Application of Membrane Separation Technologies to Wastewater Reclamation and Reuse

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ABSTRACT

As population growth and industrial and agricultural activities continue to stress the quality of the relatively fixed quantity of available fresh water on this planet, industry is challenged to investigate and develop unique and economical technologies to reclaim and reuse processing wastewater.

The four crossflow pressure-driven membrane technologies of microfiltration, ultrafiltration, nanofiltration and reverse osmosis possess unique properties which favor their use in these applications. Two of these are the facts that they are low energy (the driving force is pressure) and use no chemicals to effect separation.

This paper will define these technologies, explain their operational characteristics and detail the testing requirements for utilization of them in wastewater reclamation and reuse.

INTRODUCTION

Although the total quantity of water on this planet is more or less fixed, its quality is deteriorating, because we have been contaminating it for thousands of years, with little concern for the consequences. The issue that confronts us is the availability of water of sufficient quality. Table 1 is a summary of the world's water resources.

An analogy that may be a bit easier to understand is that if all the world's water were to completely fill a one gallon jug, the fresh water available for use would amount to only about one tablespoon.

Population growth and increased agricultural and industrial activities are contaminating our water supplies, while more stringent regulations and requirements for higher quality water for processing and drinking applications have exacerbated the problems.

The U.N. estimates that over ten million people a year die from drinking polluted water, mostly children.

Today, about 20% of the world's population is without clean water, and it is expected that, without drastic measures, half of the people on this planet will suffer from severe water shortages by 2050.

Across the United States, 39% of water use goes to energy production. Farms use another 40%, and manufacturing an additional 11%. Together, these three sectors use about 300 billion gallons of fresh water every day.

Contamination Issues

The contaminants in water supplies which compromise its quality can be organized into the classes shown in Table 2.

There are not many absolutes in the water treatment industry, but here is one: *it is impossible to make water completely free of all contaminants.* This fact has been recently underscored by the Associated Press article about PCPPs or Endocrine Disruptors found in drinking water

Table 1. Distribution of world water supply (cubic miles)

	Fresh	Saline	Total
Rivers and streams	300		
Freshwater lakes	30,000		
Salt lakes and inland seas		25,000	
Total surface water	**30,300**	**25,000**	**55,300**
Soil moisture and seepage	16,000		
Underground water to ½ mile depth	1,000,000		
Underground water to below ½ mile	1,000,000		
Total ground water	**2,016,000**		**2,016,000**
Glaciers and ice caps	7,000,000		
Oceans		317,000,000	
Total world water supply	**9,046,300**	**317,000,000**	**326,071,300**

Table 2. Water contaminants

Class	Examples
Suspended solids	Dirt, clay, colloidal materials, silt, dust, insoluble metal oxides and hydroxides
Dissolved organics	Trihalomethanes, synthetic organic chemicals, humic acids, fulvic acids
Dissolved ionics (salts)	Heavy metals, silica, arsenic, nitrate, chlorides, sulfates
Microorganisms	Bacteria, viruses, protozoan cysts, fungi, algae, molds, yeast cells
Gases	Hydrogen sulfide, methane, radon, carbon dioxide

supplies throughout the U.S. Undoubtedly, these contaminants have been present for many years, but their concentrations are so low (parts per trillion), that we have only recently been able to measure them.

WATER REUSE

Although still in its infancy, water reuse is growing at an estimated 11% per year in the U.S. Most of the recovered water is from municipal wastewater treatment plants ("reclaimed water") and is used for landscape and agricultural irrigation; however, industrial wastewater reuse is beginning to grow at an even higher rate—over 14%/year, by one estimate.

There are proven technologies available to treat any and all polluted water supplies; it's really a matter of committing financial and engineering resources. For almost all wastewater streams, a comprehensive test is required in order to select the optimum technologies and design the most cost effective water recovery system.

Due to the extreme variation in the specific kind and concentration of contaminants, industrial wastewater reuse requires the most testing and design expertise; however, with the rapidly increasing discharge regulations on both water quality as well as quantity, the incentive to recover and reuse is in place.

The process of treating wastewater and discharging it into a lake, river or aquifer from which drinking water is collected is known as "indirect reuse."

As the paradigm of water reclamation takes hold throughout the world, the concept of "direct reuse," treating wastewater at the source and reusing it directly, will become increasingly common, particularly in residential applications ("graywater reuse"). In many industrial applications, the incoming water has undergone extensive treatment for a particular process, and, overall, it is often more economical to treat this water for reuse than to simply discharge it, particularly as the cost of municipal water continues to increase.

TREATMENT TECHNOLOGIES

The arsenal of treatment technologies available today for industrial and municipal wastewater treatment is extensive. The traditional technologies are listed in Table 3.

A summary of major industrial treatment technologies follows.

As is evident from the previous table, a plethora of treatment technologies is available from removing contaminants from water supplies. For water reuse in most industrial and municipal applications, the most versatile and economical technology platform consists of the four crossflow pressure-driven processes of:microfiltration (MF),ultrafiltration (UF),nanofiltration (NF), andreverse osmosis (RO).

BACKGROUND ON MEMBRANE TECHNOLOGIES

Membrane technologies are based on a process known as "pressure-driven crossflow" filtration, which allows for continuous treatment of liquid streams. In this process, the bulk solution flows over and parallel to the membrane surface, and because the system is pressurized, water is forced through the membrane and becomes "permeate." The turbulent flow of the bulk solution over the surface minimizes the accumulation of particulate matter.

These technologies behave differently than filters in that (with some exceptions) the feed stream is pumped at a high flow rate across the surface of the filter media (membrane), with a portion of this stream forced through the membrane to effect separation of the contaminants, producing the permeate, and the concentrated contaminant remaining in the other stream (concentrate) exits the membrane element on a continuous basis. Figure 1 compares conventional with crossflow filtration.

Crossflow filtration offers the following advantages over traditional filtration technologies:

- Continuous and automatic operation
- Capable of removing contaminants down into the submicron size range
- Usually requires no chemical addition
- Backwashing capabilities
- Generally can operate in turbulent flow conditions
- Systems have a very small footprint

It is important to note that whereas with the media, cartridge and bag filtration technologies, the filtration process must be halted to backwash or replace the medium, crossflow filtration is designed to operate continuously, with the concentrate stream carrying away the contaminants. On the other hand, crossflow filters do become fouled and usually require backwashing operation.

By utilizing surface filters of specific membrane construction, very small pore sizes can be obtained, resulting in two submicron technologies: microfiltration and ultrafiltration.

Microfiltration (MF) is typically used to remove particulate material in the submicron range, most microfiltration devices in use today are designed as cartridge filters in that the entire solution passes through the filter leaving the particulate material behind, either on the filter surface or down inside the filter medium. The microfiltration devices addressed here use the "crossflow" design, which produces two exiting streams: one which has passed through the

Table 3. Traditional treatment technologies

Treatment Technologies	Suspended Solids Removal	Dissolved Organic Removal	Dissolved Salts Removal	Microorganism Removal
Biological processes				
MBR (membrane bioreactor)	X	—	—	X
Activated sludge	X	X	—	X
Anaerobic digestion	X	X	—	—
Bio-filters	—	X	—	—
Extended aeration				
Bio-denitrification	—	L	—	—
Bio-nitrification	X	X	—	—
Pasveer oxidation ditch	X	X	—	X
Chemical processes				
Chemical oxidation				
Catalytic oxidation	X	X	—	X
Chlorination	X	X	—	X
Ozonation	—	L	—	X
Wet air oxidation	X	X	—	X
Chemical precipitation	—	—	X	—
Chemical reduction	—	—	X	—
Ion exchange	—	—	X	—
Liquid-liquid (solvent)	—	—	X	—
Coagulation				
Inorganic chemicals	X	X	—	X
Polyelectrolytes	X	X	—	X
Electolytic processes				
Electrodialysis	—	—	X	L
Electrodeionization	—	—	X	—
Electrolysis	—	—	X	—
Ultraviolet irradiation	—	—	—	X
Extractions				
Incineration				
Fluidized-bed	X	X	—	X
Physical processes				
Carbon adsorption				
Granular activated	X	X	—	—
Powdered	X	X	—	X

(table continues)

Table 3. Traditional treatment technologies (continued)

Treatment Technologies	Suspended Solids Removal	Dissolved Organic Removal	Dissolved Salts Removal	Microorganism Removal
Physical processes (continued)				
Specialty resins	—	L	L	—
Filtration				
Diatomaceous-earth filtration	X	—	—	X
Multi-media filtration	X	—	—	X
Micro-screening	X	—	—	X
Sand filtration	X	—	—	X
Flocculation-sedimentation	X	—	—	X
DAF (dissolved air flotation)	X	X	—	—
Foam separation	X	—	X	—
Membrane processes				
Microfiltration	X	—	—	X
Ultrafiltration	X	X	—	X
Nanofiltation	X	X	L	X
Reverse osmosis	X	X	X	X
Stripping (air or steam)	X	X	—	—
Thermal processes				
Distillation	X	X	X	X
Freezing	—	X	X	—

L = Under certain conditions, there will be limited effectiveness.

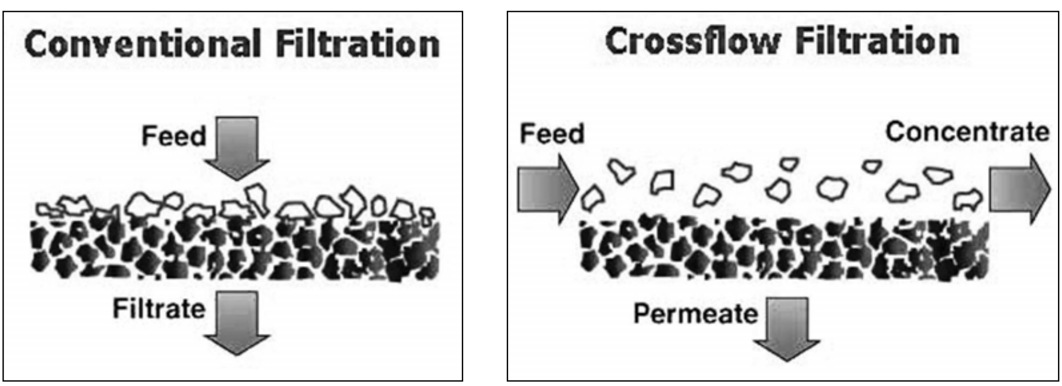


Figure 1. Conventional versus crossflow filtration

membrane media and is purified (permeate), and the other which flows across and parallel to the media surface, continuously removing the contaminants (concentrate).

Generally, microfiltration involves the removal of particulate, or suspended materials ranging in size from approximately 0.10 to 1.0 microns (1,000 to 10,000 angstroms). MF typically operates within a pressure range of 10 to 30 psi (0.68 to 2.0 bar).

Ultrafiltration (UF) is used to separate dissolved, non-ionic materials (macro molecules) typically smaller than 0.10 micron (1,000 angstroms). The removal characteristics of UF membranes can be described in terms of "molecular weight cutoff" (MWCO), the maximum molecular weight of dissolved compounds that will pass through the membrane pores. MWCO terminology is expressed in Daltons. Basically, ultrafiltration is used to remove *dissolved* organic contaminants, while *suspended* solids are removed by microfiltration. UF normally operates in a pressure range of 10 to 100 psi (0.68 to 6.8 bar). UF membranes are available over a wide range of MWCO removal properties, from about 1,000 to over 100,000 Daltons.

MF and UF processes separate contaminants based on a "sieving" process; that is, any contaminant too large to pass through the pore is rejected and exits in the concentrate stream.

Nanofiltration can be considered "loose" reverse osmosis. It rejects dissolved ionic contaminants but to a lesser degree than RO. NF membranes reject a higher percentage of multivalent salts than monovalent salts (for example, 99% vs. 20%). These membranes have molecular weight cut-offs for non-ionic solids below 1000 Daltons.

Reverse osmosis produces the highest quality permeate of any pressure driven membrane technology. Certain polymers will reject over 99% of all ionic solids, and have molecular weight cut-offs in the range of 50 to 100 Daltons.

Both NF and RO membranes reject salts utilizing a mechanism that is not fully understood. Some experts endorse the theory of pure water preferentially passing through the membrane; others attribute it to the effect of surface charges of the membrane polymer on the polarity of the water. Monovalent salts are not as highly rejected from the membrane surface as multivalent salts; however, the high rejection properties of the newer thin film composite RO membranes exhibit very little differences in salt rejection characteristics as a function of ionic valance. As indicated earlier, this difference is significant with NF membranes.

In all cases, the greater the degree of contaminant removal, the higher the pressure requirement to effect this separation. In other words, reverse osmosis, which separates the widest range of contaminants, requires an operating pressure typically an order of magnitude higher than microfiltration, which removes only suspended solids.

Table 4 summarizes the various properties and other features of these technologies.

Device Configurations

To be effective, membrane polymers must be packaged into a configuration commonly called a "device" or "element." The most common element configurations are: Tubular, Hollow (capillary) Fiber, Spiral Wound, and Plate and Frame.

The element configurations are described as follows.

Tubular. Manufactured from ceramics, carbon, stainless steel, or a number of thermoplastics, these tubes have inside diameters ranging from ¼ inch up to approximately 1 inch (6 to 25 mm). The membrane is typically coated on the inside of the tube and the feed solution flows under pressure through the interior (lumen) from one end to the other, with the permeate passing through the wall and collected outside of the tube.

Table 4. Membrane technologies compared

Feature	Microfiltration	Ultrafiltration	Nanofiltration	Reverse Osmosis
Materials of construction	Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride, Polytetrafluoroethyliene	Ceramics, Sintered metals, Polypropylene, Polysulfone, Polyethersulfone, Polyvinylidene fluoride	Thin film composites, Cellulosics	Thin film composites, Cellulosics
Pore size range (micrometers)	0.1–1.0	0.001–0.1	0.0001–0.001	<0.0001
Molecular weight cutoff range (Daltons)	>100,000	1,000–100,000	300–1,000	50–300
Operating pressure range	<30	20–100	50–300	225–1,000
Suspended solids removal	Yes	Yes	Yes	Yes
Dissolved organics removal	None	Yes	Yes	Yes
Dissolved inorganics removal	None	None	20–95%	95–99+%
Microorganism removal	Protozoan cysts, algae, bacteria*	Protozoan cysts, algae, bacteria*, viruses	All*	All*
Osmotic pressure effects	None	Slight	Moderate	High
Concentration capabilities	High	High	Moderate	Moderate
Permeate purity (overall)	Low	Moderate	Moderate-high	High
Energy usage	Low	Low	Low-moderate	Moderate
Membrane stability	High	High	Moderate	Moderate

*Under certain conditions, bacteria may grow through the membrane.

Hollow (Capillary) Fiber. These elements are similar to the tubular element in design, but are smaller in diameter, and are usually unsupported membrane polymers or ceramics. In the case of polymeric capillary fibers, they require rigid support on each end provided by an epoxy "potting" of a bundle of the fibers inside a cylinder. Feed flow is either down the interior of the fiber ("lumen feed") or around the outside of the fiber ("outside-in").

Spiral Wound. This element is constructed from an envelope of sheet membrane wound around a permeate tube that is perforated to allow collection of the permeate. Water is purified by passing through one layer of the membrane and, following a spiral path, flows into the permeate tube. It is by far the most common configuration in water purification applications, but generally requires extensive pretreatment in wastewater applications.

Plate and Frame. Sheet membranes are stretched over a frame to separate the layers and facilitate collection of the permeate, which is directed to a collection tube.

Table 5. Membrane element configuration comparison

Element Configuration	Packing Density*	Fouling Resistance†
Plate & frame	Low	High
Hollow (capillary) fiber	High	High
Tubular	Low	Very high
Spiral wound	Medium	Low

*Membrane area per unit volume.
†Tolerance to suspended solids.

Table 6. Microfiltration and ultrafiltration

Materials of Construction	Device Configuration			
	Hollow Fiber	Tubular	Plate & Frame	Spiral Wound
Polymeric				
PS	X	X	X	X
PES	X	X	X	X
PAN	X	X	X	X
PE	—	X	—	—
PP	X	X	X	—
PVC	—	X	—	—
PVDF	X	X	—	—
PTFE	X	—	X	—
PVP	X	X	—	—
CA	X	—	—	—
Non-polymeric				
Coated 316LSS	—	X	—	None
α-Alumina	—	X	X	None
Titanium dioxide	—	X	—	None
Silicon dioxide	—	X	—	None

PS = Polysulfone
PES = Polyethersulfone
PE = Polyethylene
PP = Polypropylene
PAN = Polyacrylonitrile
PVDF = Polyvinylidene Fluoride
PTFE = Polytetrafluoroethylene
CA = Cellulose Acetate
PVP = Polyvinylpyrrolidone
TF = Thin Film Composite

From the perspective of cost and convenience, it is beneficial to pack as much membrane area into as small a volume as possible. This is known as "packing density." The greater the packing density, the greater the membrane area enclosed in a certain sized device, and generally the lower its cost. The downside of the high packing density membrane elements is their greater propensity for fouling. Table 5 compares the element configurations with regard to their packing densities.

To clarify the membrane materials used for the various element configurations, Tables 6 and 7 are provided.

Table 7. Nanofiltration and reverse osmosis

Materials of Construction	Device Configuration			
	Hollow Fiber	Tubular	Plate & Frame	Spiral Wound
Polymeric				
PS*	—	X	X	X
PES*	—	X	X	X
CA	—	X	X	X
TF	—	X	X	X
Non-Polymeric				
None				

*Base polymer below TF polymer.
PS = Polysulfone
PES = Polyethersulfone
CA = Cellulose Acetate
TF = Thin Film Composite

Table 8. Membrane element cleaning capability

	Membrane Technology				
Element Configuration	MF	UF	NF	RO	Backwashable?
Plate & frame	Yes	Yes	Yes	Yes	No (except for inorganic membrane)
Tubular	Yes	Yes	Yes	Yes	Yes
Hollow fiber	Yes	Yes	Yes	No	Yes
Spiral wound	Yes	Yes	Yes	Yes	No (NF, RO) Yes (MF, UF)

Because of the extreme value of backwashing/backpulsing to minimize the effects of fouling on membrane surfaces, Table 8 categorizes membrane devices with this capability.

SYSTEM DESIGN

Figure 2 is a schematic of a complete membrane processing system (or a single membrane element).

The feed stream enters the system (or membrane element), and as the stream passes along and parallel to the surface of the membrane under pressure, a percentage of the water is forced through the membrane polymer producing the permeate stream. Contaminants are prevented from passing through the membrane based on the polymer characteristics. This contaminant-laden stream exits the membrane system (or element) as the "concentrate" stream, also known as "brine" or "reject."

The permeate rate of a given membrane element cannot be changed without varying the applied pressure or temperature. Recovery, however, can be easily changed by varying the feed flow rate to the element, and this is one of the variables that is controlled by the system designer.

For wastewater treatment and water reuse applications, the minimum recovery is usually no less than 90%.

The relationship between recovery and concentration of solute in the concentrate stream is illustrated by the data in the table and plotted in Figure 3. The concentration effect resulting

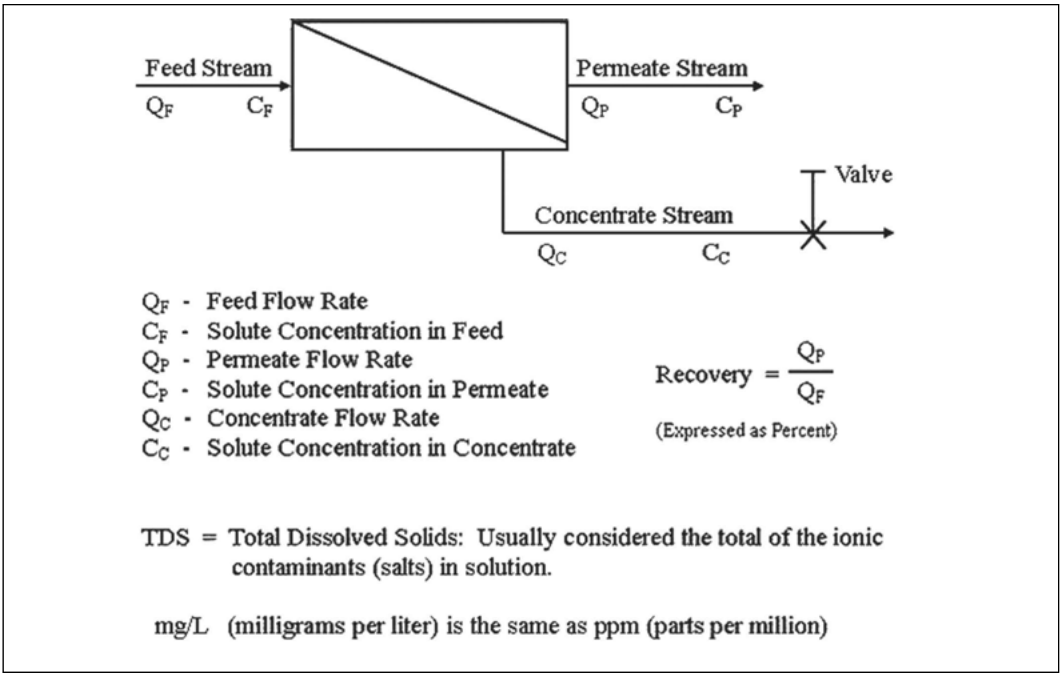


Figure 2. Membrane system schematic

from pumping a certain percentage of the solvent through the membrane is represented mathematically by the term:

$\frac{1}{1 - \text{recovery}}$, also known as “concentration factor” (X).

The advantage of operating systems at high recoveries is that the volume of concentrate is small and the flow rate of the feed pump is smaller; the potential disadvantages are numerous:

- The higher concentration of contaminants is likely to result in fouling. In nanofiltration and reverse osmosis applications, the concentrated salts solution results in high osmotic pressure, requiring a higher-pressure pump and a more pressure tolerant system.
- As higher recoveries reduce the quantity of concentrate to be discharged, the higher concentration of the concentrate stream may present regulatory discharge problems.

MBR TECHNOLOGY

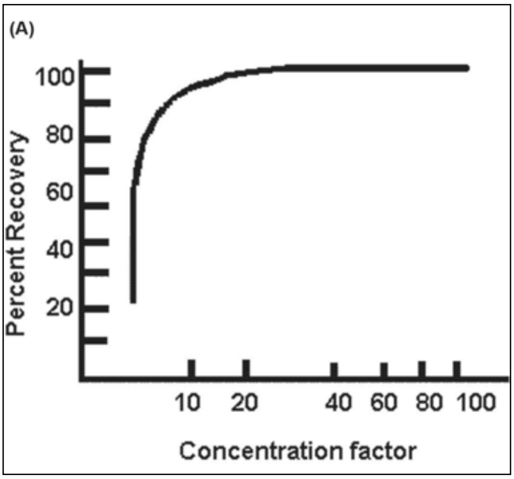
As the newest membrane technology application, and one with huge potential, MBR (membrane bioreactor) technology justifies special mention.

For wastewaters containing biodegradable contaminants, the traditional treatment method is to encourage the use of bacteria to break down the contaminant (bioremediation).

This encouragement can take the form of adding oxygen (in the case of aerobic treatment), providing a mechanical matrix (for bacterial attachment), mixing, and other approaches intended to maximize the metabolic activity of these microorganisms.

MBR offers significant advantages over traditional bioremediation processes, as listed below:

- High-quality effluent, almost free of suspended solids
- The ability to partially disinfect without the need for chemicals



(B)

$$C_c \approx \frac{C_F}{1 - \text{Recovery}} = XC_F$$

$$X = \frac{1}{1 - \text{Recovery}} = \text{Concentration Factor}$$

Percent Recovery	Concentration Factor
33%	1.5
50%	2
67%	3
75%	4
80%	5
90%	10
95%	20
97.5%	40
98%	50
99%	100

Figure 3. (a) Effect of recovery on concentration and (b) effect of recovery on concentration factor

- Complete independent control of HRT (Hydraulic Retention Time) and SRT (Sludge Retention Time)
- Reduced sludge production
- Process intensification through high biomass concentrations with MLSS (Mixed Liquor Suspended Solids) concentrations above 15,000 mg/L
- Treatment of recalcitrant organic fractions and improved stability of processes such as nitrification
- Ability to treat high strength wastes

The membrane device configurations most commonly used today are hollow (capillary) fiber and plate and frame, although tubular and spiral wound devices are becoming more widely used.

The most common biological treatment is aerobic and, typically, air is bubbled into the treatment tank. A very popular approach is to immerse the membrane element in the treatment tank and either allow the hydrostatic head of the solution to provide the driving force or to use a pump to pull the permeate through the membrane (or both). In this case, air bubbles are also directed up over the surface of the membrane, from below (air scouring), in an effort to reduce fouling.

Another design involves pumping water through the membrane system external to the treatment tank, and yet another uses a separate tank for membrane processing downstream of the biological treatment tank. Additional designs and configurations are sure to appear as MBR technology becomes more widely used.

Figure 4 illustrates aerobic MBR applications for both “immersed” and “external” designs.

TESTING

In general, every stream must be tested to develop the following design factors:

- Optimum membrane element configuration
- Total membrane area
- Specific membrane polymer
- Optimum pressure
- Maximum system recovery

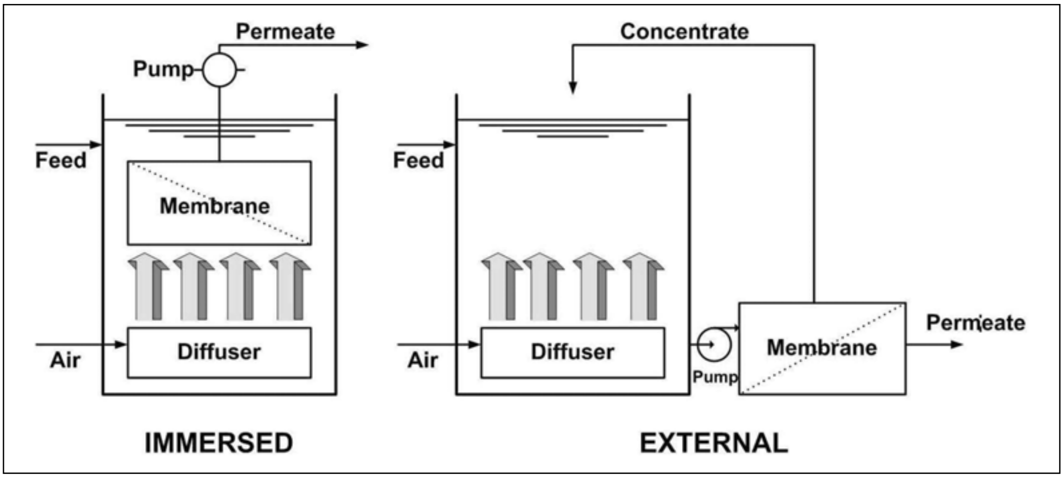


Figure 4. Aerobic MBR applications

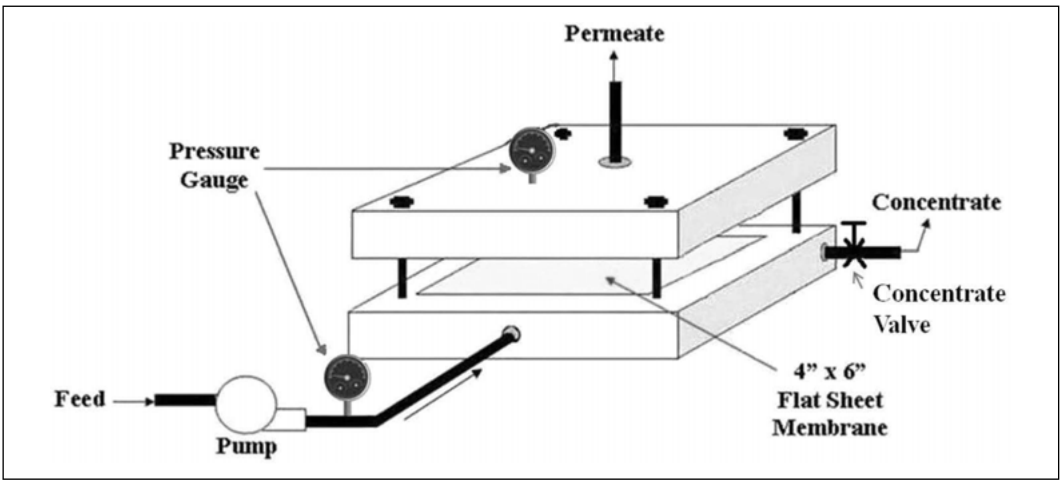


Figure 5. Cell test unit

- Flow conditions
- Membrane element array
- Pretreatment requirements

To generate the necessary design data, several testing options are available.

Cell Testing

A typical cell testing device is illustrated in Figure 5. Cell test devices are available for purchase (or through a consulting engineering firm skilled in the art), which evaluate small sheets of membranes on the stream to be processed. Typically, the sheet is placed between two stainless steel plates, and the test stream pumped across the membrane surface at a selected pressure and flow rate. The permeate is collected and analyzed for degree of separation, possible effect of the stream on the test membrane, and other properties.

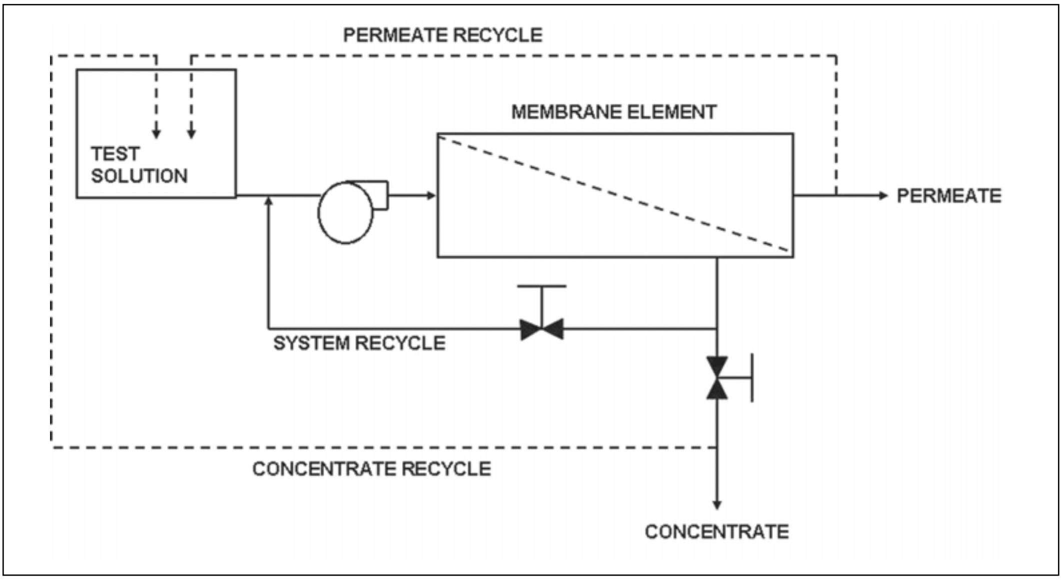


Figure 6. Applications test schematic

The cell test offers a number of *advantages*:

- Only small areas of membranes are needed; excellent for screening membrane polymer candidates.
- Can be run on small volumes of test stream.
- Takes very little time.
- Unit is simple to operate.

The *disadvantages* of this testing approach are:

- Cannot obtain engineering design data.
- Cannot be used for long-term fouling study.
- Is only useful with membranes available as flat sheet.

The cell test approach is useful as an initial step, primarily to select one or more membrane candidates for further evaluation.

Applications Testing

Figure 6 illustrates an applications test schematic. Applications testing utilizes a membrane element in a test unit capable of operating similar to a production unit. Since the data from this testing will be used to scale up the design to full size, it is essential that the membrane element manufacturer supplies an element capable of this scale up.

The applications test equipment should be designed so that very high recoveries can be achieved without compromising the flow rates required to produce turbulent flow, for example. This requires that the pump be capable of not only producing the desired pressure, but also the flow rate to accomplish the minimum crossflow velocity across the membrane surface.

Because the system must be capable of testing at very high recoveries, the concentrate valving must be adjustable to accurately produce extremely low flow rates. This typically involves the assembly of a “valve nest” using micrometer valves. Additionally, the recycle line should be equipped with a diaphragm valve for adjustment of flow and pressure.

The most important feature for application testing equipment is versatility. Different membrane elements have very specific operating parameters, and the equipment must accommodate these. To cover the entire gamut of membrane technologies, two different pieces of application testing equipment are generally required: one for MF and UF, and the other for NF and RO.

The latter must be capable of pressures up to 1,000 psi (68 bar), and it is virtually impossible to find a single pump capable of supplying the flows and pressures required for all four technologies. For MF and UF applications, a variable speed drive centrifugal pump works fine, although the variable speed feature makes it expensive.

Materials of construction are an important consideration in testing considerations: 316L stainless steel is essential for applications requiring pressures in excess of 60 psi (4 bar); below that, schedule 80 PVC is sufficient.

Applications testing is capable of generating complete design data for the full sized system. An applications test can be run on as little as 50 gallons (200L) of test stream, and after setup, can be completed in one hour or less, for each membrane element tested.

A typical applications test is run as follows:

1. To establish "control conditions," high quality water (tap water or water treated with RO or DI) is run into the system at low recovery to minimize any possible contaminant concentration effects. Take data (see Membrane Application Test Data Sheet).
2. Feedwater is then run into the unit set at low recovery, and after stabilization (usually less than 5 minutes), the following data are taken:
   - Pressures
     - Prefilter
     - Primary (feed)
     - Final (concentrate line)
   - Flow
     - Recycle
     - Permeate
     - Concentrate
   - Temperature (recycle)
   - Quality (conductivity)
     - Feed
     - Permeate
     - Concentrate

   The system recovery is then increased incrementally while adjusting the recycle valve to ensure that the correct crossflow velocity is maintained.
3. At the conclusion of the testing, high quality water is again run through the system to determine if the permeate rate or other operating characteristics have been affected.

At each recovery, in addition to the collection of flow and pressure data, analytical samples should be taken for performance evaluation. Of course, the choice of parameters to be measured depends upon the separation goals of the test. It is unusual for system recoveries to exceed 95%; however, that also depends upon the goals of the testing, and it is possible to run a well designed test unit up to 99% recovery.

Once the optimum conditions have been established, such as operating pressure and maximum system recovery, the normalized performance data will enable the test engineer to determine the total membrane area required for the full sized system.

Application testing provides the following advantages and disadvantages:

Advantages

- Fast.
- Provides scale-up data (flow, osmotic pressure as a function of recovery, pressure requirements, etc.).
- Can provide an indication of membrane stability.

Disadvantages

- Does not reveal long term chemical effects.
- Does not provide data on long term fouling effects.

Pilot Testing

Usually this involves placing a test machine (such as that used for the applications test) in the process, operating continuously on a "side-stream" for a minimum of 30 days.

Advantages. Accomplishes all of the functions of the applications test plus provides long term membrane fouling and stability data.

Disadvantages. Expensive in terms of monitoring and time requirements.

CONCLUSIONS

With the exception of the oxygen we breathe, there is no substance more critical to life than water, and no substitute for it.

Many experts feel that there is no other product whose real value so far exceeds its price, and whose price is so often unrelated to its actual cost of production and delivery.

As the world's population continues to grow, as this expanding population tends to relocate to water-short regions, and as climate changes create areas of drought, stress on the quality of our fixed water quantity will become very, very critical. This problem can only be addressed by aggressively and constructively employing such innovative conservation and water reuse.

Solutions are there, but the entire world must give water quality issues high priority and be willing to commit the investments of money, education and commitment to make these solutions a reality.