Understanding Direct Flow and Crossflow Microfiltration in Food and Beverage Industry Applications

Overview

Food and beverage production spans a wide range of process applications, which require contaminant removal or separations of components in liquids and gases, with the goal of achieving high product quality. Consumers expect the products they consume to be free of contaminants that negatively impact visual appearance, organoleptic attributes, nutritional value, and/or safety.

Filtration plays a very important role in enabling manufacturing processes and satisfying consumer expectations. Direct flow and crossflow filtration are two different filtration configurations which address different needs and magnitudes of application.

Both filtration techniques are used for microfiltration, which is the physical separation of suspended particles and bacteria from process fluids. The typical particle sizes are greater than 0.1 micron or molecular weights greater than approximately 300-500 kilodalton.

In the food and beverage industry, direct flow filtration is used in both liquid and gas applications, and crossflow filtration is used only for liquid separations. Additionally, crossflow filtration enables tighter molecular separations including ultrafiltration, nanofiltration and reverse osmosis.

An explanation of these two technology types, with special focus on microfiltration with direct flow filters and crossflow systems will lend itself to a better understanding of solutions for food and beverage microfiltration applications.

Direct Flow Filtration

Direct flow (sometimes called “dead end”) filtration is applied when all the fluid to be filtered is driven, typically in industrial applications due to a supply pressure, in a direction perpendicular to a filtering surface; few applications are done by gravity feed. Contaminants are captured within the filtration media or build up on the surface, causing the differential pressure across the filter to rise as it blocks over the duration of the filtration process. The filtrate exits the filter on the downstream side. Once a certain differential pressure has been reached, after which the fluid flow rate decreases and/or the filter reaches its terminal differential pressure, filtration is stopped and the filter is either discarded or may sometimes be regenerated for re-use (Figures 1a–1b).

Figure 1a: Schematic of Direct Flow Filtration: Feed flow direction is perpendicular to filtration surface.

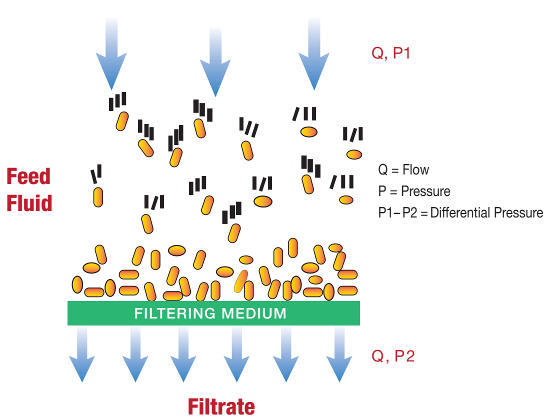
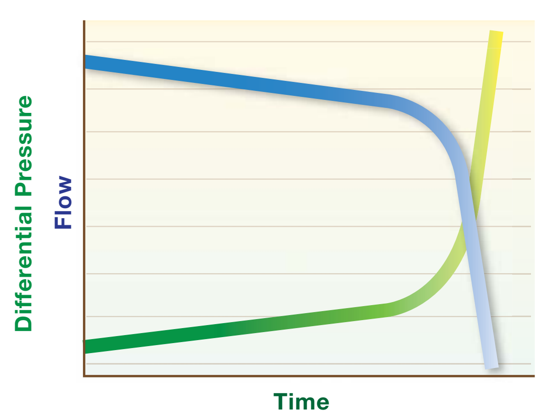


Figure 1b: Pressure Curve in Direct Flow Filtration: As differential pressure increases, flow decreases.



Depending on type, direct flow filters achieve suspended solids removal (particles, gels, haze, colloids, *etc.*), adsorptive filtration, or retention of microorganisms.

Suspended Solids Removal

In food and beverage industry applications, filters for suspended solids removal achieve retention of a wide spectrum of contaminants. Some achieve mainly solid particle filtration while others are additionally effective in gel, haze, or colloid removal.

Examples of direct flow filters for removal of relatively low suspended solids loads are the widely available array of disposable filter cartridges, bags, flat sheets, and sheet-based depth filter modules (Figures 2a – 2b), as well as metal cartridge filters. Direct flow filtration systems suited for handling higher suspended solids loads are diatomaceous earth (DE, Kieselguhr) or other types of precoat filtration systems, automated self-cleaning screen devices, hollow fiber modules operated in direct flow mode, multi-media beds, and more.

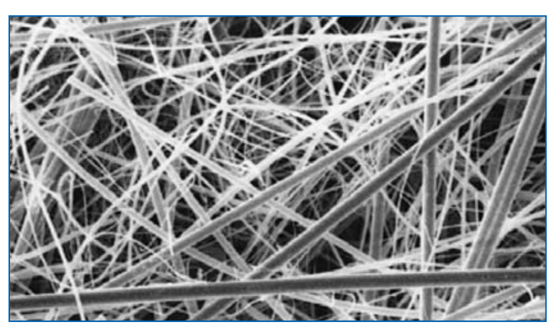
Figure 2a: Disposable and Metal Cartridge Filters

Figure 2b: Disposable Sheet-Based Modules

Disposable polymeric filters are typically cost-effective for handling low suspended solids loads in the parts per million (ppm) range (cartridges, bags) or between 0.1-1% suspended solids (sheets, sheet-based filters), depending on the characteristics of the fluids filtered. They are constructed of fibrous media (Figures 3a – 3b), such as polypropylene and polyester felt in bag filters, polypropylene in melt blown or pleated cartridge filters, glass fibers in cartridge filters, cotton in string wound filters, and a cellulose/DE/perlite matrix in flat sheets or enclosed sheet-based filters. The efficacy of particle removal depends on filter type, contaminant characteristics, fluid characteristics, filtration mechanisms involved, and measurement methods for particle removal performance[1,2].

Figure 3a: Fibrous Polypropylene Media

Figure 3b: Glass Fiber Media



Metal cartridge filters, consisting either of sintered metal powder or metal fiber media, provide a robust alternative to polymeric filters especially for high temperature applications. They are by far most commonly used in the food and beverage industry for culinary steam filtration, however they may be used in liquid applications as well. As metal filters are costly and typically offer less filtration area than polymeric cartridges, the ability to effectively regenerate them for re-use is key to achieving cost-effectiveness. Cleaning is a function of filter media structure (which often consists of several layers of metal depth media), type of contaminants, and cleaning fluids, chemicals, temperature and procedures, and must be validated by users in their specific process. This is especially true for liquid filtration applications.

DE filtration systems are used in the food and beverage industry for handling higher suspended solids loads, mainly in primary clarification of beverages or food ingredients such as beer, wine, cider, soy sauce, gelatin, fermenter broths (*e.g.* enzymes) *etc*. The fluid is passed through a porous cake of DE filter aid supported by mesh screens, filter sheets or similar structures. Additional filter aid is successively dosed into the fluid as filtration progresses, building up the filter cake which acts as the prime filtering medium. While the DE in itself is a very effective filtering media, well-known drawbacks of this older technology consist of DE handling and waste management, personnel exposure to the DE, potential for fluid channeling or dissolved ion leaching which may result in poor filtrate quality, some open systems (*e.g.* rotary vacuum drum filters, with associated high vacuum pump energy consumption), and abrasion in sewage circuits. Many DE systems are being replaced by more modern and environmentally sustainable crossflow membrane solutions.

Polymeric hollow fiber membranes used in direct flow mode are another system option for high volume, higher suspended solids load direct filtration. Pall Aria™ microfiltration systems (Figure 4) are commonly used in incoming plant water treatment as a modern alternative to traditional sand and multi-media bed direct filtration. They provide homogenous and excellent filtrate quality regardless of incoming feed water quality, are regenerable with simultaneous air scrub and reverse filtration capability, and offer a labor-, energy-, and space-saving solution.

Figure 4: Pall Aria Microfiltration System for Water Treatment

Adsorptive Filtration

Adsorptive filtration consists of passing a fluid in a direct flow mode through an adsorptive media, generally to achieve color, flavor and/or odor correction given enough contact time with the adsorptive media. A common example in the food and beverage industry is activated carbon filtration, using carbon block filters, carbon-impregnated sheets or sheet-based modules, or carbon beds. Figures 5a and 5b illustrate an example of color correction achieved in a wine application for distillery use, with carbon-impregnated lenticular modules.

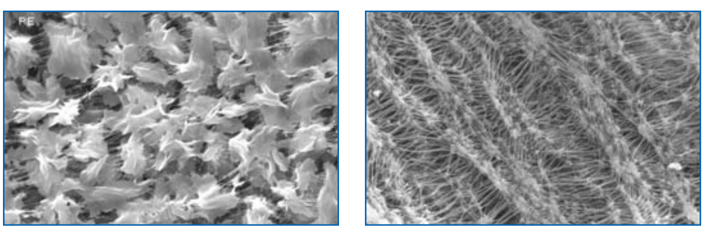
Figure 5a: Color correction of white wine with SUPRAdisc™ AKS sheet-based modules – before *(left)* and after *(right)* treatment

Figure 5b: Carbon-Impregnated Lenticular Modules

Microbial Removal

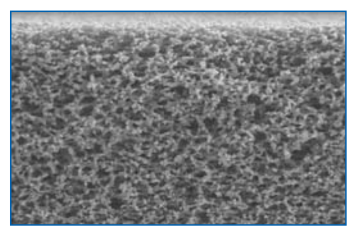
Disposable membrane filter cartridges are employed for validated microbial removal. These typically consist of cast or stretched membrane, comprised of materials such as nylon, polyvinylidene fluoride (PVDF), polytetrafluorethylene (PTFE), polyethersulfone (PES), *etc*. (Figures 6a–6c).

Figure 6a and 6b: SEM Images of Media Used in Disposable Membrane Filters



Nylon **PTFE**

Figure 6c: Cross-Sectional SEM Image of PES membrane



PES

During microbial filter performance validation, an array of production filters from different manufacturing lots are challenged with a known concentration of model or application-specific microorganisms. The achievable logarithmic titer reduction (LRV) or microbial removal performance is determined from these destructive tests. The results are then correlated, using a robust safety factor, with a non-destructive pass/fail filter integrity test value, which enables the user to employ a sensitive integrity test device to confirm whether the filters will function as specified. The integrity test confirms the absence of defects in the filter or leaks in the filter installation.

Tight flat sheets or sheet-based products can also achieve a degree of microbial titer reduction, however their microbial performance is variable and influenced by incoming microbial load and process parameters such as line pressure fluctuations and flux (flow rate per filter area). As such, many filter vendors do not assign claims for microbial removal or retention to sheet-based products.

Membrane filters in liquid or compressed air/gas applications are best used together with effective pre-filtration for suspended solids removal, such that their main function is primarily microbial removal.

Food and Beverage Industry Direct Flow Microfiltration Applications

Direct flow filtration is indispensable in many food and beverage industry applications.

Liquid filtration examples include polishing of beverages and other liquid food products and ingredients for visual clarity, microbial removal to stabilize packaged products, incoming plant water or process water filtration, particle pre-filtration to optimize performance of downstream equipment or prolong downstream membrane filter life, removal of hazardous particles (*e.g.* metal shavings originating from process equipment), trap filtration (*e.g.* fluid polishing post-DE, carbon or other multi-media beds or resin columns), load-out filtration, adsorptive filtration for color adjustment, and more.

Air and gas filtration examples include tank vent filtration for protection of storage tank or starter culture tank contents from particle, microbial and/or bacteriophage contamination, compressed air/gas filtration in aseptic production or fermentation to keep the process environment free of microorganisms, fermentor off-gas filtration to protect the environment, filtration of product-contact gases such as in whipping or foaming, culinary steam filtration for removing rust particles and other suspended solids debris from the steam generation system, and more.

Crossflow Filtration

Crossflow filtration is a filtration configuration in which the feed fluid to be filtered is continuously recirculated tangentially to a filtration membrane surface. Hence it is also called tangential filtration.

The supply pressure forces the purified fluid through the membrane as filtrate (permeate), while suspended solids in the feed fluid, too large to pass the pores of the membrane, are retained in the increasingly concentrated retentate stream (Figure 7a). The target product in crossflow filtration is the result of precise separation of permeate (filtrate) from retentate (concentrate), and can be the permeate, the retentate, or both.

Different from direct flow filtration, the retained solids in the retentate do not build up on the membrane surface, but rather they are swept away from the membrane surface, which prevents thickening of the solids layer for a relatively long period of time (as compared to direct flow filters) (Figure 7b). The filtration process ends when a maximum concentration level of the retentate is reached (expressed as volumetric concentration factor or VCF), such that further continuation of the process is no longer technically possible or cost-effective.

Diafiltration is a method sometimes employed during crossflow filtration. As filtrate is being removed from the system, buffer solution or deionized (DI) water is added to the feed fluid/retentate stream, diluting it and washing out small molecules to either increase retentate purity or improve permeate yield (Figure 7c).

Figure 7a: Crossflow Filtration Principle: Feed flow direction is parallel to filtration surface and perpendicular to permeate flow direction.

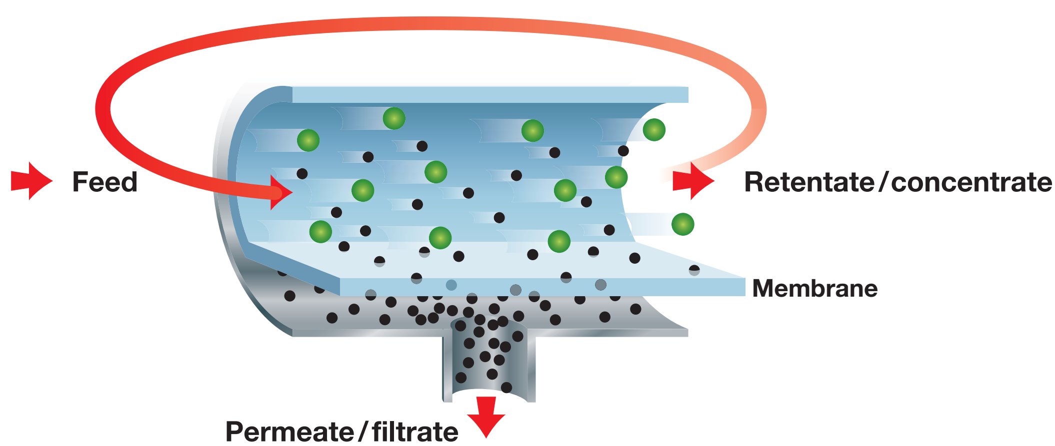


Figure 7b: Pressure Curve in Crossflow Filtration

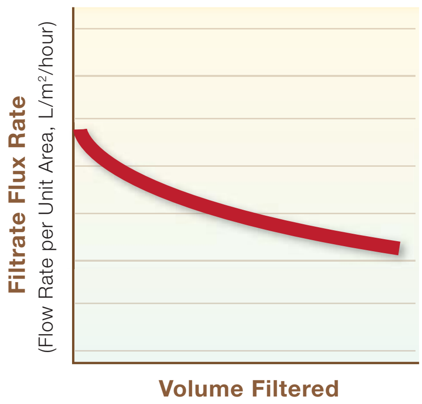
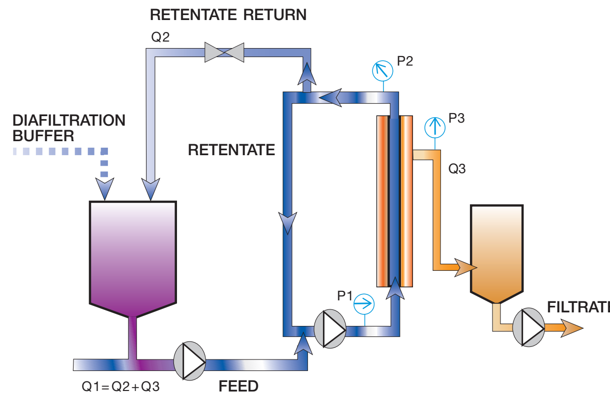


Figure 7c: Schematic of Crossflow Filtration in Simple Fed Batch Mode, with Diafiltration



Q = Flow; P = Pressure; P1-P2 = Differential Pressure; (P1+P2)/2 – P3 = Transmembrane Pressure

Examples of crossflow filters typically used in the food and beverage industry are the widely available systems using longitudinal modules consisting of polymeric (*e.g.* hollow fibers, spiral wounds) or inorganic (*e.g.* ceramic, sintered metal) membrane materials (Figures 8a–8b).

Figure 8a: Pall Microza* hollow fiber module with cutaway view of hollow fibers and cross-sectional view of a single hollow fiber

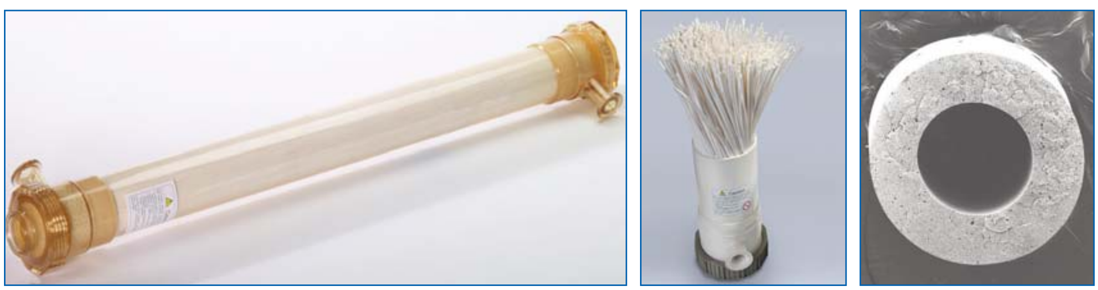
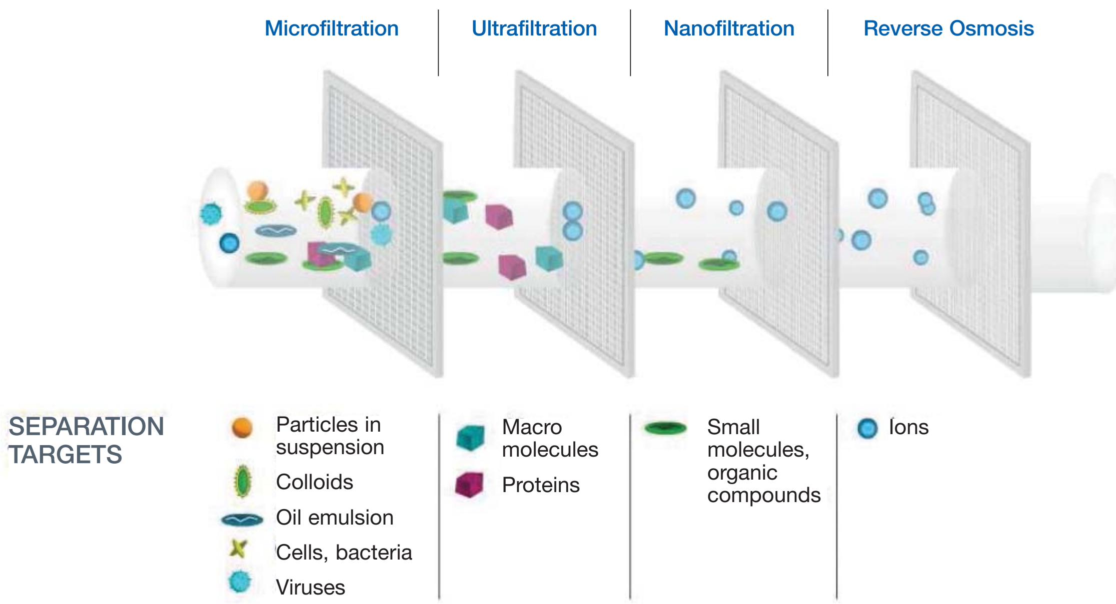


Figure 8b: Pall Membralox® ceramic module with ceramic membranes and cross-sectional view of membrane configurations

Microfiltration for particle and microbial removal is just the coarsest end of their capability spectrum; these crossflow devices also achieve finer, dissolved solids micro-molecule, atomic and ionic separation in the ultrafiltration, nanofiltration and reverse osmosis ranges, depending on their structure and pore size (Figure 9).

Microfiltration removes suspended materials and achieves microbial bioburden reduction. Ultrafiltration rejects high molecular weight compounds like proteins, but allows low molecular weight compounds such as small peptides or sugars to pass through. Nanofiltration removes most small molecules and organic compounds, including small peptides, sugars and divalent ions such as calcium, magnesium, sulfates, and phosphates. Reverse osmosis removes monovalent ions such as sodium, allowing passage only of water molecules.

Figure 9: Filtration Spectrum of Crossflow Filtration and Separation



Crossflow Microfiltration

Crossflow microfiltration is an alternative solution to clarifying fluids containing higher suspended solids, which can include microorganism bioburden reduction in the sub-micron range.

Unlike other high suspended solids handling technologies such as centrifugation, where cell size and density as well as fluid viscosity influence the separation efficiency, membrane separation offers a physical barrier that will always provide the optimum separation. For the selection of membrane pore size, it is important to have a good understanding of the feed composition, especially particle composition, structure and size distribution. To prevent deep membrane fouling, membrane pore size should be smaller than the smaller particles present in the feed. This is of particular importance when suspended solids are not soluble in CIP (clean-in-place) chemicals. As a consequence, crossflow filtration is never used for the fractionation of rigid particles according to their size because a significant quantity of particles would be trapped within the membrane structure.

In crossflow microfiltration applications, some permeate flux enhancement techniques can be used. Backwashing and backpulsing are the most popular. Obviously, in both cases, the membrane structure should withstand backpressure from the permeate side.

Backwashing is a "gentle" process that periodically re-injects a volume of permeate back through the membrane using a "low" pressure pump, such as a centrifugal pump.

On the other hand, backpulsing is a short back pressure spike corresponding to the re-injection of a defined volume of permeate at high differential transmembrane pressure. It should be applied from beginning to end of the run and started very soon after generating permeate.

Backpulsing or backwashing not only sustain permeate flux by regularly destroying the accumulated deposit at the surface of the membrane but also contribute to the transmission of dissolved macromolecules (*e.g.* proteins, polysaccharides, enzymes, *etc.*).

Nevertheless, there are many cases where EFM (enhanced flux maintenance) techniques are not used because their efficiency is not good enough to justify the design over cost.

When processing solutions containing hard particles (*e.g* slurry, salt crystals, activated carbon, *etc.*), the crossflow velocity should be reduced in order to minimize membrane abrasion. By doing this, the kinetic energy of the particles is minimized, which reduces the risk of filtration layer damage. Advantageously, the incoming feed will be pretreated before entering the filtration loop to remove the largest particles having the highest mass.

Pretreatment of incoming feed is important to prevent the plugging of membrane lumens. Generally, pretreatment should remove any suspended solids larger than 1/10th of the membrane lumen diameter. Above that size, the "drag effect" may cause velocity slowdown in the lumen up to the point of blockage. For example, for hollow fibers with 2.4 mm lumen diameter, pre-filtration at 200-250 µm is highly recommended.

Food and Beverage Industry Crossflow Microfiltration Applications

In the food and beverage industry, crossflow microfiltration (or clarification) is applied in a wide range of applications, especially for cost-effective continuous processing of fluids with higher suspended solids, large feed volumes and high flow rates, and in some cases for fluids requiring special chemical or temperature resistance. In addition, applications in which the retentate is the product are also candidates for crossflow microfiltration.

Usually, clarification is used to remove suspended solids from feed streams to produce a clear permeate, with significantly reduced turbidity. Clarification to remove turbidity typically applies to beverages such as wine, beer, and fruit juices where the smart combination of process parameters and membrane characteristics produces good visual and organoleptic quality of clarified solutions. Oenoflow™ systems for clarification of wine and cider, PROFi systems for beer clarification, Membralox systems for fermenter broth clarification, and Microflow™ systems for fruit juice and cheese brine clarification are examples of proven solutions (Figures 10a–10d).

Figure 10a: Oenoflow XL-A Wine Clarification System

Figure 10b: PROFi Beer Clarification System

Figure 10c: Microflow Cheese Brine Clarification System

Figure 10d: Membralox Fermenter Broth Clarification System

Oenoflow HS systems for recovery of wine and juice from lees and Membralox systems for recovery of beer from excess yeast are examples of high suspended solids crossflow applications in which the retentate, *i.e.* the lees or tank bottoms, is concentrated during filtration. This process not only reduces the amount of waste but increases the yield of high quality wine, juice or beer. Additionally, the concentrated solids from surplus yeast can provide a value added product. With a higher concentration and the absence of fermentable sugars and alcohol, the yeast can be sold to industries including cosmetic, pharmaceutical or animal feed at a higher price.

In the fermentation industry, microorganisms are grown in bioreactors to produce valuable molecules (amino acids, vitamins, enzymes, yeast extract, *etc.*) from carbon sources (typically sugar). To be able to extract and purify these molecules, the first processing step is to separate the biomass and produce a clear filtrate. Crossflow microfiltration allows achieving high concentration of biomass (up to 20-23% dry suspended solids with appropriate lumen diameter) and even further increased yield with diafiltration. Because the filtration membrane is a physical barrier, the permeate quality is significantly better compared to other clarification solutions by centrifugation or DE filtration (RVDF, filter press, *etc.*). This positively impacts the performance of downstream processing steps.

In the sweeteners industry, dextrose is produced by starch enzymatic hydrolysis. These 30-40 °Brix syrups are further clarified at 60-70 °C (140-158 °F) to remove proteins, fat and fibers (“mud”). In this continuous process, feed flow rates range from 30 to > 150 m^3/h (130 to >660 US gal/min) thus requiring very large crossflow systems.

In the dairy industry, Membralox GP (“graded permeability”) ceramic membranes enable very precise separations. Developed in the mid 80’s, bacteria removal from skim milk is now a well-established application to produce premium quality extended shelf life milk. Crossflow microfiltration with GP membranes (pore size 0.8 µm or 1.4 µm) dramatically reduces bacterial contamination while allowing almost complete transmission of milk proteins.

Milk fractionation is another good example of how a precise separation is achieved to break down the milk into two high value-added streams: native casein (concentrate) for higher cheese or cultured product yield, and ideal whey (permeate) for creation of high value ingredients.

Due to sharp pore size distribution and precise transmembrane pressure profile control, casein micelles are fully retained while whey protein transmission is optimized. In the concentrate, casein represents up to 90% of total proteins and even > 95% with further diafiltration.

Other dairy microfiltration applications include sweet cheese whey clarification to remove casein fines, fat, bacteria and denatured proteins. With further concentration by ultrafiltration and diafiltration, the micro-filtered permeate becomes whey protein isolate (WPI), a source of high value-added ingredients.

There are many more sophisticated applications that can benefit from the features of Membralox GP microfiltration membranes.

Conclusion

Experience has shown which filtration techniques are technically best suited and most cost-effective for food and beverage industry applications. To select the optimum filtration solution, it is important to understand the application and where it is located in a process (both upstream and downstream processing steps), the goals of the filtration and contaminant removal specification, fluid characteristics, flow volume and magnitude of the installation, required technical success criteria, and economic considerations.

Footnotes and References

[1] Pall Technical Article: "Understanding Particle Filtration in Liquids in Food and Beverage Industry Applications"

[2] Pall Technical Article: "Understanding Particle Removal Performance in Liquids with Cartridge and Bag Filtration"

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FBTADIRCROSSEN June 2016