SECONDARY-FLOW ENHANCED FILTRATION SYSTEM

Introduction

The largest problem for all filtration has always been fouling of the filter media. Fouling control dictates the service life of the filter in all filtration applications. In the last decade, cross-flow filtration (CFF) has found its way into more and more applications because of its much better fouling control as opposed to conventional pressure (dead-end) filtration which is prone to plugging due to the formation of a cake (deposit) layer on the filter surface. Early on, CFF was applied mainly to solute separation processes, such as ultra-filtration (UF), nano-filtration (NF), and reverse osmosis (RO). Currently, this technique is also used for micro-filtration (MF) and particulate separation (PF). Because CFF is now used in a wide range of applications, a new, patented technique that skillfully induces a secondary flow called Dean Flow has been developed by Filtration Solutions, Inc. (FSI) to further enhance CFF performance.

Background

Cross-flow filtration differs from dead-end filtration (Figure 1) because in addition to the feed fluid being pressurized against the filter media surface (common to both types of filtration), the fluid is also forced to pass across the filter media. A portion of the feed permeates though the filter media and the balance of the feed sweeps tangentially along the surface of the media to prevent the formation of the cake layer. Flow velocity is of fundamental importance to the performance of CFF. Should the flow velocity across the surface of the filter media become zero, the cross-flow ceases and dead-end filtration begins. Additionally, the cake layer that forms on the filter media becomes thicker as the flow velocity parallel to the medium decreases. The thickness of the cake layer in a flow channel is determined by the shear force on the membrane surface which is roughly in direct proportion to the feed viscosity and the feed flow velocity. Therefore, higher fluid velocity entails a thinner cake layer, a lower hydraulic resistance, and a higher filtrate flux.

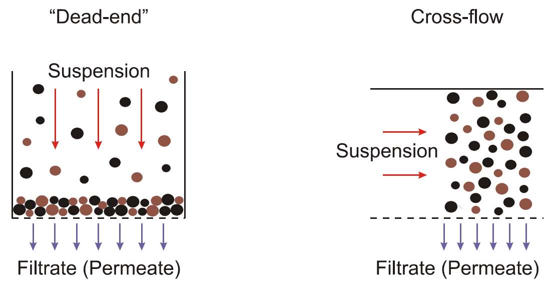


Figure 1: Dead-End vs. Cross-Flow Filtration

Because of the tangential sweeping force, CFF offers quite an improvement over dead-end filtration for surface fouling control of filter media. However, there are still two inherent problems with CFF that remain to be improved. The first problem is concentration polarization. Because the feed mixture components permeate at different rates, concentration gradients form in the fluids on both sides of the filter media. This concentration polarization reduces the permeating component's concentration difference across the filter media, thereby lowering its flux and the membrane selectivity. The second problem is the uneven pressure distribution caused by the pressure drop between the feed inlet and outlet. The result is that more fouling tends to occur at the inlet end, which has a higher trans-media pressure drop than the outlet end.

The incorporation of Dean Flow into a CFF application provides an effective method to cope with the two inherent CFF problems and thus increases the service life of conventional cross-flow filters.

Generation of Dean Flow

W. R. Dean first brought up the generation of the Dean Flow phenomenon while studying the secondary flow created by the motion of fluid in a curved pipe [1]. When flow passes through a straight pipe at a critical velocity (i.e. the transition between laminar and turbulent flow), a sudden increase in the loss of head is observed. No such sudden increase in the loss of head is generally observed in a pipe of significant curvature, even when the flow rate is much higher than the critical rate. This phenomenon suggests that the pressure drop is much smaller in a curved pipe than in a straight pipe at the same flow rate. This flow in a curved channel has been characterized as double-vortex flow [2], as shown in Figure 2. The Dean number K is the characteristic parameter used to describe the conditions for the formation of vortices in this situation:

$$K = (v \cdot d/\upsilon) \cdot (d/R)^{0.5}$$

where v is the tangential velocity of the fluid, d is the diameter of the pipe, R is the radius of the pipe curvature, and υ is the kinematic viscosity of the fluid. The higher the Dean number is, the stronger the vortices are.

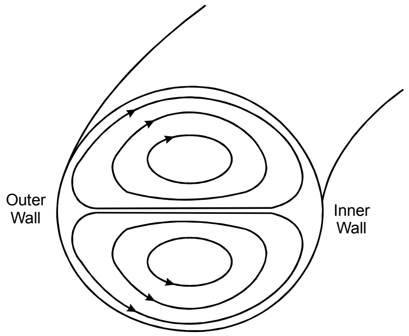


Figure 2: Dean Flow in the Cross-section of a Curved Pipe

Early studies [3] on this secondary flow phenomenon were mainly focused on the heat transfer in a coiled heat exchanger. These studies showed that the heat transfer coefficient was much higher in a curved pipe than in a straight pipe. In recent years, studies [4, 5] on the double-vortex secondary flow have shown that it can be employed to greatly reduce the filtered material concentration polarization in filters. As the fluid spins in a curved channel, a control mass of fluid travels radially, eventually reaching the outer wall where it must change direction toward a return path. The resulting flow profile takes the form of a vortex in which a fluid particle moves in three dimensions. Experimenters [6] have reported that such a vortex flow exists in both the laminar flow and turbulent flow region, and the vortex structure persists up to 1000 times the critical flow rate. When incorporated into a filter design, this vortex profile generates a high shear rate which acts to transport material (e.g. debris) away from the membrane surface to reduce concentration polarization.

Besides the alleviation of the concentration polarization through the vortex mass transportation flow profile, Dean Flow is also useful for equalizing the fouling distribution difference between the filter inlet and outlet that is normally encountered with CFF. The uneven fouling problem can be minimized and the filtration performance can be further enhanced by generating a custom Dean Flow in which the strength of its vortex action is directly proportional to the flow rate and the geometry of the curved channel being used. Since the feed flow has the highest tangential velocity at the filter inlet in CFF, this means that the vortices are the strongest at the inlet end. This feature can compensate for the higher fouling at the inlet end of the CFF filter.

Design of FSI's Secondary-Flow Enhanced Filtration System

The filter design developed by FSI makes use of a cross-flow filtration assembly that is composed of a cylindrical filter housing and a cylindrical filter (can be either a membrane or a depth filter) mounted within the housing cavity as shown in Figure 3. This arrangement processes the fluid from the outside in. A spiral guide extends through the annular gap between the interior surface of the housing wall and the outer filter surface so as to define a fluid flow passage extending between the feed input and the retentate output. Fluid enters the filter assembly and into the fluid flow passage along a tangential flow path around the filter. The pitch and width of the spiral guide defines the cross-sectional area for the fluid flow passage. With proper design of the flow passage based on operating conditions, Dean Flow will be generated as the feed flow travels along the spiral fluid flow passage. Note that this arrangement is also favorable for back-washing by the admission of dynamic bursts into the filtrate side (located at the center of the cylindrical filter).

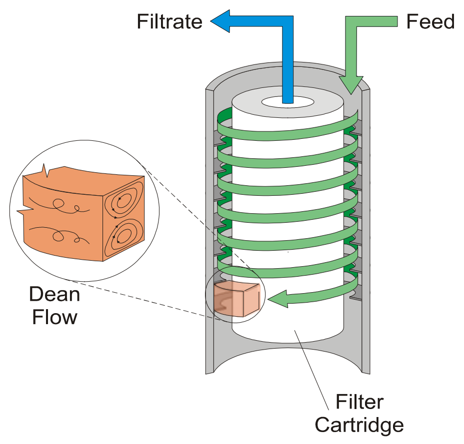


Figure 3: Dean Flow Enhanced Filtration System

To effectively generate Dean Flow, a computational fluid dynamics (CFD) analysis was performed based on the geometries of prospective housings within the practical ranges of flow capacity. The aspect ratio of the flow passage cross-section was chosen as a parameter in an analysis to optimize the filter housing design. Figure 4 shows an example of the CFD model, which covers 180º of a spiral passage as shown in Figure 3. The flow was treated as an incompressible viscous fluid and Navier-Stokes and continuity equations were set up as the governing equations for this model. Figure 5 shows the velocity contour of the secondary flow in the cross-section at the middle portion of the modeled fluid passage shown in Figure 4 (shaded volume). The results confirmed that a distinct counter-rotating double-vortex pattern with the eyes of the vortices biased toward the inside wall (filter media surface)

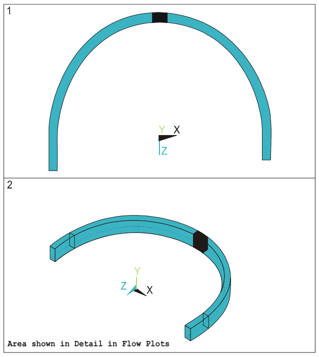


Figure 4: CFD Model of Partial Flow Passage

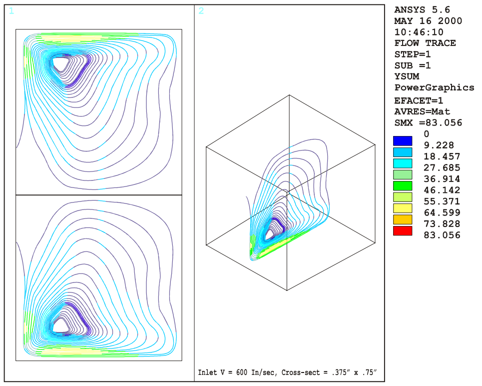


Figure 5: Velocity Contours at Cross-Section

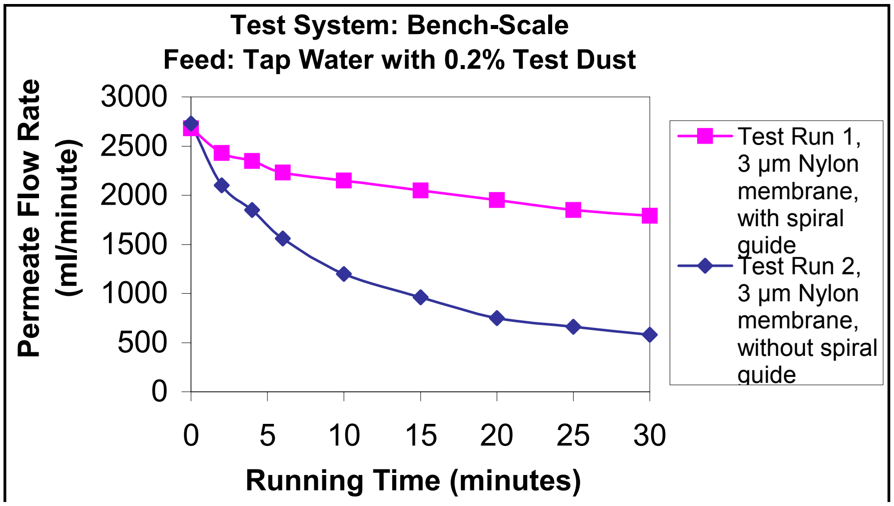
is generated as the processed fluid flows through the spiral passageway. The vortex currents in the spiral passage provide high shear filtration across the filter surface to remove the debris trapped on the surface and transport it away, resulting in superior fouling control.

Testing of FSI's Secondary-Flow Enhanced Filtration System

A membrane filter cartridge was tested in diesel fuel with 0.1% ISO fine test dust. In this test, the lower 2/3 of the cartridge was located in the filter housing with spiral guides to promote Dean Flow and the upper 1/3 of the cartridge was located in a part of the housing that had no spiral guides. Figure 6 shows the cartridge removed after testing, a vivid contrast is shown with and without cake layer formation. The lower part has no visible cake layer formation due to the vortices generated by the Dean Flow, which kept the surface clean. This test result clearly reveals the advantage of using Dean Flow with membrane filtration.

Figure 6: Cartridge Showing Dean Flow Effect

Tests have been conducted comparing cross-flow filters with and without a spiral guide using the arrangement shown in Figure 3. Figure 7 depicts the permeate flow rate from the filter unit as a function of time. A filter cartridge manufactured using a Pall Biodyne membrane with a pore size of 3 microns was installed in a cylindrical housing. The cartridge had an outer diameter of 3 inches and a length of six inches (the surface area is around 0.3 square feet). The spiral guide spanning between the housing wall and the filter cartridge provided a spiral passageway 9 millimeters wide and a pitch, or height, of 16 millimeters. Tap water containing 0.2% ISO 12103-1, A4 test dust was circulated through the tested filter unit at approximately 8 meters per second for trials lasting approximately 30 minutes. As seen in Figure 7, Test Run 1 employing a spiral guide maintained a superior permeate flow rate throughout the trials as compared to Test Run 2 where no spiral guide was present. The permeate flow rate also degraded less for Test Run 1.



Case Study: Pre-treatment of Coastal Seawater for RO Desalination

A filtration system that combines CFF with Centrifugal separation, Dean Flow fouling control and Back-wash technologies was designed and constructed. The system is called CCDB using the acronym. In this case, the CCDB system was developed by FSI for coastal seawater filtration. The development was sponsored by the US Navy for use in the pre-treatment of shipboard RO desalination. Centrifugal separation was harnessed by injecting high velocity feed flow into the cylindrical housing tangentially. Note that centrifugal separation will be effective in accomplishing particulate filtration for relatively large particles that have higher specific gravity than the feed fluid, but it really only provides a rough screening for mechanical protection in this application.

Silt Density Index (SDI) [7], which indicates the quantity of particulate matter in water, was used to qualify the filtered seawater. The manufacturer of the RO system recommends an SDI of 5 or less for the feed water. The filtration of coastal seawater is a very tough application. Coastal seawater usually contains large amounts of silts, colloidal solids, plankton, and algae that can plug even highly reliable filters that function well under normal conditions. The Back-wash and Dean Flow components of the developed system help it deal with these organic foulants. The current shipboard pre-treatment system (dead-end filtration) can provide a service life measured in months for typical operation in the open-ocean but the service life can be cut down to hours if the system is operated in coastal areas.

Land-based testing using the CCDB system developed by FSI was performed at Wrightsville Beach, North Carolina. With natural seawater, the measured SDI at the test site was 6.7, which is theoretically the highest number (most challenging) possible. An 80% recovery rate (filtrate/feed) was used for the CFF. Various types of off-the-shelf filter media were used for testing. Figures 8 and 9 show the permeate flux and trans-media pressure as a function of running time, respectively, for one of the tested filter media, i.e. a 5 micron absolute

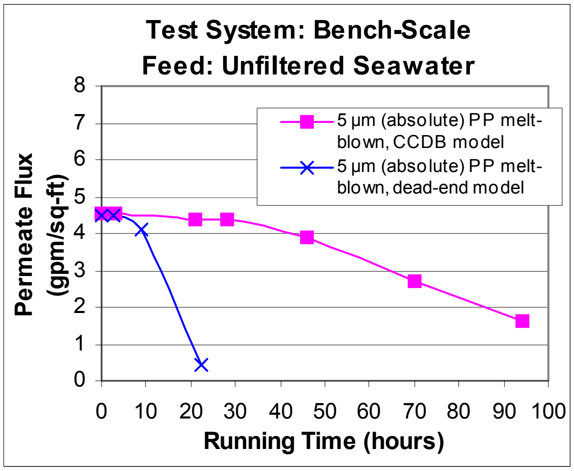


Figure 8: Comparison of CCDB with Dead-End Filtration, Permeate Flux vs. Time

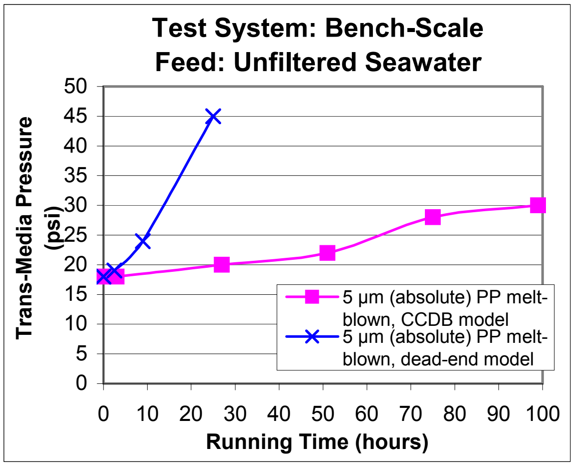


Figure 9: Comparison of CCDB with Dead-End Filtration, Trans-Media Pressure vs. Time

polypropylene melt-blown cartridge. The CCDB system provided a service life about five times longer than the conventional dead-end system with the same type of filter media installed. The SDI level for the permeate was measured to be between 4.7 and 4.9 in this test.

A further comparison was made using less challenging seawater. The feed seawater was a mixture of natural seawater and seawater which had passed through a multimedia filter (1 to 9 ratio). The SDI of the mixed seawater was in the range of 5.5 to 5.9 during the test. Figures 10 and 11 show the permeate flux and trans-media pressure as a function of running time respectively. The service life of the CCDB system is at least five times better using the same type of 1 micron nominal polypropylene filter cartridge. The SDI level for the permeate was measured to be between 3.7 and 4.2 in this test.

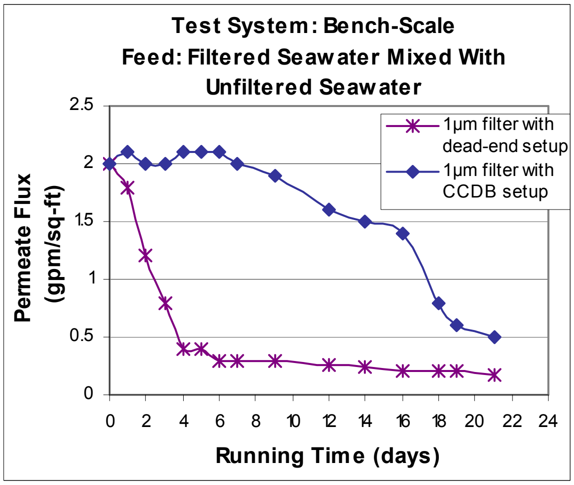


Figure 10: Comparison of CCDB with Dead-End Filtration, Permeate Flux vs. Time

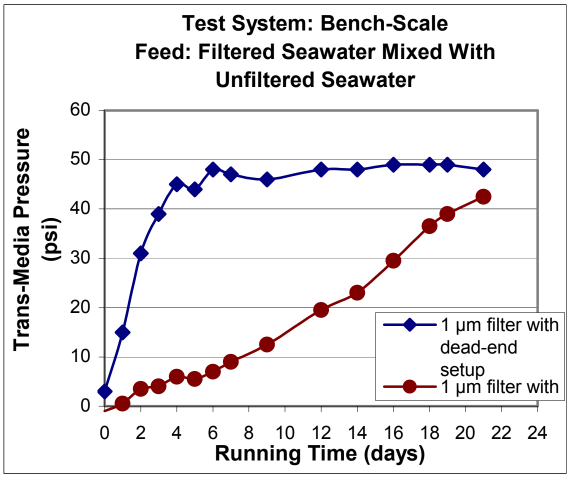


Figure 11: Comparison of CCDB with Dead-End Filtration, Trans-Media Pressure vs. Time

Conclusions

The following conclusions were drawn based on FSI's testing:

1) Dean Flow can be generated effectively with the right boundary and operating conditions.
2) With the proper design of the flow passage within the filter housing, Dean Flow can be generated to enhance filtration performance.
3) Regardless of the type of filter media used during testing, FSI's CCDB system consistently showed superior performance and filter service life compared to the conventional dead-end filtration system currently being used by the Navy.

Dean Flow has proven to be effective for performance enhancement of traditional cross-flow filtration in applications with high solids content. Furthermore, by combining this technology with back-washing in a filtration system, the resulting system has proven to be highly effective for difficult applications such as coastal seawater filtration where suspended colloidal solids tend to plug filter media through extrusion under pressure. The CCDB technology is also effective for applications involving both high concentrations of suspended solids and compressible gellular types of solids.

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