MF/UF Membrane Filtration: A State-of-the-Art Review

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MF/UF MEMBRANE FILTRATION: A STATE-OF-THE-ART REVIEW

Eric M.V. Hoek, Ph.D. | Founder & CEO | Water Planet, Inc.

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ABSTRACT

Over the past two decades, membrane filtration products – microfiltration (MF) and ultrafiltration (UF) – have proliferated globally to become the gold standard for removing suspended solids, colloids, pathogens and emulsions from virtually every type of water source: traditional and non-traditional, fresh and saline. Hence, everywhere and anywhere filtration or clarification is required membrane filtration has the potential to replace conventional flotation, sedimentation, and media filtration processes.

Membrane filtration is preferred because it offers an absolute separation barrier, more compact footprint and greater automation over conventional processes; however, membrane fouling drives cost up and reliability down such that many applications for difficult to treat waters are not currently served by MF/UF membrane filtration. Why? Because commodity polymer membranes have proven unable to do the work and ceramics are too expensive. This critical technology gap must be bridged to enable more widespread application of MF/UF, and hence, expansion in the reuse of industrial and municipal wastewaters – a key for global water sustainability.

This paper reviews state-of-the-art MF/UF technologies and what Water Planet is doing to deliver next-generation improvements for MF/UF membranes that are already bridging the critical technology gap.

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1. INTRODUCTION

Water scarcity and the need for advanced treatment

Clean, fresh water is essential to support human life, food and energy production, industrial processes and the natural environment. Traditional fresh water resources are become increasingly over-stressed and polluted, and hence, we will rely on non-traditional – difficult to treat – water sources going forward.

Membrane filtration is the key because it offers improved separation performance, a more compact footprint and greater automation over conventional media filtration. However, membrane fouling drives cost up and reliability down such that many applications for difficult to treat waters are not currently served by membrane filtration.

As a result, this critical technology gap must be bridged to enable more widespread application of membrane filtration, and hence, expansion in the reuse of industrial and municipal wastewaters – a key for global water sustainability.

What are membrane and media filtration?

Conventional methods to remove suspended solids from water involve gravity based flotation and clarification, but these processes are only effective for particles larger than 50-100 micrometers (μm). These processes can be extended to remove smaller particles through the use of coagulant and flocculant chemicals, which induce small particles to stick to one another and grow into larger particles.

The performance and cost are largely tied to labor and chemicals. The key operational challenge is that these processes require a lot of operator attention to get the chemical dosing levels right, and often don't meet effluent water quality targets.

Media filtration involves the use of a natural "media" including sand, anthracite, garnet or nutshells and sometimes mixtures of different media contained in a single filter housing. Traditional media filtration easily removes particles down to 5-10 μm in size via depth filtration, which means particles are removed by adsorption to the media surfaces throughout the depth of the filter media.

Like gravity based processes, to be effective for smaller particles, media filtration requires the use of coagulant and flocculant chemicals to grow small particles into sticky large particles. However, once all the media surface area is occupied, the filter stops removing particles and passes them straight through at the influent concentration; this is termed "break through."

It is critical that media filters be monitored closely to assure filter media is back-washed before break-through occurs. Also, media filters require a "ripening period" after backwashing; a short period when the filter is not effective at particle removal and filtrate must be wasted or recycled back to the head of the plant.

The key operational challenges for media filtration are (1) to backwash before break-through occurs and (2) bypass during the filter ripening period. A well operated media filter will be backwashed once or twice per day.

Herein, "membrane filtration" refers to microfiltration (MF) and ultrafiltration (UF), which are porous barrier materials with pore sizes of about 20-200 nm designed to selectively separate particulate substances from water based on the relative size of particles and membrane pores (see Fig. 1). Nanofiltration and reverse osmosis membranes are non-porous, typically selected for removing organic molecules, metals, minerals and salts from water.

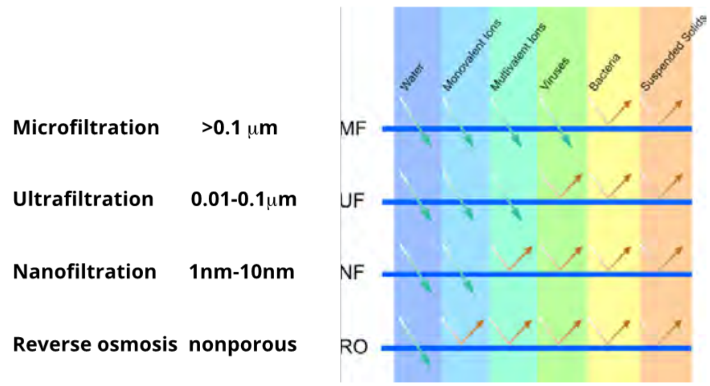

Figure 1. The membrane filtration spectrum showing all forms of pressure-driven membrane processes by pore size, typical designation and classes of substances removed.

Membrane filtration offers an absolute barrier for removing particles larger than the membrane pore size, which includes virus, bacteria and protozoan cyst particles as well as abiotic suspended solids (clays, silts and mineral precipitates). Filtration membranes are most commonly made from commodity "polymer" materials like polysulfone and poly(vinylidine fluoride) or commodity "ceramic" metal and metal oxide materials.

Traditional applications for membrane and media filtration are clarification and disinfection of surface water in fresh drinking water treatment and seawater desalination plants, tertiary filtration of municipal wastewater to enable non-potable reuse (typically, landscape irrigation) and clarification of industrial effluents to achieve discharge standards or as pre-treatment ahead of advanced polishing technologies like reverse osmosis, nanofiltration, activated carbon or ion exchange.

A key distinction between media and membrane filtration is that, unless a membrane is damaged and loses integrity (ability to reject particles larger than the nominal pore size), membranes do not require "filter ripening" or experience "break-through." This has led to membrane filtration becoming much preferred over media filtration for most common applications.

2. MEMBRANE FILTRATION PRINCIPLES

How does membrane filtration work?

Membrane filtration is a pressure-driven filtration process where one influent (feed) stream is split into two new streams: (1) the filtered or "permeate" stream and (2) the concentrated or "retentate" stream. In pressure-driven membrane filtration, the rate of water filtration is described as the "water flux," which is the permeate flow rate divided by the available membrane area. The flux through a MF/UF membrane is proportional to the trans-membrane pressure (TMP) and the membrane permeability.

TMP is the difference between the applied feed pressure and the residual permeate pressure. However, due to the extremely high permeability of MF/UF membranes, TMP is also affected by static head-loss associated with the weight of water and the height it must be lifted to pass through the filtration system (approximately 1 psi per 2 feet). Therefore, a 6 foot tall MF/UF membrane filtration module necessarily requires a minimum of about 3 psi to operate simply due to headloss, whereas the membrane may contribute a similar pressure loss the biggest pressure losses are associated with membrane fouling and operational efforts to mitigate fouling related pressure losses.

What is membrane fouling?

Membrane fouling describes the loss of permeability due to accumulation of feed solids on or within a membrane's pores. Suspended solids, bacteria, oil, clays and organic matter foul membranes, which leads to increased backwashing, cleaning, downtime and operating cost along with decreased throughput and membrane useful life. Hence, the biggest cost driver for MF/UF membranes is the fouling propensity of the influent water.

Generally, the sustainable flux decreases with feed suspended solids (the primary fouling materials); lower flux increases capital cost by requiring more membrane area to meet the throughput target. Also, higher feed solids requires more frequent back-washing and cleaning, during which times the filtration system is not filtering forward. Even worse, using filtrate for backwashing amounts to filtering the water twice and then throwing it out. Backwashing is the most expensive operational aspect of membrane filtration – reducing overall water recovery and increasing process downtime.

What are the different operating modes of membrane filtration?

Membrane filtration occurs in two basic operating modes: (1) cross-flow (Fig. 2a) and (2) dead-end (Fig. 2b). Generally, cross-flow membrane filtration (CFMF) employs turbulent cross-flow and periodic back-washing to mitigate membrane fouling due to high solids feeds. CFMF uses membrane modules with larger aperture feed/cross-flow channels. targeting higher flux operation using less membrane surface area per module ("packing density").

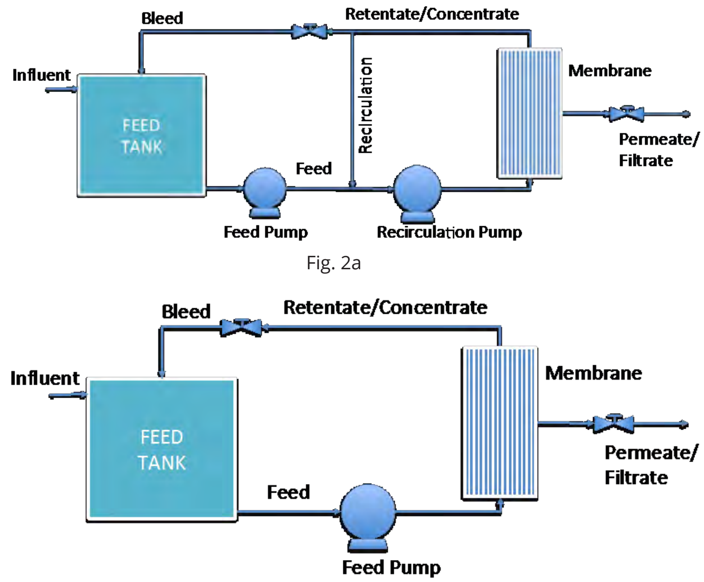

Figure 2. Basic operating modes of feed-and-bleed membrane filtration including (2a) cross-flow for higher solids feeds, higher permeate fluxes, and lower surface area membrane modules and (2b) dead-end for lower solids feeds, lower permeate fluxes, and higher surface area membrane modules.

In contrast, dead-end membrane filtration (DEMF) uses high packing density membrane modules and high frequency backwashing, vibration and/or air scouring to mitigate fouling from relatively low-solids feeds.

Summing up all the factors leads to the observation that flux is a function of the axial location along the feed/retentate side of the membrane due to the axial location dependence of friction and head losses. While filtration through a 6 foot tall MF/UF membrane filtration module minimally requires about 3 psi due to head-loss, factoring in membrane, cross-flow and fouling related pressure losses typical operating pressures are in the range of 10 to 20 psi for dead-end and 20-40 psi for cross-flow operations.

What are the different types of membrane filtration modules?

Membrane modules come in all different form factors ranging from single bore cylinders to flat sheets and multi-bore monolithic structures (Fig. 3). Single bore cylindrical membranes include tubular (~0.5 to ~1 cm inside diameter), capillary (~1.5 to ~3 mm inside diameter) and hollow fiber (~0.1 to ~1 mm inside diameter) forms, which are generally used for high, medium and (relatively) low suspended solids feed streams, respectively, and small, medium and large installation sizes, respectively.

Multi-bore monolithic membranes generally have inside diameters ranging from ~0.5 mm to ~9 mm; being used for high solids and high temperature feed streams in process separations (dairy, biotech, pharmaceuticals, etc.) and challenging industrial wastewaters. Flat sheet plate-and-frame and spiral wound membranes are used for relatively high and low-solids feed streams, respectively.

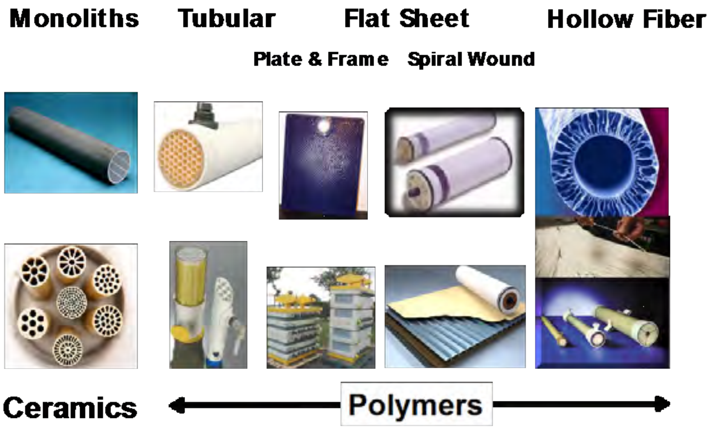

Figure 3. Images of different types of membrane module types for polymeric & ceramic materials.

Each type of module employs a unique filtration flow pattern, but they can be broken down into two basic approaches: (1) outside in and (2) inside out (Fig. 4). Generally, outside in filtration is for maximizing membrane surface area and is commonly combined with dead-end filtration through hollow fibers and flat sheet plate-and-frame modules, whereas inside out filtration is for employing high cross-flow rates to mitigate fouling due to higher solids concentration feed streams, which is commonly employed for monolithic, tubular and spiral wound modules.

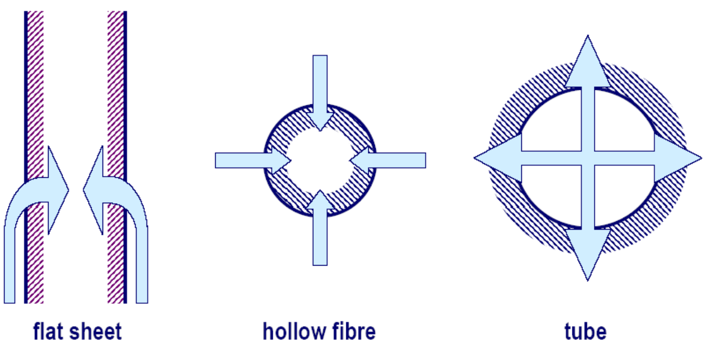

Figure 4. Different filtration flow regimes employed in different membrane module form factors.

How does materials chemistry affect membrane filtration performance?

Generally, more hydrophilic membrane materials tend to be more resistant to fouling, which translates into slower loss of permeability during forward filtration and more complete recovery upon back-washing or cleaning (see Figure 5).

Classical definitions of hydrophilicity derive from how a water drop spreads across a material surface: if the droplet beads up into a sphere, the surface is hydrophobic, and if the droplet spreads into a flat lens, the surface is hydrophilic.

Hydrophilic membrane materials attract water so strongly that it requires an extreme amount of force (i.e., high permeate flux rate) to cause a foulant particle into intimate contact with a membrane. In contrast, hydrophobic membrane materials repel water so strongly that very little force (i.e., low flux) is required to make foulants stick.

Not all hydrophilic materials resist fouling to the same extent. In particular, certain membrane chemistries are hydrophilic, but at a molecular level may attractive certain foulant material chemistries. Ultimately, what this means is that hydrophilic membranes are not be universally fouling resistant depending on the specific material chemistry that delivers their hydrophilic interface.

One classic trade-off is that more hydrophilic polymers tend to be less robust, and hence, have shorter useful lives and when they inevitably foul, operators are limited in the type and concentration of cleaning agents that can be applied. So, cleaning can be difficult.

In contrast, more robust hydrophobic polymers are reasonably long lasting and can be cleaned with harsh chemistries, but their hydrophobicity lends itself to more rapid permeability loss and incomplete recovery upon backwashing and cleaning.

Ceramics are a more ideal combination of hydrophilic and robust, but they cost 10-20 times more (per unit area of membrane). Hence, they have achieved limited market share due to the high capital investment and are used only when no other options are available.

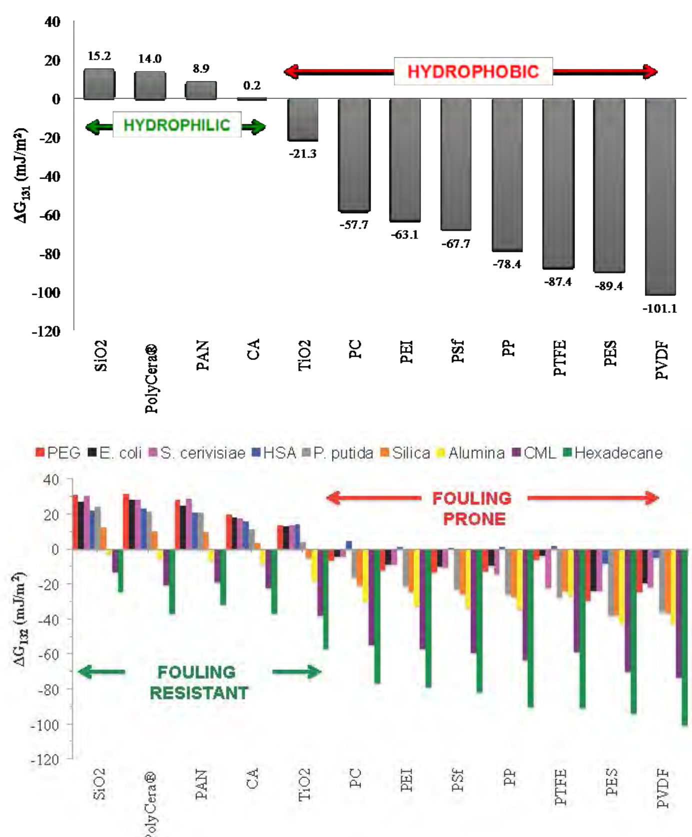

Figure 5. Plots of (top) free energy of cohesion or hydrophilicity for common polymeric and ceramic membrane materials and (bottom) free energy of adhesion or fouling propensity for polymeric and ceramic membrane materials along with a wide range of organic, microbial and inorganic fouling materials

3. COST DRIVERS IN MEMBRANE FILTRATION

Is dead-end or cross-flow better for preventing fouling?

Theory informs us that suspended solids are dragged towards and through the membrane in proportion to the filtrate flux squared. Thus, fouling rates are highly dependent upon the rate of filtrate flux through the membrane. Higher operating fluxes require very high cross-flow shear and more frequent backwashing, but offer lower capital investment; and vice versa.

Theory also informs us that very, very small particles (<0.5 μm) tend not to be influenced by cross-flow shear, whether induced by air scouring or high hydraulic cross-flow velocity. In contrast, large particles tend to be easily swept away from higher cross-flow shear. Therefore, one's choice of a dead-end or cross-flow mode of operation depends highly on the type of suspended solids that will be encountered on a case-by-case basis.

Large particulates (oil emulsions and bioflocs) are tolerated using high cross-flow shear – either by air scouring or hydraulic cross-flow, whereas small particulates (natural organic matter) are more challenging and require frequent backwashing and chemical cleaning.

Hydraulic cross-flow operations tend to consume more energy because of the extra pressure losses associated with pumping water, and hence, are used for smaller scale installations and higher suspended solids feeds (oily water treatment, industrial tertiary filtration, and process separations). Air-scoured dead-end operations are generally preferred for large-scale installations with lower suspended solids where energy costs are significant (municipal drinking water, tertiary filtration, membrane bio-reactors and seawater RO pretreatment).

How do design & operating practices affect MF/UF membrane cost?

The required membrane area and capital cost of a MF/UF system declines sharply as the target operating flux increases; however, the applied feed pressure, cross-flow shear, energy consumption and operating costs required to sustain the target flux also increase (slightly) non-linearly with increasing flux.

Depending on the nature (fouling propensity) and concentration of feed suspended solids, higher or lower rates of cross-flow shear, backwashing and cleaning are required, which also impact the operating cost. When one considers both the declining capital cost and escalating operating cost as a function of target operating flux, there inevitably exists a cost optimum at a specific target flux. However, there is no universal optimum and it is largely a function of a few parameters: (1) the cost per unit area of the membrane, (2) membrane replacement rate, (3) energy demand, and (4) the extent of backwashing required to maintain the flux.

As a result, for ceramic membrane based systems to compete with polymeric membrane based systems, they must be operated near to dead-end at relatively low fluxes, which keeps energy and back-washing to a minimum. In addition, the capital investment must be amortized over 20+ years because of the much higher cost of membrane materials (primarily municipal scenarios).

For shorter amortization situations (primarily industrial scenarios), ceramics cannot compete on cost with polymerics. However, in many cases ceramics are the only option because commodity polymerics don't work at all, or the operating cost is too high due to a combination of excessively short membrane life and excessively high process downtime – both being due to frequent/intense back-washing and cleaning.

4. SUMMARIZING THE STATE-OF-THE-ART

The current state-of-the-art paradigm is that ceramics are relatively robust (long-lasting), fouling-tolerant and easy to clean, but very expensive, whereas polymerics are relatively affordable, but less robust, fouling-prone and difficult to clean.

A new membrane material is needed offering the robustness and fouling resistance of ceramic membranes but available at a commodity polymeric membrane price point. This could generically be referred to as a "polymeric-ceramic" membrane as depicted in Table 1 below.

Table 1. Comparison of polymeric and ceramic membranes

Polymeric	***Ceramic***	***Polymeric-Ceramic***
✓ Inexpensive	✓ Expensive	✓ Inexpensive
✓ High-packing density	✓ Low-packing density	✓ High-packing density
✓ Easy to manufacture	✓ Difficult to manufacture	✓ Easy to manufacture
✓ Less robust	✓ More robust	✓ More robust
✓ Less fouling tolerant	✓ More fouling tolerant	✓ More fouling tolerant
✓ Difficult to clean	✓ Easy to clean	✓ Easy to clean

Moreover, the fast kinetics of fouling limit MF/UF system performance, energy, chemicals, downtime, water recovery and, ultimately, cost. Any excursions in feed water quality demand nearly instantaneous adjustments to flux optimization methods such as cross-flow, backwashing and chemical cleaning; however, conventional controls are static and non-adaptive. More intelligent, self-adaptive control system software is needed to allow standard membrane filtration hardware to make real-time adjustments to flux optimization methods.

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5. BRIDGING THE TECHNOLOGY GAP WITH SMART MEMBRANE PRODUCTS

In conclusion, MF/UF membrane filtration lies at the heart of sustainable water reuse now and into the future; however, membrane fouling is the “tail that wags the dog” and drives the design, operation and costs of membrane filtration.

What is needed are:
- More fouling tolerant and easy-to-clean MF/UF membranes
- Advanced controls to deal with the fast kinetics of MF/UF fouling

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ABOUT THE AUTHOR:

Eric Hoek, Ph.D.
CEO / Founder, Water Planet, Inc.

Dr. Eric Hoek has over 20 years of experience in water treatment membrane technology innovation and application. A start-up company founded in 2005, based on new membrane material invented by Dr. Hoek, was acquired by a large multi-national chemical company for $200 million in 2014. Dr. Hoek completed UCLA’s Anderson School of Management, Executive Program, General Business Management and Director’s Education & Certification in 2014