device. High area has the advantage of lower cost per unit of filtration area, and potentially higher productivity per device. The high-pleat density within a device can, however, result in decreased efficiency in terms of utilization of contained area.

In this study, novel high-area versions of Millipore Express® SHC and Millipore Express® SHRP cartridges were evaluated for scalability relative to 25 mm membrane discs in OptiScale® 25 format. It was found that for clean water permeability, the scalability factor was about 0.5 for Millipore Express® SHC HA and about 0.7 for Millipore Express® SHRP HA. Since the HA devices contain about twice as much membrane area as the standard area devices, for non-plugging streams there was only a small flow rate per cartridge advantage of Millipore Express® SHC HA but a moderate advantage for Millipore Express® SHRP HA. For plugging streams where caking is not a predominant fouling mechanism, the HA devices exhibited near linear scalability. This was because, as the membrane fouls, it becomes the dominant resistance to flow. In such a circumstance, the HA devices have a clear advantage over the SA devices. An exception to the high area advantage can be in plugging streams where caking is the primary fouling mechanism. When the particles are larger than the membrane pores, the volume available in a dense pleat pattern to form a cake is limited. In such a case, prefiltration is recommended to remove large particles.

A model was developed that can be used to predict scalability as a function of membrane plugging when caking is not predominant. This model can be used to quantify the advantage of HA devices for a given set of operating conditions, membrane fouling properties (as determined with OptiScale® 25 testing), and filtration endpoint. The model also provides an understanding of the mechanisms underlying the measured scaling factors.

Compared to competitor devices, Millipore Express® SHC HA showed comparable scalability factors for both clean and plugging streams. However, Millipore Express® SHC filters were demonstrated to have higher absolute throughput capacity for several streams representing a wide range of particle size distributions. Since the EFA of Millipore Express® SHC HA is about the same as competitor devices, this means that, on a 10-inch cartridge basis, Millipore Express® SHC HA filters will have a higher throughput capacity than competitor devices.

References

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