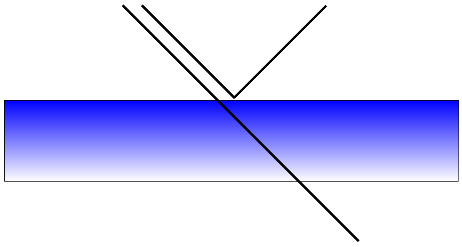
The Membrane Filtration Handbook



by

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With contributions and editing

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‘The Membrane Filtration Handbook’ represents a total of almost 80 years of experience accumulated by the authors from the humble beginning of membrane filtration technology to today’s state-of-the-art membranes and system designs,

The book would not be in existence without a firm friendship between the authors and without the support of our wonderful and understanding spouses, Connie Wagner and Suzanne Nicolaisen.

A word of caution to the reader as expressed by an old hand in the membrane filtration industry:

Membranes are not for the faint of heart!
Dan Comstock, circa 1988

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Foreword

In the broad spectrum of industrial processes membrane filtration is a relative newcomer, emerging in the late 1950s, developing in the 1960s and the 1970s, in fact only becoming an industrially useful technology from the beginning of the 1980s. Even in the 1980s and into the 1990s the users were often left with the pain when something went wrong, and they needed to have a certain adventurous streak to risk employing a new and relatively unproven technology in their manufacturing operations.

The first large application was reverse osmosis for drinking water in areas of the world where water is scarce. The sources were mainly ground water and surface water. Later, seawater desalination was developed. Many arid areas and islands are totally dependent on membrane filtration for their water supply.

Membrane filtration, with the exception of very few highly specialized applications, deals with aqueous solutions. The industry was quick to investigate membrane filtration as a new technology, and there was an exceptionally good fit in some industries and applications. For instance, huge volumes of cheese whey result from cheese production. With the consolidation of cheese plants, the problem of disposal of the cheese whey increased gradually. Membrane filtration has a perfect fit with this problem and solved it making entirely new and profitable products for the dairy industry. Electro-deposition paint used, for instance, in the automotive industry is diluted in the painting cycle, and only if the solids are concentrated can the paint be reused. Membrane filtration extends the life cycle of the paint and reduces cost for the industry.

Membrane filtration has come of age and has found its place in the spectrum of industrial processes. The authors of this book were employed in the industry from early in the 1970s and have been in the center of the development in various positions. They have contributed to this development, and are well known in the industry for their theoretical and practical knowledge.

The membrane filtration industry is still of a moderate size. The authors, who are nearing the age of retirement, are often asked to recommend candidates for position in the industry. We sometimes find it hard to come up with candidates, and we have concluded that persons with the right background and experience are few and far between. We have also found that only few educational institutions offer appropriate courses in membrane filtration to the new generation of specialists.

There is an abundance of scientific literature dealing with the theoretical aspects of membrane filtration, but there is very little with useful instruction on how to make it work in practical applications. When a plant has a problem and the product stream cannot be treated as planned, little or no help is to be found in the literature.

One of us, Jørgen Wagner, wrote the 'Membrane Filtration Handbook' with the subtitle 'Practical Hints and Tips', in 1994. It was first privately published and later available from Osmonics (now GE Osmonics). An amazing number of plant managers and plant operators are familiar with this book, and they are frequently referring to it and applying its contents in their day to day situations.

Since the publication of the 'Membrane Filtration Handbook' the authors have been individually and jointly involved in solving many problems in connection with membrane filtration, both as it pertains to developing theoretical explanations and applying theory to practical solutions. In the course of this effort we have found that practical solutions should not be expected from academia, that academia often is unable to communicate their useful concepts in an understandable form and that experience from industrial applications are not being applied in water purification and vice versa.

This book does not contain an abundance of scientific formulas of dubious practical use nor long theoretical explanations. In other words, it will not emulate the majority of existing literature. Neither is this book intended for use by the absolute novice to membrane technology. Although it does describe and explain the fundamentals of membranes and membrane technology, some basic knowledge of membranes and chemistry is assumed.

Most of the information is based on experience with flat sheet membranes, spiral wound elements and fiber systems. Spiral wound elements account for the vast majority of membrane area installed worldwide, while the market share of fiber systems, ceramic systems and tubular systems is relatively small. Ceramic and fiber membranes are getting more accepted because they have developed technically, and prices have dropped dramatically for some membrane configurations. Little information regarding tubular systems has been included, but the general concepts can be applied.

The authors have consciously avoided the use of theoretical explanations and formulas in the text of this book. Some practical calculation programs for dimensioning and predicting the performance of membrane filtration systems are available at www.MembraneConsult.com and www.wagnerdk.dk. They will be updated and expanded from time to time.

The authors intend this book to meet a need for better guidance with respect to employing membrane filtration for various applications in water purification as well as industrial processes stressing practical applications, problems and solutions. This book does not pretend to break new ground, but to present the cumulative benefits of experience gained through the working life of the authors, who feel that writing it is an obligation of duty to those who will carry the torch after them.

Jørgen Wagner and Bjarne Nicolaisen
April 2012

Part 1

Membranes

History and Present State

Terms, expressions and definitions

Any technological area develops and uses special expressions and defines its own meaning of generally used words and expressions. This is also the case for membrane filtration. With the purpose of avoiding misconceptions and misunderstandings a list of terms, expression and definitions commonly used in connection with membrane filtration has been compiled in Appendix A, which includes figure A1 showing often used abbreviations applied for multi-stage recirculation systems.

Membrane history

Life as we know it is dependent on water. 60% of the human body is water with the cells in the body consisting of up to 90% water. 80 different chemical elements have been identified in the human body with approximately 25 being considered essential to life. Several thousands of chemical compounds are being produced in the body or ingested with the food. Every cell in the body is surrounded by a membrane ensuring that the right composition is available to keep the cells alive. The concentration of the various compounds can be widely different inside the cells and in the liquid surrounding the cells. The existence of living cells have been known for 400 years and it was shown that the human body consists of living cells in 1839.

The membrane surrounding living cells consists of phospholipids with embedded proteins serving to selectively transport nourishment into the cells and removing metabolized waste. Nature's membranes are infinitely more sophisticated than any synthetically manufactured membrane employed in the relatively new technology described as membrane filtration, which has become important in water purification and industrial processing over the last 40 to 50 years.

The definition of a membrane is a semi-permeable barrier, which allows some species to pass through while rejecting others based on molecular size, molecular shape, electrical properties and other characteristics. Where nature is capable of achieving membrane filtration at little or no pressure difference, the technology we call membrane filtration often require high pressure differences to drive the process.

Osmosis was first described around 1750 studying a sugar solution where water passed a semi-permeable barrier at a velocity depending on the concentration of the sugar. The smaller the molecule, the higher is the osmotic pressure it can exert, and the higher the concentration, the higher the osmotic pressure.

If common table salt (sodium chloride, NaCl) is added on one side of a water filled chamber divided into two identical parts by a suitable membrane, the level of the liquid will rise in the half of the chamber with salt in order to equalize the chemical potential of the solutions. The pressure required to bring the liquid level of the salt solution back to the original and equal levels of the two half parts of the chamber is called the osmotic pressure of the salt solution.

The osmotic pressure of seawater, which is essentially a 3.5% solution of NaCl is close to 30 bar.

Toward the middle of the 20th century with an increasing population in many arid parts of the world it became clear that water could turn out to be a scarce commodity in the future. California stood out as one such area, and the United States federal government granted money to attempt to find a solution to future water scarcity. The focus was on utilization of water sources considered to be unsuitable for drinking water purposes. Among them was seawater, which at the time could only be converted to drinking water by very expensive and energy consuming evaporation.

The work using membranes to desalinate seawater was initiated at the University of California Los Angeles (UCLA) in the mid 1950s and later spearheaded by the Office of Saline Water. Further development was performed at the University of Florida. This early work focused on the use of cellulose acetate (CA) membranes. The process was dubbed reverse osmosis (RO). However, CA has pressure limitations, pH limitations and it is susceptible to attack by microorganisms. CA membranes had notable successes in purification of brackish and surface water, but desalination of seawater was on the verge of the capabilities of the CA membrane.

While the effort was directed toward making the tightest possible membrane, it turned out that it was possible to make a CA membrane with fairly controlled pore sizes in the 10,000 to 100,000 molecular weight range. This range was called ultrafiltration (UF) and it soon became evident that filtration in this range could become interesting in several areas.

Now the effort was concentrated on finding more suited membrane materials than CA for seawater desalination. Polysulfone or aryl compounds, was introduced in the mid 1960s and became the main contender in seawater desalination with many successful installations in operation, especially in Middle East countries.

As it turned out, polysulfone was also suited for UF membranes with notable achievements in the food and dairy industry, where it to this day is the most important membrane for protein fractionation in, for instance, treatment of cheese whey.

The government grants continued to be in effect and resulted in the development of a new RO membrane made of polyamide in the mid to late 1970s. The characteristics of this type of membrane are superior to CA and aryl compounds, and it soon took over the major portion of the RO market. It has excellent temperature and pH characteristics with the main disadvantage of being susceptibility to oxidizing agents.

In the meantime several other membrane materials were developed, for instance polyvinylidene difluoride (PVDF) and polyacrylonitrile (PAN), in the area of UF and in a new defined area called microfiltration (MF) bordering on particle filtration. MF is presently the fastest developing membrane technology.

The gap between RO and UF was closed by development of a new type of polyamide membrane, and the area is called nanofiltration (NF). An NF membrane is unique in the sense that it exhibits selective rejection of negatively charged ions with more than one charge. The NF area is developing rapidly into new application areas.

Ceramic membranes, for instance aluminum oxide (Al_2O_3) and silicon carbide (SiC), are well known, but have met with limited success in spite of their great resistance to temperature and chemical attack. Price seems to be the main stumbling block.

Other types of membranes like sintered stainless steel and track etched membranes are considered to be specialties without much practical application.

Water purification, including seawater desalination, is by far the largest application area for membrane technology measured in membrane area in operation. However, the general industry has adopted all four areas of membrane technology, and in many cases industrial processes have been completely redesigned based on the capabilities of membranes.

Membrane filtration is also widely applied for purification of gases, for instance carbon dioxide (CO_2), using organic and inorganic membrane materials. Pervaporation is a temperature driven membrane process where a gas is driven through the membrane, either purifying the feed solution or recovering a specific component in the permeate. Electrodialysis is a membrane process utilizing the different velocity of movement for different ionic species with an electrical field as the driving force. However, these areas of membrane filtration technology fall outside of the scope of this book.

A historical overview would not be complete without an attempt to look into the future.

It was stated earlier in this chapter that the osmotic pressure of a feed solution must be overcome in order to effect production of purified water in the reverse osmosis process. At least two new and ingenious methods employ existing but modified membrane designs and utilize the osmotic pressure to achieve a desired effect.

Forward osmosis uses the osmotic pressure gradient between a solution with high osmotic pressure and a dilute feed to produce a flow of water through the membrane with the effect being that water is separated from the solutes. The technology still needs to be developed to a point where large plants are realistic. It holds promise in desalination of seawater, landfill leachate treatment and several other applications areas.

Direct osmosis utilizes the different salt concentrations between two solutions separated by a membrane, for instance between the outflow of fresh water from a river and seawater, to produce electrical energy. Small scale osmotic power plants have been built in Europe with moderately good results. There is still room for doubling the efficiency compared to theory, and the technology holds the promise of being able to provide a steady supply of energy in the future replacing carbon based fuels.

Membrane Processes

The membrane filtration processes discussed in this book are pressure driven, and they can logically be divided into four sub-processes according to a number of parameters of which the rejection characteristics and the net driving pressure (NDP) are the most important. The four processes are:

1. Reverse Osmosis (RO)
2. Nanofiltration (NF)
3. Ultrafiltration (UF)
4. Microfiltration (MF)

There are some similarities and dissimilarities between the operational conditions applying to RO and NF, to UF and to MF, which will be discussed toward the end of this chapter. Some specific information is provided in Table 1-1.

Several other membrane processes are being practiced, such as pervaporation, electrodialysis, direct osmosis and forward osmosis. Pervaporation is driven by temperature difference and electrodialysis is driven by voltage difference. Their industrial importance is, however, small and they will not be discussed.

Reverse Osmosis

RO is a liquid/liquid separation employing the tightest possible membrane, which ideally allows only water to pass and rejects all solutes and suspended materials. The rejection for sodium chloride is approaching 100% with practically achievable values of 99%.

The operating pressure in seawater desalination, which is the most demanding RO application, is up to 70 bar. Other special applications may require pressures up to 150 bar.

Open RO membranes with reduced rejection, >90% for sodium chloride, have been developed for less critical applications with the purpose of reducing the operating pressure, thus saving energy.

Nanofiltration

In the context of this book nanofiltration is intended to describe a membrane filtration process, which exhibits specific rejection for ions with two or more negative charges (anions), such as sulfate and phosphate. NF will also reject uncharged, dissolved materials. Small positively charged ions (cations) will 'follow' the anions to maintain electrical balance, while large positively charged ions may be rejected according to the size and shape of the molecule in question.

NF normally requires approximately 10 bar operating pressure, but for special applications it may be as high as 35 bar.

An interesting and important characteristic of the NF membrane is that the rejection of sodium chloride can vary from 0 to 50 % depending on the concentration and composition of solutes in the feed.

As a peculiarity it should be mentioned that NF under very special conditions can separate monosaccharides from di- and poly-saccharides.

Ceramic NF membranes possibly represent another class of NF, where the molecular weight and chemical structure of the molecules plays a role rather than electric charge.

Ultrafiltration

A UF membrane rejects high molecular weight components like proteins, while low molecular components freely pass through the membrane. The rejection of monosaccharides, disaccharides, salts, amino acids, organic solvents, inorganic acids or sodium hydroxide is normally less than 2 percent. All suspended matter is rejected.

UF operates in the pressure range of 1 to 10 bar.

Microfiltration

MF will ideally reject only suspended solids, while even large molecular weight protein will pass through the membrane. However, there may be a discrepancy between theory and actual operating conditions.

MF operates in the 0,2 to 5 bar pressure range, often below 1 bar.

RO and NF Operation

Water purification is by far the largest membrane application. RO and NF membranes were mainly developed with the purpose of meeting the demands of water purification, where the dissolved solids are rejected, building up in the feed side of the system and increasing the osmotic pressure of the feed solution. RO in essence rejects all dissolved solids, while NF allows ions with one charge like sodium chloride to pass. This results in some upper limitations with respect to the various concentrations of solutes in the final concentrate, which especially comes into play in industrial applications, but which also sets the limit for seawater desalination. Some examples are provided in the following:

- Maximum 6% NaCl (mono-valent – mono-valent)
- Maximum 10% $NiCl_2$ (mono-valent – di-valent)
- Maximum 15% $NiSO_4$ (di-valent – di-valent)
- Maximum 40% sucrose
- Maximum 25% glucose

Viscosity of the feed and concentrate may be a limitation. However, it is rarely an issue since RO and NF are generally used to separate low molecular weight solutes from water.

UF Operation

The operation of UF is sometimes limited by viscosity. A theoretically improbable phenomenon, which resembles osmotic pressure but is still unexplained, forms another limitation in real life. The latter can be observed when a UF system is shut down with a high concentration of a high molecular weight protein in the system. The observation is that permeate is flowing back into the concentrate. The limitations of UF can be summarized as follows:

1. In general, a viscosity in the concentrate of more than 100 mPaS (= cP) should not be exceeded, but the limit is dependent on the equipment.
    a. 25% true protein (milk, soy, egg white, blood, enzymes etc)
    b. A few percent polysaccharide
    c. 2% xantan
    d. 5% carrageenan
2. Ten times difference in molecular weight is required to achieve good separation.

MF Operation

The operation of MF is primarily limited by viscosity and volume-percent of suspended solids according to the following:

The rules for viscosity are the same as provided for UF above.

Volume percent suspended solids can at best approach 90%. Please notice, there may be a huge difference between volume-percent suspended solids and percent TDS.

General about Operation

The feed to membrane filtration equipment should, in general, be free of suspended solids, although some membrane configurations can tolerate certain levels. Fiber configurations present a special challenge, mainly due to the design and characteristics of the various types of equipment. This subject will be discussed in a later chapter.

Varying degrees of pretreatment of the feed is necessary in most cases.

Table 1-1. Comparing liquid/liquid membrane processes

	Reverse Osmosis	Nanofiltration	Ultrafiltration	Micro filtration
Membrane	Asymmetric	Asymmetric	Asymmetric	Symmetric Asymmetric
Thickness: Membrane Thin-film	150 µm 1 µm	150 µm 1 µm	150 - 250 µm 1 µm	10-150 µm
Pore size	<0,002 µm	<0,002 µm	0,002 - 0,2 µm	>0,2 µm
Rejection of	HMWC, LMWC Sodium chloride Glucose Amino acids	HMWC All saccharides Di- and polyvalent anions	Macro molecules Proteins Polysaccharides Virus	Particles Suspended solids Bacteria
Membrane material(s)	CA Thin-film	CA Thin-film Sulfonated PSO	Ceramic PSO, PVDF, CA, PAN, Thin-film	Ceramic PP, PSO, PVDF
Membrane Module	Tubular, Spiral wound, Plate-and-frame	Tubular, Spiral wound Plate-and-frame	Tubular, Hollow fiber, Spiral wound, Plate-and-frame	Tubular, Hollow fiber Spiral wound Plate-and-frame
Operating pressure	10 - 150 bar	5 – 35 bar	1 - 10 bar	0,2 - 5 bar

Operational limits in membrane filtration

Evaluating a membrane filtration process three separate subjects must be considered:

- The membrane material
- The membrane configuration
- The membrane filtration equipment

This chapter deals with some general operating conditions, mostly of a physical and chemical nature, pertaining to the membrane configurations and equipment, whereas the membrane material will be discussed in more detail in the next chapter.

Temperature

Membrane filtration was mostly developed with the purpose of supplying clean and safe water for domestic and industrial use. The original membrane material for RO was cellulose acetate (CA), which has an inherent temperature limitation at 35°C. Contemporary membrane materials, and among them the most commonly used polyamide (PA) for RO and NF, tolerate higher temperature, but the basic construction of the most commonly used membrane configuration, the spiral wound element, poses another upper temperature limit at 45°C, which is sufficient for most water purification processes.

The application of membrane filtration has expanded vastly from the original scope into industrial processes taking place at higher temperatures or with a requirement for thermal disinfection, which places higher demands on materials other than the membrane. Newer and more advanced materials and combinations of materials generally allow operation up to 80°C.

Only a few polymeric membrane materials allow operation over 100°C, whereas ceramic membranes for UF and MF do not have temperature limitations.

Table 1-2. Temperature limits	
Process and membrane	**Maximum temperature**
Water purification (RO, UF): Cellulose acetate Other polymers	 35°C 45°C
Industrial applications (general): RO, NF, UF, MF	 50°C
Industrial applications (special, polymer): RO, NF, UF, MF	 80°C
Industrial applications (ceramic): UF, MF	 >140°C

The combination of materials involved in a membrane filtration system poses another problem, since they have different thermal expansion. Especially when working with polymeric membranes, heating or cooling a system must take place at a moderate pace, for instance 1°C per minute. The limits for the most common applications are listed in table 1-2.

Pressure

All polymer membranes are to some degree sensitive to pressure causing an irreversible compaction of the actual membrane material. In addition to this phenomenon, pressure may compact the materials used to support the actual membrane resulting in a restriction for the flow of permeate. CA membranes has an inherent temperature limit of 35°C and the following applies to other polymer membranes than CA.

The manufacturers provide specifications, which are generally on the conservative side and ensure a membrane life commensurate with the membrane warranty. This type of specification is mostly based on experience and should only be exceeded if shorter membrane life than stated in the warranty is acceptable. Table 1-3 provides some guidelines. The number in parenthesis is valid only for an extremely special construction of a spiral wound element.

Table 1-3. Typical pressure limits (bar)

Configuration	**Standard**	**Special**
Tubular, supported	42	70
Tubular, unsupported	7	-
Spiral wound	42	70 (120)
Plate and frame	40	200
Hollow fiber (inside-out)	5	-

Membrane compaction is a function of the combination of temperature and pressure. As shown in the previous chapter, RO and NF operate at high pressure, whereas UF and MF are performed at low pressure. Membrane compaction is consequently most important in RO and relevant, to some extent, in NF.

A useful tool to evaluate membrane compaction and the resulting negative effects on operation is the Wagner Diagram named after one of the authors. It is presented and discussed in appendix E.

As general guidelines, the combinations of 80 bar pressure at 25°C and 25 bar at 80°C are the points where membrane compaction starts, but the relationship between pressure and temperature is not a linear function and there are no firm rules. However, temperature has a greater effect than pressure.

pH

The pH-scale ranges from 0 to 14 with 0 representing extreme acidity and 14 extreme alkalinity. The midpoint, pH 7, is the neutral point, which is representative for pure water. High or low pH increases the speed and severity of chemical attacks, and various materials have different resistance to chemical attacks. The most commonly used material for RO and NF membranes, polyamide (PA), will be hydrolyzed at high and low pH. High temperature will further aggravate the severity of the damage caused by hydrolysis.

Table 1-4 provides information about the pH tolerance of membrane materials.

Table 1-4. pH range for materials used as membranes.

pH	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiC membranes	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
Al_2O_3 membranes		Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	
Stainless steel membranes		Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
Polysulfone, fibers		Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	
Polysulfone, cast on PP	Green	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
Polysulfone, cast on PE			Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue			
Sulfonated polysulfone on PP	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue
Sulfonated polysulfone on PE			Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue			
PVDF	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue				
Polyamide TFM on PE			Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue				
Polyamide TFM on PP	Green	Green	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Green	Green	Green
PAN membranes				Blue	Blue	Blue	Blue	Blue	Blue	Blue					
CA membranes						Blue	Blue	Blue							

Glossary to table 1-4:

SiC	Silicon carbide (ceramic)
Al_2O_3	Aluminum oxide (ceramic)
PP	Polypropylene
PE	Polyester
PVDF	Polyvinylidene difluoride
PAN	Polyacrylonitrile
CA	Cellulose acetate

Blue color indicates the status as of 2012. Green color indicates potentials which has been demonstrated only in the laboratory.

Low pH can have a dramatic effect on a thin-film polyamide membrane at elevated temperature. The data in the figure 1-1 are from an actual study and illustrate that the element lifetime of a particular brand of spiral wound membrane decreased by a factor of 10 for each 15°C temperature increase. Please note that the numbers on the y-axis are orders of magnitude.

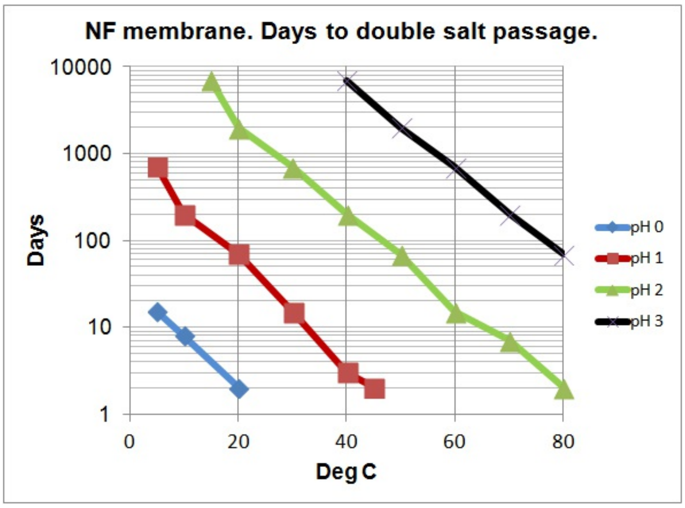


Figure 1-1. Effect of pH and temperature on a NF membrane

Oxidation

There is an astonishing array of chemicals with an oxidizing effect. They are able to break down most organic compounds, which is the reason they are useful in many processes. Unfortunately polyamide thin-film membranes are prone to chemical attack by oxidizing agents even in small concentrations. Consequently, this group of membranes used for RO, NF and UF should never be exposed to oxidizing agents. Most UF and MF membranes, as opposed to RO and NF membranes are very resistant to oxidizing agents.

Perhaps the best known oxidizing agent is sodium hypochlorite (NaOCl), which as a household chemical is known as bleach. Less well known is percarbonate and perborate, which can be found in some detergents and dish washing soaps. Hydrogen peroxide (H_2O_2) is used in small concentrations for cleaning of skin abrasions and hair bleaching. Other oxidizing agents are well known in the laboratory but not commonly used.

Some oxidizing agents used in the laboratory and in industrial processing are:

Halides: Fluorine (F), Chlorine (Cl), Bromine (Br), Iodine (I)

Halides in oxidation state -1 are harmless, e.g. chloride as found in table salt, NaCl. All other oxidation states, e.g. as NaOCl, will damage PA membranes.

Chlorinated organic compounds:

Chloramine belongs to this group. The term chloramine is generic and does not specify a single and well defined substance. Standard methods of detection of compounds which can damage PA-membranes do not always work well since the chloramines react very slowly.

Oxygen-containing chemicals:

Ozone, hydrogen peroxide, peracetic acid, persulfate, percarbonate, perborate, permanganate.

Peracetic acid is probably the least harmful of this group of chemicals. It can be used in very low concentration and still be efficient.

Nitrogen containing chemicals: Nitric acid

Formulated acidic cleaners are mostly a blend of nitric acid and phosphoric acid, which are standard cleaning agents in the dairy industry. However, it is barely acceptable to use this blend since the membrane life will be reduced. A few percent pure nitric acid will destroy membranes in days rather than months.

Heavy metals: Chromium, Iron, Manganese, Nickel

Some heavy metals and compounds of heavy metals can act as a catalyst for oxidation, e.g. iron hydroxide $Fe(OH)_2$, which is commonly present in most membrane systems. The metal will cause formation of halide radicals and they will attack the membrane locally.

Table 1-5 lists the limitation of several membrane materials.

Table 1-5. Tolerance of membranes to oxidizing agents		
Membrane material	**CIP**	**Continuous**
SiC	No restrictions	No restrictions
Al_2O_3	No restrictions	No restrictions
PVDF	1000 ppm NaOCl	Good tolerance
PSO	200 ppm NaOCl	<200,000 ppm hours
CA	20 ppm NaOCl	<0,5 ppm NaOCl
PAN	Avoid NaOCl	Avoid any oxidizer
PA thin-film composite	Avoid chlorine compounds	Avoid chlorine compounds
Sulfonated PSO	50 to 1000 ppm NaOCl	Unspecified, but high
RC	200 ppm NaOCl	<0,5 ppm NaOCl

Glossary to table 1-5:

CIP Cleaning in place
PSO Polysulfone (there are several slightly different types on the market)
RC Regenerated cellulose

Oxidizing agents can be used only under extremely controlled conditions as recommended by reputable suppliers of cleaning chemicals in connection with PA thin-film composite membranes. The more fouled the membranes are, the smaller is the chance that the membranes are damaged, since the dirt acts as a barrier and protects the thin-film layer.

Most membrane specifications show the tolerance of the membrane to sodium hypochlorite expressed in so-called ppm-hours, meaning the number of ppm of sodium hypochlorite multiplied by the number of hours of exposure, which will double the passage of salt from the concentrate to the permeate. The ppm-hour limit is not absolute, since exposure of the membrane to 100 ppm of sodium hypochlorite for one hour is more detrimental than exposure of 1 ppm for 100 hours.

Some oxidizing agents, for instance peracetic acid, are less aggressive than sodium hypochlorite, but it is difficult to quantify the actual difference.

Damage to a thin-film membrane can be observed by exposing it to a suitable dye at low pressure. The dye will penetrate where the membrane is damaged and can be observed as a stain on the backside of the membrane. A virgin membrane will not allow any dye to pass.

Colored spots indicate local attack from oxidizers.

Penetration of dye in larger areas indicates damage by high or low pH, or by oxidizing agents. It can be extremely difficult to determine the reason for chemical membrane damage.

Hydraulic Conditions

A membrane filtration system functions based on the flow to, from and through the system. The flows are mainly determined by the membrane configuration and the design of the system.

The upper limit for the feed flow depends on the mechanical strength of the membrane configuration, usually not by the membrane and the membrane material. High flow rates produce a high pressure drop in the system and consequently over the membrane elements. One specification for membrane elements is the allowable pressure drop.

The concentrate flow compared to the feed flow designates the recovery of permeate in the stage in question of the system. While it is usually desired to recover as much permeate as possible, it is necessary to maintain a liquid velocity (crossflow) over the membrane surface sufficient to prevent deposits of material on the membrane (fouling). The actual system design must ensure a proper liquid velocity based on the permeate recovery rate. If the nature and composition of the feed flow tend to cause fouling, the crossflow should be relatively high.

The permeate flow depends on the flux rate of the membrane, most often indicated in liters per square meter per hour (LMH) or gallons per square foot per day (GFD). The flux rate of a membrane for water under a set of controlled circumstances is part of the membrane specification. The flux rate in production will virtually always be a fraction of the water flux.

The permeate recovery rate per element is of importance in water purification, but less important in lower flux industrial applications.

Suspended solids

Water purification applications with feed of surface water, well water or seawater are designed to function for extended periods of time without cleaning placing high demands on the quality of the feed with respect to suspended solids, which may cause fouling and necessitate cleaning. One common method to determine the quality of the feed water is to measure the silt density index (SDI) and keep it below a certain value.

The content of suspended solids in the feed is of a lesser or no importance in connection with industrial application where cleaning is performed according to need, often on a daily basis. In addition, the nature of the suspended solids determines the potential for fouling. For instance, the 10% content of aluminum and titanium oxide in electro-deposition paint causes no problem for membrane filtration.

Viscosity

Viscosity of the feed is not in itself a problem, but high viscosity leads to higher pressure drop for a given flow. As long as the pressure drop is acceptable and the flux is satisfactory and stable, viscosity does not pose an operational problem. Handling high viscosity feeds in a membrane system is more of an engineering challenge than a membrane problem.

Solvents

For polymer membranes the rule is simple. Ethyl and methyl alcohol are acceptable and do not damage the membrane. All other solvents may damage the membrane, even in ppm concentrations.

Ceramic membranes are tolerant of just about anything. However, the other parts of the system may be subject to attack.

Solvents are extremely difficult to treat in membrane filtration systems and each one has its own set of problems. There are a few systems made entirely in PVDF for treating/handling powerful solvents like methyl isobutyl ketone (MIBK).

Flux and pressure

A well operating membrane filtration system must have a reasonable and stable flux and the energy consumption should be as low as possible. In order to achieve these conflicting goals, the process must be optimized with respect to product flux, pressure and temperature. High permeate flux is not a goal in itself because it can lead to unstable operating conditions.

Flux as a function of pressure is shown in the figure 1-2 in a very general way but it reflects actual operation with good accuracy.

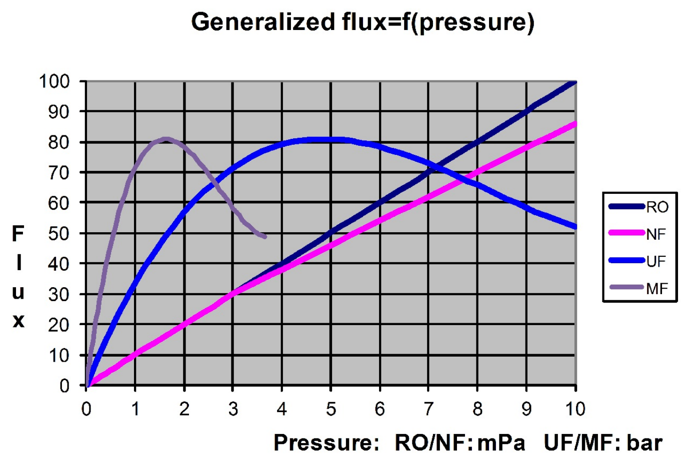


Figure 1-2. Flux and pressure

The conditions are simple for RO. There is a linear relationship between pressure and flux within the operational pressure range. When the net driving pressure (NDP) doubles, the flux doubles.

NF is similar to RO but the relation between flux and NDP is not entirely linear toward the high end of the NDP curve.

UF is more complicated. At low NDP the flux increases in a linear manner with increasing NDP, but at a point it peaks and actually starts to decrease with increasing NDP. This point is reached at an NDP of 3 to 5 bar for most products, but the exact point is highly product dependent, meaning that the capacity of a UF system depends more on the product than on the pressure and the membrane. It is important to perform solid pilot testing before committing to the design for a UF system.

MF behaves like UF, but in a more extreme manner. The linear increase in flux as a function of pressure is true only at very low NDP and only over a very narrow range. Polymer membranes peaks around 0,5 bar and ceramic membranes in the range 0,5 to 2,5 bar. It is virtually impossible to operate an MF system at ideal pressure and flow conditions, meaning that the resulting flux rate is much lower than theoretical possible, and in many cases it can be observed to be rapidly decreasing.

In conclusion, in RO and NF processes pressure can be used to control flux, whereas pressure does not solely determine the flux rate in UF and MF processes

Flux and temperature

If the temperature of a membrane process is not dictated by other conditions, it should take place at the highest possible temperature within the temperature limit for the membrane and other system components for the simple reason that the flux rate increases with temperature.

The water flux for most membranes increases by 3.3% per degree Centigrade temperature increase. Consequently, a temperature increase of 30°C doubles the water flux. This is not necessarily true for the product flux, because chemical and bacteriological phenomena tend to limit the flux rate in a number of ways. The full potential flux increase based on temperature can only be realized on pure water and on very few other products. In most other cases it is more realistic to calculate with 1% increase per °C.

Increased operating temperature can result in precipitation of calcium salts and denaturation of protein causing precipitation, and it may favor growth of microbes causing biofilm formation on the membrane.

In connection with many dairy and pharmaceutical products 'less is more' as it pertains to operating temperature, meaning that if one starts the operation at low temperature and low flux, the result may be a higher permeate flux at the end of the day than if one started the operation at high temperature and high flux.

Only when the product is viscous, for instance when working with gelling agents, is high operating temperature a true advantage. It will perhaps not provide a high flux, but it will reduce the tendency of the product to cause blocking of the system.

Calculation of the change of flux increasing or decreasing the temperature from a certain point is fairly simple:

Below 25°C: $\text{Coefficient} = (1 + TC/100)^{(\text{Temperature}-\text{Ttest})}$

Above 25°C: $\text{Coefficient} = 1 + (TC/100)*(\text{Temperature}-T_{test})$

where:

'Coefficient' is the factor with which to multiply flux at 25°C

'TC' is the temperature coefficient, % flux increase per °C

A summary is provided in table 1-6.

Table 1-6. Temperature coefficient for flux	
Water. TFM membranes	3,3% per °C
Water, PSO and CA membranes	2,7% per °C
Most products, all membranes	1% per °C

Membranes: Materials, structure, limits

Membrane materials

With more than a dozen major membrane manufacturers and an even larger number of suppliers of membrane filtration devices it is difficult to gain an overview of the real selection and to compare their specifications and characteristics, especially since vastly different nomenclatures and designations are used. In reality, however, only a few basic types and materials are used for the major portion of membranes being applied in practical applications.

Integral membranes

The designator 'integral' in connection with membranes indicates that the membrane is made from a single material cast as a fairly thick film (0,10 to 0,25 mm) with the two sides being treated chemically and/or physically differently to form a skin layer on one side, which is the actual membrane and a porous sub-structure promoting the passage of permeate. An integral membrane is often sturdy enough to be positioned directly on a support in the membrane filtration device. However, in most cases an integral membrane is cast on a support layer, which can, for instance, be polyester or polypropylene paper.

The membrane material in the earliest efforts to produce viable RO, NF and UF membranes for filtration purposes was **cellulose acetate (CA)**. While viable membranes were made, CA has several distinct limitations among which some are narrow pH-tolerance, low temperature tolerance and susceptibility to attack by microorganisms. Among the advantages of CA is that this material is tolerant of chlorine, that it is hydrophilic and that the price is comparatively low. CA membranes are, for instance, well suited for small household drinking water systems. Although more modern membrane materials largely have replaced CA for general purposes, CA is still the material of preference in some applications.

Since 1975 **polysulfone (PSO)** in various grades of this material has been used for UF and MF membranes. PSO dominates, for instance, in food and dairy applications, where sanitary operating conditions must be maintained, because of the high tolerance to pH, temperature and chlorine. PSO does not tolerate oil, grease and polar solvents in more than trace amounts.

Sulfonated polysulfone is a specialty polymer used for very stable NF membranes. Sulfonated polysulfone tolerates the full pH-range and a highly oxidizing environment. It is an expensive material and it is rarely used.

Polyvinylidene difluoride (PVDF) is a traditional membrane material used primarily for MF and open UF. It is difficult to make membranes with good and consistent separation characteristics. The main advantage of PVDF is high resistance to very low pH, hydrocarbons and oxidizing environments, as well as a high water flux.

Modified **polyacrylonitrile (PAN)** has excellent stability against hydrocarbons, and it is extraordinarily hydrophilic. The use is limited by the brittle nature of the membrane and high price.

Non-polymer membranes can also be designated as integral membranes. **Silicon carbide (SiC)** and **sintered stainless steel** are examples. They are used for MF and open UF only. It can be debated if a membrane substrate of aluminum oxide (Al_2O_3) and coated with a membrane of titanium oxide (TiO_2) should be categorized as an integral membrane or a composite membrane.

Composite membranes

The designator 'composite' in connection with membranes indicate that two or more membranes are made in a sandwich of which the top functional layer is a thin-film membrane. They are described in different terms and with different acronyms like thin-film composite (TFC) and thin-film membrane (TFM). Composite membranes for RO and NF generally exhibit a combination of relatively high flux and very high salt rejection, commonly higher than 99.5%. The restistance to pH and temperature is good, but the tolerance to oxidizing environments is low.

Composite membranes are made in two-layer and three-layer designs, using proprietary formulations and processes. Most often a composite membrane consists of a PSO membrane as support for the very thin skin layer which is polymerized in situ on the PSO UF/MF membrane. In a three layer design two thin-film membranes are situated on top of the PSO support membrane. Around 1980, FilmTec patented and marketed a two-layer design, called FT30. The FT30 membrane rapidly became the industry standard for water desalination, and this type of membrane has dominated the water desalination market ever since. After a legal dispute it was ruled that the patent belonged to the US Government, because the basic development was performed under a government sponsored contract. This ruling provided all companies with the right of manufacturing composite membranes. The concept has been improved and refined over the years, but the basic design remains unchanged. All leading manufacturers of RO membranes produce this type of membrane.

In the mid 1980s DESAL introduced a three layer composite membrane. These membranes had difficulties competing with the two-layer membranes in water desalination, but proved to work better in industrial processes where it is more stable and less prone to fouling. The three-layer design is available for RO and NF, and it is still a good choice for treating difficult process streams. DESAL is the only producer of three layer composite membranes.

Membrane volume

The total worldwide consumption of membranes based on membrane area, is approximately as follows:

Composite RO membranes:	85%
Composite NF membranes:	3 - 5%
Polysulfone UF and MF membranes:	5 - 7%
Other membranes:	3 - 5%

Materials like polyacrylonitrile (PAN), ceramic materials (Al_2O_3 and SiC) and cellulose (hydrolyzed cellulose) are included in the group of ‘other membranes’.

Selection of membrane material

It can be difficult to select the right membrane and membrane material for a given application. The first step is to determine the preferred process (RO, NF, UF or MF) and evaluate the membrane materials available. Based on the process environment the best suited membrane material can then be selected. Table 1-1 (Membrane Processes), Table 2-3 (Products and Processes) and Table 1-7 (Chemical resistance of several membrane materials) are helpful in the process of membrane selection.

Table 1-7. Chemical resistance of some membrane materials

	CA	PAN	Cellulose	Composite	PSO	PVDF	Al_2O_3	SiC
Temperature, 50°C	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Temperature, 80°C	No	No	No	Yes	Yes	Yes	Yes	Yes
Temperature, >80°C	No	No	No	No	Maybe	No	Yes	Yes
3 < pH < 8	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
pH<3 or pH>8	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
pH close to zero	No	No	No	No	No	Yes	Maybe	Yes
pH close to 14	No	No	No	No	Maybe	No	Maybe	Yes
Humic acid	Yes	Maybe	Yes	Maybe	No	No	No	Maybe
Proteins	Maybe	Maybe	Yes	Yes	Yes	Maybe	Yes	Maybe
Polysaccharides	No	Maybe	No	Maybe	Yes	No	Maybe	Maybe
Textile wastewater	No	Yes	No	Yes	Yes	Maybe	No	No
Aliphatic	No	Yes	Yes	No	No	Maybe	Yes	Yes
Aromatic	No	No	Maybe	No	No	Yes	Yes	Yes
Oxidizers	Maybe	Maybe	Maybe	No	Yes	Yes	Yes	Yes
Ketones, Esters	No	No	Maybe	No	No	Yes	Yes	Yes
Alcohol (ethyl,	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Except for established applications the choice of membrane material can be difficult, and more than one membrane material often comes into question. As a general rule, only well planned and well performed pilot testing provide good answers to membrane selection questions for a given process.

pH and temperature resistance

The pH resistance of the various materials has been discussed previously in this chapter. When decisions are made with respect to a membrane filtration process, it is not sufficient just to look at the membrane material. The same membrane is often available in several configurations (plate-and-frame, tubular, spiral wound, etc.) and a membrane system incorporates a number of components with different restrictions with respect to pH tolerance than the membrane. The pH limitations stated by most membrane manufacturers are in reality the limitations presented by the overall membrane configuration or membrane system rather than by the membrane material, meaning that the weakest material in the system determines the limitation.

The predominant membrane configuration is the spiral wound element, and although the following observations are valid for all membrane configurations, the spiral wound element has been chosen as the prime example.

Membranes are usually cast on a backing material which may form the limiting factor. The most widely used backing material is polyester (PE) which has excellent temperature stability, but limited tolerance to high pH environments. As a result, most membrane specifications state a maximum 11.5 pH limit. However, many membranes can be cast on polypropylene (PP) backing material with excellent pH stability but limited temperature tolerance. More lately polyether ether ketone (PEEK) offering excellent pH and temperature resistance has been introduced. The point is that when a suitable membrane material has been identified and a membrane configuration has been chosen, it must be ascertained that the combination is available in a configuration withstanding the intended working environment.

Since spiral wound elements contain many different polymers, there may be other limiting factors than those set by the backing material. The central tube, the antitelescoping device (ATD) and interconnector (IC) are commonly made of polyvinyl chloride (PVC) or acrylonitrile butadiene styrene (ABS), but neither of these materials have great temperature resistance. PSO is a more expensive material which provides both good pH and temperature resistance, thus it is commonly chosen for central tubes and ATD/ICs in industrial processing.

A specified pH-limitation may be flexible to some degree and can be exceeded for short periods and under the right conditions without detrimental effects. Low pH is usually not as problematic as high pH. Exceeding pH limitations at elevated temperatures is almost guaranteed to cause problems.

Composite membranes in oxidizing environments

The world of membrane filtration is still waiting for a good composite RO membrane tolerating e.g. 20 ppm sodium hypochlorite. Some readily available composite RO membranes have a degree of chlorine resistance, but they do not stand up to today's general performance demands, and claims of chlorine resistance should be taken with a grain of salt. In contradistinction, most composite membranes tolerate hydrogen peroxide reasonably well in limited concentration at low temperature and for short durations of time.

However, deposits of heavy metals like rust on the membrane surface or in the system will make the membrane vulnerable to chemical attack with iron attaining the role of a catalyst and causing oxidation damage of the membrane.

Sulfonated PSO is used for NF. It offers very high resistance to oxidizing agents and very good temperature stability. However, it is used only in select processes due to high price and insufficient separation characteristics.

Membrane structure

Almost all RO, NF and UF membranes are asymmetric. This differentiates most membranes from conventional filters, which are symmetric, or, in other words, has an identical structure on both sides of the filter material.

Many MF membranes, like ceramic, PP, stainless steel, Teflon and track etched membranes, are not truly asymmetric. This makes them vulnerable to pore plugging and cleaning may be difficult both mechanically and chemically.

Membranes have a tight top layer, the skin layer, facing the product to be treated. It is thin, typically <<0.1 micron. The total thickness of the membrane is approximately 150 - 250 micron with the bulk of the membrane providing structural support for the skin layer. The asymmetric structure means that the pores widen at a distance from the skin layer and thus prevents pores plugging. This counteracts the tendency of membrane fouling since fouling materials tend to be either totally rejected or to pass through a membrane.

The pore size of membranes can in broad terms be stated as follows in table 1-8:

Table 1-8. Nominal Pore size, micron	
MF	5 to 0,1
UF	0,1 to 0,01
NF, RO	0,001 (theoretical)

So far, actual pores have not been observed in RO and NF membranes using a microscope, but in spite of this, water passes through the membrane and salt is rejected. The lack of pores in NF and RO membranes means that even today membrane scientists do not really understand how or why these membranes function several decades after the introduction of the first membrane, or at least they do not know in any detail. Let it suffice to say that if the first RO membrane had been tested by someone without a practical sense looking at the membrane through a microscope, it might have been discarded since it did not have any pores substantiating that it could work.

In spite of the lack of exact knowledge, we are able to predict the performance of an RO membrane with a good degree of certainty. It is more difficult with respect to NF membranes. As a general rule, if more than three solutes are present in a solution, one can only make an educated guess as to the results of an NF process even when an accurate and complete feed analysis is available.

Membrane manufacturers

The number of manufacturers of RO membranes and elements is increasing with the RO companies, which started some 40 years ago getting bigger and very few newcomers managing to grow significantly. All of the original membrane manufacturers have been acquired by major chemical companies.

The UF market is much smaller and more fragmented with the number of suppliers rapidly increasing, but with some newcomers appearing to have little knowledge of element design and membrane applications. The same comment is valid for MF.

Ceramic membranes have been available for decades and have until now failed to earn a large market share. There are several reasons, the most important being price. The price for polymer membranes has dropped by a factor of 100 over 40 years while ceramic membranes have maintained their price level. Ceramic membranes need to demonstrate vastly superior performance to become successful, which is possible only in some very specialized applications.

The list of membrane suppliers of UF and MF is long and is growing rapidly. There are many new companies emerging in the Far East, primarily in China.

Membrane configurations

When a membrane has been deemed to be functional in a process it needs to be incorporated into a membrane configuration, which, in turn, will function in a membrane filtration system for a defined purpose in a desired application. The designators for various membrane configurations are arbitrarily called modules, cartridges, elements and several other names. The majority of membrane configurations are pressure driven, with only microfiltration configurations being driven by vacuum. Most membrane configurations are designed with cross flow over the membrane modules, but dead-ended configurations are used in some processes.

The spiral wound element is the workhorse of membrane configurations. The spiral wound element design was originally made for water desalination, but the very compact design and the low price made it attractive in other applications and industries. Special redesigned elements have emerged, mainly as a result of trial and error, for numerous industrial applications, for instance in the dairy industry, the pulp and paper industry and for high purity water in the electronic industry. Special materials are being used to provide the spiral wound element design with increased tolerance to temperature, pH and pressure. Although these designs are available, only a very few manufacturers offer them and are willing to stand behind the specifications.

The tubular membrane design was among the first to be applied for industrial applications. The configuration is simple employing tubes with diameters from 10 to 25 mm with the membrane usually cast or deposited on the inside of the tube. Institutions involved in membrane research and development seem to favor the tubular design, perhaps due to the fact that flow conditions in a tube are well known and well defined, and because it is relatively simple to theorize about mass transfer. One of the advantages of the tubular design is that it is highly tolerant to suspended solids like fibers, which interfere with the operation of most other membrane configurations. However, the tubular design has several disadvantages:

- Large foot print of the equipment
- Membranes exchange is difficult and time consuming
- The larger the diameter of the tubes, the higher the energy consumption
- High internal volume requiring large volumes of water for flushing and excessive amounts of chemicals for cleaning
- Once locked into the tubular design it is costly to change supplier and membrane configuration

However, the advantages of the tubular membrane design outweigh the disadvantages in several applications, and it definitely has a lasting place in the overall picture of membrane filtration, although the market is limited.

When a membrane is first developed, it is usually tested in some design of test cell as a flat sheet. It is tempting to move on to a flat sheet, full scale system, a concept pioneered by **DDS**. The **plate-and-frame** flat sheet configuration was successful in Europe from 1975 to 1990 and also made some inroads in the United States. A combination of lack of further development combined with an inflexible price schedule more or less made this configuration obsolete. **Alfa-Laval** acquired the design, which is still used for some special applications, where the rugged design outperforms other membrane configurations.

Several newer plate-and-frame systems have been developed, especially for high pressure RO applications. The best known is probably the **Rochem** RO system for treatment of landfill leachate and for on board seawater desalination.

A few plate-and-frame MF designs have been developed, either as pressure driven or submerged vacuum driven systems

There are a few other ingenious plate-and-frame systems. For instance, the **CR-Filter** design with a rapidly rotating knife-like rotator over the membrane surface, has a niche in applications with high levels of suspended solids, especially fibers. The design allows very high flux (>100 LMH) to be maintained for extended periods of time. The system is expensive, but the price is justified in some applications.

Several other plate-and-frame designs compete for market niches of dubious size, for instance the **New Logic** design with a vibration imposed on the membrane in a flat sheet membrane design.

Membrane configurations employing various designs of fibers have a long history in membrane filtration technology. The **hollow fine fiber** configuration with the membrane on the outside of a porous fiber dominated seawater desalination for two decades with the aryl type membrane, but was replaced when the polyamide membrane became available. The original design of hollow fine fibers was prone to fouling and required a high degree of pretreatment. A similar concept is presently being employed in wastewater treatment with the promise of reducing sewage plant investment considerably.

The hollow fine fiber design is a so-called 'outside-in' describing the direction of the flow of the permeate. 'Inside-out' designs are more commonly applied with an opening diameter typically less than 2 mm, which can be viewed either as fiber or a tubular configuration. The design allows the membrane to be unsupported as opposed to tubular designs. The **hollow wide fiber membrane configuration** was an early market contender but lost its prominence due to price and the inherent mechanically weak design. The configuration has been redesigned to operate with vacuum as opposed to pressure as the driving force in large applications in water and wastewater treatment.

Ceramic membrane configurations to some extent break with previous designs, since they can be made in tubes and in solid blocks with multiple flow channels, the so-called monolith design. From the standpoint of operation they can be driven by either pressure or vacuum with crossflow, dead ended or a combination of both.

The remainder of this chapter will summarize the major variables of the various membrane configurations ending with a comparison of their characteristics as they pertain to general application areas.

The spiral wound element

Numerous spiral wound elements are available using many different materials providing a variety of characteristics suited for a number of applications. The basic design of the spiral wound element aims at water purification with special materials and constructions enabling this element design to perform more demanding applications in terms of temperature, pressure, pH-resistance, etc.

The most important construction details for industrial size elements are listed in the following.

Dimensions:	
Outer diameter in inches	18, 16, 12, 8, 6,2, 5,8, 4, 2,5
Length in inches	60, 40, 38
ID of the central tubes	Varies, please consult specification sheets
Outer wrap:	
Fiberglas wrap (FRP)	Standard for high pressure water purification
Tape wrap	Standard for low pressure water purification
Vexar wrap	Used where sanitary conditions are required
Durasan™ (GE Water)	A prefabricated netting sleeve (for sanitary conditions)
TurboClean (TriSep)	A prefabricated rigid sleeve (for sanitary conditions)
Central tube:	
Material	ABS, polypropylene, polysulfone, fiberglass
Connection	Male or female
Brine seal:	
Design	U-cup, lip, O-ring, none
Material	ABN
Anti-telescoping device (ATD):	
Design	Star, holes, angled holes
Material	ABS, PVS and PSO
Interconnector (IC):	
Material	ABS, PVC, PSO and stainless steel
Product spacer (Vexar):	
Pattern	Diamond, parallel, corrugated
Thickness in mil	30 (standard), 50, 65, 80, 100, 120
Membrane backing:	Polyester (standard), polypropylene
Glue:	Polyurethane
Driving force:	Pressure (standard), vacuum

Tubular membranes

Dimensions:	
Internal diameter in inches	Typically 1,0 or 0,5
Length of the tube in inches	Typically 130 or 197
Tubes per module	Variable, but up 18 meter combined flow path
Membrane housing:	
Material	Stainless steel, PVC, no housing
End cap:	Bundles connected in parallel or series
Driving force:	Pressure

Plate-and-frame configuration

This membrane configuration include several different designs with the common denominator that they use flat sheet membranes, while the arrangement and the flow pattern of the supporting plates may differ widely. It is not possible to provide meaningful characteristics for plate-and-frame systems in general. Pressure is the most common driving pressure, but a few systems use vacuum. The more important manufacturers of this configuration are:

DDS, M35-M39:

A family of horizontal modules with oval shaped membranes, used for UF and MF, mostly in the dairy industry. Good for highly viscous products. The membranes are mounted on PSO support plates.

Millipore:

Square cassette systems, mostly for laboratory use or small scale pharmaceutical production.

Rochem:

DISK-TUBE, 8 inch diameter circular membrane for RO, NF and UF using a housing like a spiral wound element capable of pressures up to 200 bar.

CR Filter:

The CR-filter is an ingenious system, which can operate on feeds high in suspended solids, including fibers, and still provide high flux.

New Logic:

The system relies on physical vibration of the membrane stack to create the primary movement of liquid across the membrane. Shear force and volume product treated has been decoupled.

Kubota:

Vacuum driven system used in connection with membrane bioreactors (MBRs) with the cross flow achieved by air scouring.

Fiber configuration

Dimensions of the fiber:

Internal diameter	Typically 2 to 3 mm
External diameter	Typically ID plus 1 mm
Length	Typically 1 meter

Housing:

Material	Stainless steel, PVC, polysulfone (PSO)

Driving force: Commonly vacuum, pressure is an option

The fiber configuration is available in several designs with the membrane on the outside (outside-in) and in the inside (inside-out) of the fiber. Inside-out is mostly used for surface water treatment and outside-in for effluent treatment and in food processes.

Ceramic membrane configuration

Design:	Monolith round, diameter in mm	10, 25, 30, 50, 80, 146
	Monolith square, side length in mm	146
	Length (round and square) in mm	300 to 1000
Channel:	Round channels, diameter in mm	Commonly 2 to 3
	Square channels, side in mm	Commonly 2 or 5
	Number of channels	1 (single tube) to approximately 2000
Monolith material:	Commonly aluminum oxide (Al_2O_3) or silicon	

carbide (SiC) with several others used

Membrane material: Aluminum oxide (Al_2O_3), silicon carbide (SiC), zirconium oxide (ZrO_2), silicium (Si)

Driving force: Commonly vacuum, pressure is an option

Comparison of membrane configurations

When choosing the best suited membrane for an application several parameters, which are not easily quantified, must be evaluated. In the following the membrane configurations discussed in this chapter are ranked with respect to several parameters falling in this category.

The following abbreviations are used:

Ceramic	CER
Fiber inside-out	FIO
Fiber outside-in	FOI
Plate/and/frame	P&F
Spiral wound	SWE
Tubular	TUB

The ranking in the following is to some extent subjective and open to critique and correction. The parameters chosen for evaluation are important when designing a membrane filtration system, but the list is by no means complete. The ranking is from left to right with 'best' to the left and 'least good' to the right.

Capital cost for system:
Note that the cost of the membranes is usually only a fraction of the total system cost. The ranking is from lowest to highest system cost.

FOI → SWE → P&F → FIO → TUB → CER

Variable cost per cubic meter of permeate:
Several cost groups must be factored in for the total cost to treat a volume of a product, for instance energy, maintenance and membrane replacement. The ranking is from lowest to highest variable cost

FOI → SWE → FIO → P&F → TUB → CER

Membrane density:
Intended to illustrate the space requirements of a system, for instance in terms of membrane area installed per floor area or room volume. High density indicates a small building volume. The ranking is in order from high to low membrane density.

FOI → FIO → SWE → P&F → CER → TUB

Tendency to fouling:
Fouling in some shape or form occur in with all membrane configurations and in all membrane filtration systems originating from suspended solids in the feed, concentration of soluble components, microbial growth, etc. The ranking is from lowest to highest tendency to fouling.

CER → SWE → FIO → P&F → TUB → FOI

Cleanability:
All membrane systems must be cleaned intermittently, systems for water purification at intervals of months and sanitary systems in food and dairy applications on a daily basis. The ranking is in order of good to difficult cleanability.

TUB → FOI → SWE → P&F → FOI → CER

Tolerance to fibers:
Fibers of all materials can form mats and balls which can plug flow channels. The ranking is on order of excellent tolerance to very low tolerance.

TUB → FOI → CER → P&F → FIO → SWE

Flow requirement:
Systems operated with crossflow over the membrane surface require various volumes of feed flow largely depending on the internal volume of the system compared to the area of membrane. High flow requirement typically means high energy consumption. The ranking is in order of low to high flow requirement.

FIO → FOI → SWE → P&F → CER → TUB

Pre-filtration requirement:
The content of suspended solids in the feed is one avoidable factor in the picture of fouling. The need for pre-filtration is more or less pronounced for the various membrane configurations. The ranking is from low (open) to high (tight) pre-filtration requirement:

TUB → FOI → P&F → CER → FIO → SWE

Ease of membrane change
Change of membranes ranges from a simple and easy to complicated and time consuming. The cost is included in the variable costs. However, it is an issue to take into account. Ranking is from simple and easy to complicated and time consuming.

FIO → SWE → FOI → P&F → CER → TUB

Part 2

Membrane Filtration Systems

Design, Components and Control

Modes of operation

A number of operational parameters must be established before the mode of operation for an industrial membrane system can be chosen. Most of them are best determined through pilot testing, which will be discussed in a later chapter.

First the nature of the feed to be treated and the desired result of the treatment must be evaluated. The choice of process depends, of course, on the components in the feed, which the membrane should reject (RO, NF, UF or MF). In addition to the actual composition of the feed with respect to components to be purified or concentrated, the content of undesired components in the forms of fibers and other suspended solids is important, both with respect to choosing the membrane configuration and determining the nature and the degree of the necessary pretreatment.

The concentration ratio expressed as the volume of feed divided by the volume of concentrate is also important for the design of the system.

Several other conditions may influence the system design and mode of operation, for instance when sanitary conditions are required as it often is the case when treating food and dairy products.

If frequent cleaning-in-place (CIP) is required this feature must be incorporated into the system design.

The design and dimensioning of membrane filtration systems attain varying degrees of complexity, largely depending on the mode of operation. Projection programs are available from the membrane and element manufacturers for standard applications like water purification and seawater desalination. Design and dimensioning of systems for treatment of cheese whey in the dairy industry depends largely on several decades of experience resting with the original equipment manufacturers (OEMs). The programs used are not available to the public, although the knowledge is decades old and common knowledge within each of the organizations of the OEM's manufacturing sanitary systems. Each company considers the knowledge to be proprietary. When it comes to new applications with no prior experience available the design and dimensioning is mostly based on the pilot test results, educated guessing and incorporation of generous safety factors.

Continuous operation is the chosen mode for the vast majority of industrial membrane filtration systems with batch operation used only in special situations.

In the following, the term industrial or non-water systems denotes systems that treat other products than water, for instance milk, whey, antibiotics, pulping liquids and oily waste.

Batch operation

This is a discontinuous mode of operation used in the laboratory when treating very small volumes, in pilot testing and in the pharmaceutical industry when discrete identification of product lots is required.

The batch to be treated is typically contained in the feed tank and supplied to the membrane system by a feed pump. The permeate is collected in the permeate tank and the concentrate returned to the feed tank. Operation is continued until the content of the feed tank has reached the desired composition or until the desired volume of permeate has been removed.

The composition of the feed to the system changes and the flux rate decreases gradually during operation until the end point has been reached. Batch mode, figure 2-1, is the simplest mode of operation being relatively easy to describe mathematically.

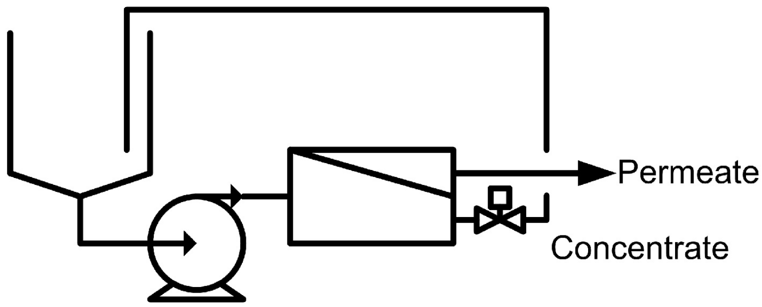


Figure 2-1. Batch Operation

A variant of the batch mode called fed batch or semi-batch, see figure 2-2, involves addition of start product to the feed tank at the same rate of removal of permeate, thus maintaining a constant level in the feed balance tank until the desired concentration or purification has been achieved.

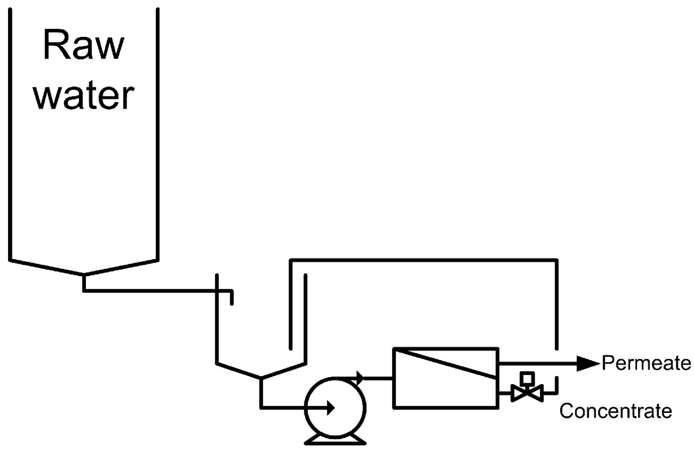


Figure 2-2. Semi-batch operation

Semi-batch is mathematically quite complicated. Where batch is considered to be a 100% efficient process, semi-batch resembles a single stage recirculation system and is quite inefficient. Nevertheless, semi-batch is often used when the volumetric concentration ratio is high, due to the ease with which semi-batch can handle a very small concentrate volume.

Batch and semi-batch mode can be used for all membrane filtration processes, RO, NF, UF and MF.

Single pass

All seawater desalination system, the majority of water purification systems and some industrial systems operate in single pass mode, which is a continuous form of operation where the feed flow, the permeate flow and the concentrate flow are constant over time, often for months and sometimes for years. A single pass system is normally fed by one feed pump being the only pump in the system.

As permeate is removed from the system the concentration of solutes in the concentrate increases. Single pass operation is consequently mostly employed in applications with a relatively low flux rate, such as RO and NF. As permeate is removed, the crossflow velocity decreases toward the exit end, where the need for crossflow is the greatest with the purpose of controlling fouling. As a general rule, the concentration factor is limited to 2:1 (50% permeate recovery) in a one stage single pass system.

Using the spiral wound element as an example, one stage consists of a number of parallel pressure housings each with 6 or 8 elements, see figure 2-3. The permeate recovery in a seawater desalination system is usually around 40% or slightly higher but less than 2:1.

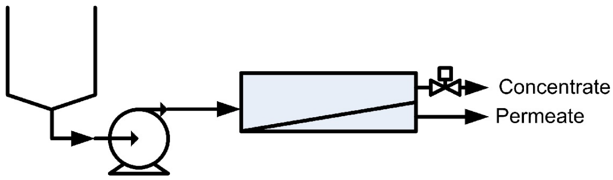


Figure 2-3. Single pass, 1 stage

In purification of brackish water, surface and wastewater, where a higher recovery rate is desired, the system is normally designed with an array of two stages with half the number of pressure vessels in the second stage compared to the first stage, see figure 2-4. This allows up to approximately 75% permeate recovery.

The conditions in a single pass system can be described mathematically with good certainty. The various membrane element manufacturers provide projection programs for standard applications.

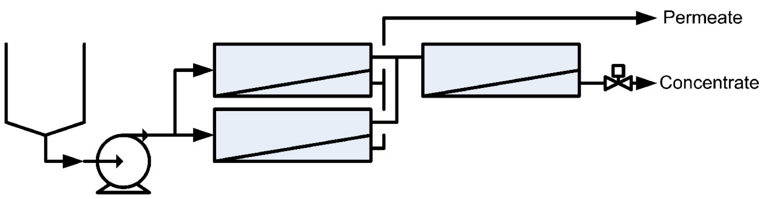


Figure 2-4. Single pass, 2 stage, 2:1 array

Single pass with concentrate recycling

A variant of the simple single pass system is single pass with concentrate recycling, see figure 2-5, leading a portion of the concentrate back to the feed with the purpose of increasing the crossflow velocity over the membranes. The downside of this mode of operation is the increase of the concentration of solutes in the feed, which results in a higher concentration of solutes in the permeate. Consequently this design is a compromise between hydraulic requirements and acceptable permeate composition.

Single pass with concentrate recycling can be viewed as a step in the direction of multistage continuous operation. A mathematical description of the conditions in the system becomes quite complicated, but iterations can be made using the power of modern computers.

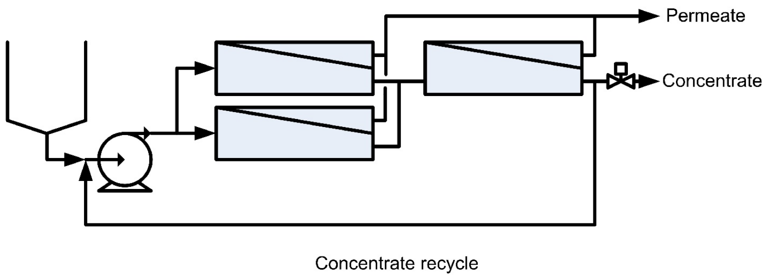


Figure 2-5. Single pass, 2 stage, 2:1 array, concentrate recycling

Multistage recirculation mode

Most industrial systems operate in a the multistage recirculation mode, see figure 2-6, which allows high concentration ratios because the crossflow velocity qua the design can be maintained throughout all recirculation loops regardless of the content of solutes in the concentrate. The design of the loops is normally identical throughout the plant, but may be designed to vary somewhat depending on the actual conditions.

The multistage recirculation mode is well suited for high flux applications, UF and MF, but MF is often operated in some variety of dead ended mode for reasons to be discussed in the following. Demanding industrial RO and NF applications also operate in this mode. Most industrial or non-water systems operate in the multistage recirculation mode.

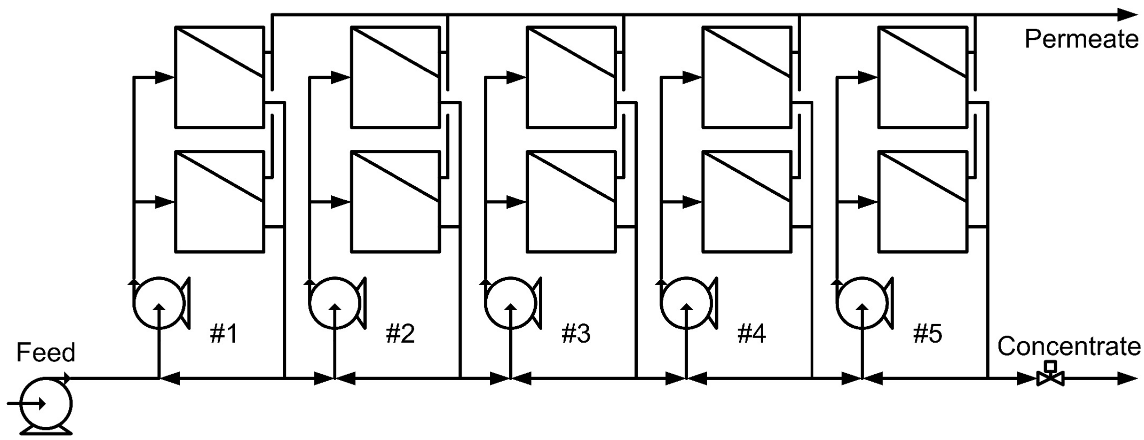


Figure 2-6. 5 stage recirculation system

The composition of the concentrate as well as of the permeate changes from loop to loop, but is constant in a loop over time due to the high rate of recirculation in each loop, with the composition of the concentrate changing incrementally from loop to loop.

The product in industrial applications is most often the concentrate in contrast to water applications. A variant of multistage recirculation using diafiltration, see figure 2-7, is employed when one or more solutes in the feed, which is not rejected by the membrane, are desired to be reduced. Water is injected into the common feed line for the loops at one or more suitable points diluting the concentrate by 'washing' out the solute in question. In this mode of operation the system can be said to be divided into preconcentration, diafiltration and final concentration stages, although all loops may still be identical.

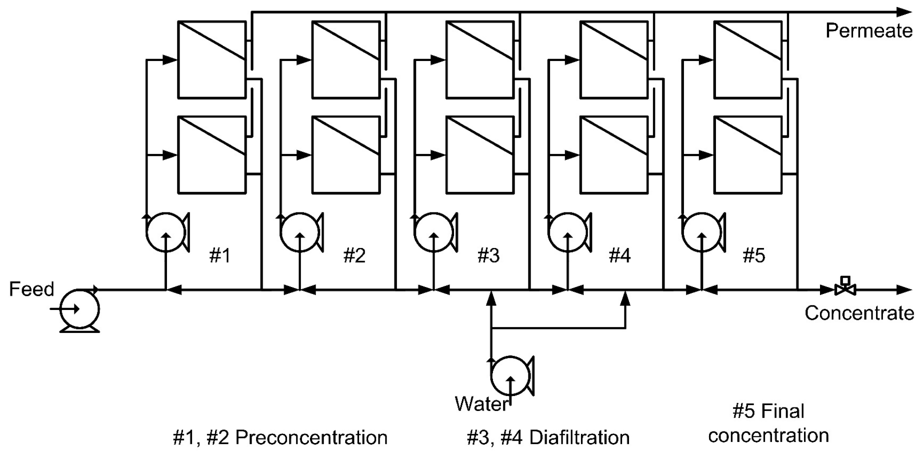


Figure 2-7. 5 stage recirculation system with diafiltration

As already mentioned, the multistage recirculation mode reduces the risk of fouling by maintaining a high and constant cross flow velocity. The design slightly compromises the permeate flux rate, but the advantages outweigh the disadvantages in most situations.

The multistage recirculation mode of operation is the most difficult to depict mathematically, but brute computer force can calculate the proper design of a system.

Dead ended mode

Microfiltration is virtually the only technology of the four basic forms for membrane filtration, which routinely operates in dead ended mode resembling conventional particle filtration, with the driving force normally being between 0.3 and 0.5 bar, see figure 2-8. The pressure or vacuum is normally supplied by pumps, but it is possible to gravity feed a dead ended system by placing it submerged at the bottom of a tank of suitable depth.

Since truly dead ended operating mode does not provide crossflow and since suspended solids tend to build up on the surface of the membrane, several measures to keep the membrane surface clean are employed.

- If the system is pressure driven and a concentrate valve is placed after the element, it is possible to employ intermittent crossflow by opening the valve at time intervals. The same effect can be achieved with a small pressure pump feeding the dead end of the element in vacuum driven systems.

- Backflushing is the process of driving water or a cleaning liquid through the membrane from the permeate side with the purpose of loosening and removing deposits of solids on the membrane surface by reversing the flow through the system.
- Air scouring by injecting air into the feed stream of through the membrane from the permeate side is rare but employed in at least one system design.
- A water jet directed at outside-in membranes in employed in at least one system.
- It is common to apply a short maintenance cleaning at fairly short time intervals, for instance every 15 minutes using one or a combination of the measures described in the points above.
- When the flux can no longer be restored the system must undergo a chemical cleaning as for other membrane filtration systems.

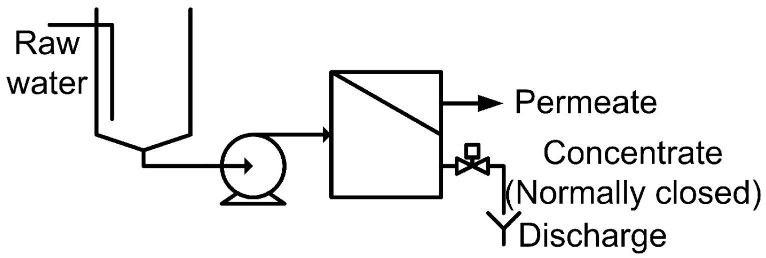


Figure 2-8. Single pass dead-ended operation

It is also possible to design a hybrid system with a combination of dead ended and crossflow operation, see figure 2-9.

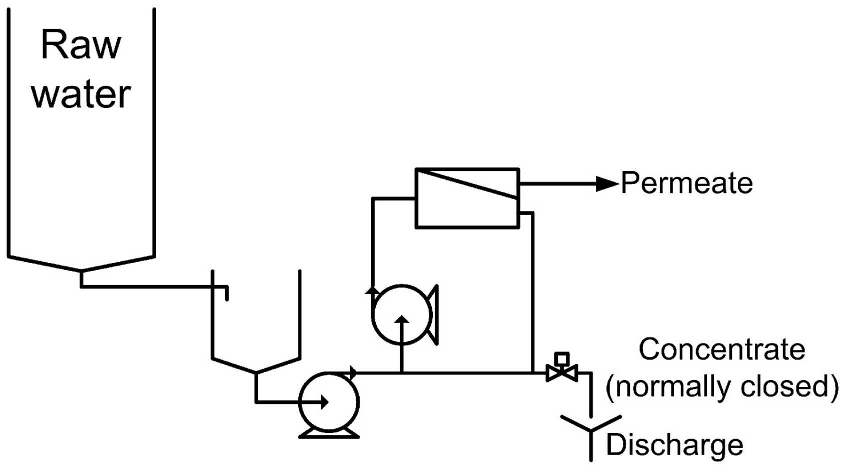


Figure 2-9. Dead ended single loop operation with recirculation

Membrane filtration systems

Membrane filtration technology is based on the capabilities and the functionality of an array of different membranes. However, the membrane can be viewed as a passive component, albeit the most important one in a membrane filtration system. The membrane needs a certain environment with the optimum combination of pressure, flow, temperature and other parameters in order to take advantage of its full potential in a given process.

A membrane filtration system is essentially composed of four groups of components, devices and software:

1. System components
   a. Piping
   b. Clamp and flanges
   c. Tanks
   d. Heat exchangers
   e. Valves
   f. Pumps
   g. Membrane housings
2. Measuring devices
   a. Pressure
   b. Flow
   c. Temperature
   d. TDS (refractive index)
   e. Mass flow
3. Control devices
   a. PLC
   b. PC
   c. Main frame
4. Control loops for
   a. Pressure
   b. Flow
   c. Temperature
   d. Dissolved Solids
   e. Viscosity
   f. Liquid level (in tanks)

The next few chapters are dedicated to describing the components, devices and software, which make the membranes perform to the peak of their capabilities.

System components

When designing a membrane filtration system the first consideration should be to decide on well suited and safe materials of construction, which will stand up to the operating conditions, not cause problems in prolonged operation and being available at a reasonable price. In this context it should also be remembered that the cleaning agents used in connection with membrane filtration systems generally are pretty harsh, and that all components and materials must be able to withstand cleaning of the system, as well as the operating conditions.

Using seawater desalination as an example, the pressure housings are generally made from fiberglass reinforced plastic (FRP) while the piping, manifolds and other components are in stainless steel. However, the term 'stainless steel' is misleading because the indicated non-corrosive nature of the material only is true under certain sets of conditions. Due to the low temperature of seawater from the North Sea ordinary qualities of stainless steel are sufficient for seawater desalination systems in this area. Seawater from the Red Sea occurs at temperatures up to 35°C and a suitable quality of more durable and expensive Duplex steel must be used.

A vast variety of products are treated in industrial membrane filtration applications, which means that a careful choice of materials of construction is mandatory in each individual case. Not least due to the harsh conditions of most cleaning regimens in industrial applications, stainless steel (AISI 316Ti, W1.4571) is often the material of choice. Also here careful consideration should be given to choosing the right quality of stainless steel. Furthermore, stainless steel is mandatory as the material of construction in, for instance, the food, dairy, pharmaceutical and petrochemical industries.

An effective cleaning regimen can help to actively prevent corrosion of stainless steel parts in a membrane system. This can be achieved by cleaning all surfaces thoroughly once a day. Even better is a wash with nitric acid to passivate the stainless steel surfaces. These practices have kept systems in operation for many years, which otherwise should have corroded quickly.

Reasonably priced stainless steel fittings up to 4 inch diameter are readily available, but prices for fittings above 4 inch diameter tend to soar because there is very little demand for these large diameters.

But sometimes not even the best quality stainless steel is sufficient. Some NF systems treating fairly concentrated sodium chloride at elevated temperature are made entirely from titanium.

Ordinary steel should never be used for components in direct contact with any liquid in a membrane filtration system. It is inevitable that rust eventually forms and enter the membranes with endless problems as a result. Low quality stainless steel and brass are commonly used in water purification systems causing longer term problems in the operation.

Only high quality polymers should be used in membrane filtration systems. This group includes polysulfone (PSO), polyvinylidene difluoride (PVDF), chlorinated polyvinyl chloride (C-PVC), polyoxymethylene copolymer (Delrin) and other mechanically strong materials with good chemical and thermal resistance. Polyethylene (PE) and polypropylene (PP) are used extensively in the low price water market being sufficient for this application.

Gaskets are an often forgotten item when reviewing materials. It seems that EPDM is a material which is very useful in almost all cases, where a cheap material like nitrile rubber would fail.

The following is short characterization of some materials commonly used in membrane filtration systems:

- **ABS**: Useful material in water purification systems.
- **PE**: Good chemical stability, but with very limited temperature stability.
- **PP**: Chemically a very resistant polymer, but with limited temperature stability, and it has a tendency to creep.
- **PSO**: PSO comes in several slightly different materials. Probably the best material for use in membrane applications. It is totally resistant to temperature and the pH values found in membrane systems. Its main weaknesses are a tendency to become brittle, and a high sensitivity to ketones and aromatic compounds.
- **PEEK**: A modern polymer which is better than PSO, but also very expensive.
- **PVC**: Mostly used for low pressure piping. It is inexpensive, but has severe temperature limitations. It can only be used for little demanding applications, such as water purification.
- **C-PVC**: Significantly better temperature stability than ordinary PVC.
- **PVDF**: An excellent but rather expensive material. It has good heat stability and is chemically almost as resistant as Teflon.
- **FRP**: A composite material widely used for housings. It has become the standard in water desalination in spite of its obvious shortcomings. Corrosion resistance is its prime advantage, closely followed by low price.

Pipes

A major portion of a membrane filtration system consists of piping. It is generally easy to obtain the right quality and type of pipes needed. Dairy type pipes turn out to be the best suited for many industrial applications, and often it is the least expensive solution, simply because large quantities are produced. In addition, the quality and the nature of the interior surface of dairy piping are excellent.

Avoid welding as far as possible since welds are potential corrosion hazards. Use pull-outs to make T-connections and branches in the piping system. Pull-outs are used extensively in the dairy industry and are easiest made in connection with thin walled pipes.

Clamps and fittings

The only connection systems proved to be consistently good and reliable in all applications is the TriClover type clamp (TriClamp). It is somewhat expensive, but it offers many advantages with respect to clamp connections up to 6 inches in diameter. For clamps larger than 6 inch diameter, other brands of high quality flanges are used due to pressure limitations for the TriClover type. TriClamps are not universally accepted, but they are so widely used that the name TriClamp often designates this type of clamp in general rather than the original product from TriClover.

The Victaulic coupling has proved to be a very good option as a non-sanitary context. It is available in many sizes and it tolerates high pressure.

If feasible, thread connectors should not be used. They are non-sanitary and difficult to dismantle and assemble correctly, but they are rather inexpensive.

Flange connections are demanded in some industries. Flanges come in many different types, and a type of sanitary flange is available. They are big, bulky, heavy and quite labor intensive to assemble and to dismantle and are for these reasons best avoided.

Tanks

The tanks used in membrane filtration systems should be made with either a conical or slanted bottom to allow total drainage. Otherwise it is inevitable that particles, crystals or other sediments collect in the bottom of the tanks, and this will sooner or later lead to chemical, mechanical or bacteriological problems, or a combination of the three. The tanks should have loose covers allowing access for flushing and manual cleaning.

It is also important that the tanks, whenever possible, are kept free from built-in devices such as heating coils and level switches. As far as possible, all measuring devices should be placed outside the tanks. Level control is best performed with a pressure transmitter, and temperature measuring devices should be placed in the piping rather than in the feed tank.

The best suited material for the tanks is stainless steel. Most other materials have inherent temperature limitations. Tanks with 100 to 300 liter volume are adequate for industrial membrane filtration systems. 50 liters is a fair size for pilot plants

It is common to have a permeate tank placed next to the feed balance tank in larger UF systems, and it is customary to build the two tanks as one unit with an overflow between them. This allows permeate and concentrate to be separated during production, but still permits permeate to flow freely to the feed balance tank during system flushing and cleaning when an unusually large permeate flow occurs, see figure 2-10.

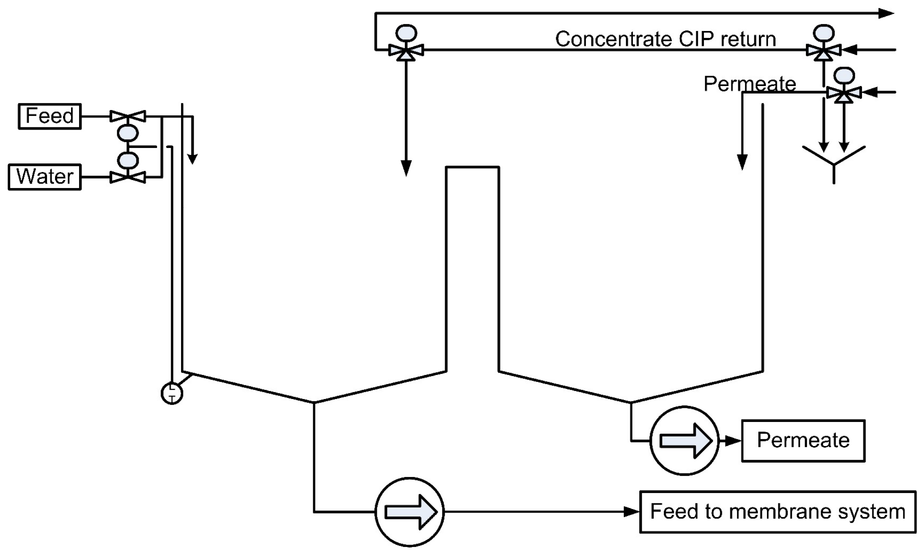


Figure 2-10. Combination feed and permeate tank

Level control of the liquid in the tanks can be done inexpensively using a pressure transmitter and two pneumatic valves. The level transmitter transforms the level in the tank into a signal of 3 to 15 psi. The two pneumatic valves controlling feed and water level should be split range, meaning that one operates in the range of 3 to 9 psi (water valve) and the other in the range of 9 to 15 psi (product valve), see figure 2-10.

Both valves are fully open when the tank is empty. The water valve will close fully when the level rises. At a higher liquid level the product valve starts to close and it is now ready to regulate the amount of product flowing into the tank. This is an elegant solution, since the water supply acts as a security, should the feed flow stop. It also allows easy rinsing and cleaning. Rinsing is initiated simply by stopping the feed flow.

It is recommended that a manually adjustable pressure transmitter be used for regulation of the inlet valves. It is a simple solution and it works well in real life situations.

Heat exchangers

The use of multi-tube (tube and shell) heat exchangers is very common for heating and cooling purposes in membrane filtration systems. The heating or cooling medium is on the outside of the tubes, and the product flows on the inside. This construction allows for high pressure, easily up to 70 bar.

The function of a multi-tube heat exchanger is different from that of a conventional plate heat exchanger:

- The product temperature change in one pass is small, typically 0.5°C or less.
- The product flow is very high, compared to the flow of heat exchange medium.
- The pressure drop on the product side is very low, typically 0,1 to 0,2 bar.

Valves

Different industries have different requirements to the valves used in a membrane filtration system. The pharmaceutical, food and dairy industries require sanitary valves, butterfly valves and needle valves (butterfly valves cannot be used in the USA). Most other industries have requirements only to the functionality of the valves. Ball valves and needle valves are generally used in water applications.

Some mechanical engineers claim that ball valves and butterfly valves cannot be used for flow or pressure control. In theory this may be right, but experience contradicts this standpoint in the membrane world, although these types of valves may be difficult to use for control purposes. A positive aspect of ball valves and butterfly valves is the capability to allow a huge difference in flow and pressure drop, which is often needed to achieve the correct conditions for production and cleaning respectively.

It can be a major challenge to control a multistage recirculation system with a high volumetric concentration ratio, which means that the control is based on a very small volume of concentrate. The type of concentrate valve needed here is a needle valve. If the concentrate does not contain suspended solids a needle valve will work just fine, but even small amounts of suspended solids can effectively block the concentrate outlet through a needle valve and cause major control problems.

An unconventional solution to this problem is the so-called 'always-plugged-concentrate-valve' concept. Two timers and an automatic valve are installed with the valve normally fully closed. Timer one determines the length of the period between valve openings. Timer two determines how long the valve is open. When timer one is activated, the concentrate valve opens fully and a fast flow of concentrate occurs. When timer two is activated the concentrate valve closes fully. In this way an astonishingly accurate control of the concentrate discharge can be achieved.

The control valve for the concentrate is often too small for the very large flow of water during CIP.

Therefore, it may be necessary to install a CIP valve in parallel to the concentrate valve as shown in figure 2-11. The CIP valve is often a 3 or 4 inch diameter butterfly valve. If the length of pipe from the T to the valve is shorter than or equal to three times the inner diameter of the pipe, the design is considered to be sanitary. In RO systems, it is possible to use a large dairy low pressure piston valve, although that is against all rules. The trick is to route the high pressure to the side of the piston pressing against the seal at the outlet; in other words direct flow opposite to the standard direction of flow. During production, pressure keeps the valve closed; the valve cannot be opened. During CIP and flush, the line pressure is so low that the valve can be opened.

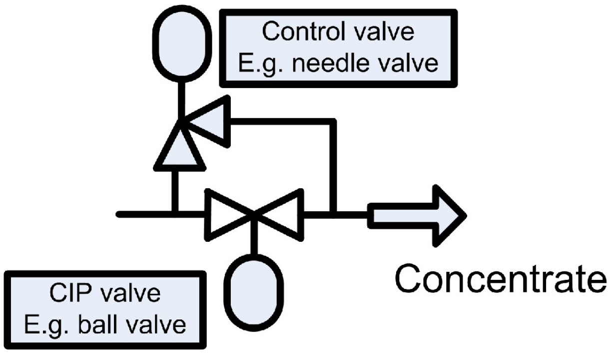


Figure 2-11. Concentrate valve arrangement

A pump can act as an unusual valve. A positive displacement pump controlled by a frequency converter can be used as a back pressure valve in systems treating highly viscous products and liquids with high suspended solids. This setup can also be used on shear sensitive products like egg white.

There are many opinions about electrically versus pneumatically operated valves, but the general experience is better with pneumatically operated valves for the following reasons:

- They do not stop functioning when wet
- They do not burn out if they get stuck
- They are simple to repair
- Most types are explosion proof

Still, the choice is a matter of taste and a matter of which type is already in use in a manufacturing facility.

Pumps

The subject of different types of pumps and the guidelines for selecting and dimensioning the pumps for a membrane filtration is a complex one, which deserves a special and more exhaustive discussion than the other system components. It has consequently been decided to devote an independent chapter of this book to pumps.

Pumps

Second only to the membrane, the pumps are the most important components in a membrane filtration system. The membrane is a passive component, and without pressure and flow there would be no membrane filtration process. Viewing the broad spectrum of membrane filtration the demands to the pumps are many and varied:

- The applied pressures range from -0,5 bar in vacuum driven MF to 80 bar in seawater desalination.
- The flow rates range from a few liters per hour to several hundreds of cubic meter per hour in large water purification systems.
- The temperature range is from just above freezing to 90°C or even higher for some industrial applications.
- The pH value in the treated liquids spans almost the entire pH scale, at least from 1 to 13.
- The total dissolved solids load is from almost nothing to 60% in some dairy applications.
- The viscosity goes from 1 cP in pure water almost to the consistency of mud in special applications.

Although membrane filtration has taken off as an independent unit process, the number of membrane filtration plants is relatively small seen with the eyes of the pump manufacturers, and very few pumps have been developed or redesigned especially for membrane filtration applications.

The operating conditions of a membrane system are often considered unusual from the point of view of a pump manufacturer because flows and pressures can vary considerably from production to cleaning and they are rarely exactly at the design point of the pumps.

The following types are used in membrane filtration systems:

- Single-stage centrifugal pump
- Multi-stage centrifugal pump
- Piston pump (not commonly used)
- Diaphragm pump (rarely used)
- Mohno-type pump (rarely used)

Single stage centrifugal pumps are characterized by their ability to deliver large volumes within a narrow pressure range. Depicting this in a graph with pressure on the vertical axis and volume on the horizontal axis produces a rather flat curve close to the horizontal plane. It is said that centrifugal pumps have a 'flat' characteristic or pump curve.

Single-stage centrifugal pumps (50 Hz 3000 rpm/60 Hz 3600 rpm) with closed impellers are most commonly used in membrane filtration systems operating at moderate pressures. Centrifugal pumps designed for the dairy industry are particularly useful because they have very flat characteristics, which is a special advantage when they are used as booster/recirculation pumps in multi-stage recirculation systems.

Multi-stage non-sanitary centrifugal pumps are used almost exclusively in membrane filtration plants for high pressure applications with seawater desalination systems being the prime example. A multi-stage centrifugal pump is essentially a series of centrifugal stages on a common drive shaft. The pressure is increased incrementally from stage to stage with the number of stages determining the achievable final pressure the pump can deliver.

The piston pump, the diaphragm pump and the Mohno-type pump are positive displacement pumps characterized by the ability to provide almost infinite pressure at constant volume, limited only by the materials employed.

Positive displacement pumps should be avoided in membrane filtration system, if not mandated by special circumstances, the main reasons being that they cause unacceptable vibrations in the piping system and that a safety valve is necessary to prevent damage to the piping system in case of production upsets. However, centrifugal pumps for low flow and high pressure have been hard to come by, so positive displacement pumps are needed for small RO systems.

The alternative to positive displacement pumps is finding ways to use centrifugal pumps, which is fairly easy in larger systems. Frequency converters allow centrifugal pumps to operate above the design parameters at 50 Hz 3000 rpm/60 Hz 3600 rpm. Frequency converters have come down in price over the last few years and are commonly used in connection with membrane filtration equipment. If the power supply from the net is at 50 Hz with a specified 3,000 rpm for the pump, and if the frequency of the power supply to the pump in increased to 80 Hz, the rpm will be 4800, a phenomenon known as 'overcloking'. Designating the net frequency N1 and the converted frequency N2, the flow, the pressure and the power consumption will increase according to the following rules:

- The outflow from the pump increases linearly according to N2/N1
- The Pressure increases to the power of two according to $(N2/N1)^2$
- The energy consumption increases to the power of three according to $(N2/N1)^3$

The design of the pump motor determines how much overclocking can be done.

The pumps used for recirculation in multistage recirculation plant deserve special attention. The unusual condition, especially in connection with RO, is that although the pressure increase generated by the pumps is small, e.g. 5 bar, the pressure in the feed line may be as high as 40 bar, meaning that the recirculation pump casing must be able to withstand the higher pressure and the mechanical seal must be of special design. The pump bearings taking up the axial load must also be very strong. Such pumps are becoming more commonly available, although they tend to be rather expensive.

The primary objective of a pump is to move liquid. Pressure is created when a restriction in the discharge line is introduced, for instance a valve. The various types of pumps have different abilities in overcoming restrictions and they react differently. Table 2-1 attempts to illustrate this.

The challenges to pumps used in membrane filtration systems will be further discussed in the following. Suppliers of the various pump types will be mentioned and listed here and in appendix B, probably incompletely and somewhat contrary to the general scope of this book, but the lists will serve as the basis for a rough evaluation. The parameters listed and evaluated for available pumps are solely based on scattered experience with the performance of the pumps in practical use, possibly not doing full justice to the actual capabilities of the various products.

Table 2-1. Pump characteristics		
Type	Pressure	Flow
Single-stage centrifugal	There is a maximum pressure (P_{max}), where flow is zero. Pressure can vary from P_{max} to almost zero. P_{max} is typically less than10 bar.	The flow can vary from nil to a large figure. The limit is set by the maximum motor power, the inlet port and the outlet port
Multi-stage centrifugal	There is a maximum pressure (P_{max}), where flow is zero. Pressure can vary from P_{max} to zero. P_{max} is typically less than 26 bar, but can be up to 70 bar.	The flow can vary from nil to the max design flow (F_{max}). A typical flow range is from F_{max} to one third of this value. F_{max} is dictated by the maximum motor power and internal restrictions in the pump.
Piston	The pressure is in principle unlimited. The limit is set by the motor and the physical strength of the pump housing and the piping.	The flow is almost constant.

Centrifugal pumps

A meaningful way of viewing centrifugal pumps in connection with membrane filtration is according to the speed of the impeller:

Low Speed: 3000 rpm at 50 Hz or 3600 rpm at 60 Hz (2-pole standard motor).
High speed: Higher impeller speed, either by gears or using a frequency converter.

Single stage, low speed centrifugal pumps

The most common centrifugal pumps are of the low speed type, meaning 3000 rpm by 50 Hz and 3600 rpm by 60 Hz. Lower speeds are rarely used in membrane filtration systems, since the investment tends to increase and the pump characteristics tend not to be well matched to the requirements.

Closed impellers provide the gentlest treatment of the product and they increase the pump efficiency. Open impellers are rarely used in pumps for a membrane filtration systems.

The suppliers of single stage, low speed centrifugal pumps are legion.

Single stage, high speed centrifugal pumps

High speed, single stage centrifugal pumps are mainly used in seawater desalination. Several types of pumps of widely varying designs are available.

Sunstrand (USA) supplies single stage centrifugal pumps operating at up to 30,000 rpm. The high impeller speed is achieved by using a mechanical gear, enabling the pump to deliver 70 bar or higher in a single stage. The efficiency of the smaller pumps tends to be poor, although better than one might expect. The larger capacity pumps operate at a reasonable efficiency. The main advantage is a very small pump housing. The complicated gear box causes a high noise level.

EnviroTech (USA) sells a peculiar pump, Roto Jet, where the high pressure side is static. A drum with water is rotating fast and the velocity of the liquid is transformed into pressure in a Pitot tube reaching into the liquid at the periphery of the drum where the speed is the highest. It is a very unusual design.

Grundfos (Denmark) sells a multistage pump operating well above 3000 rpm. It can be driven by an electric motor, operating at e.g. 100 Hz, meaning that the pressure is quadrupled compared to the standard 50 Hz. It may be driven by a Pelton turbine as an energy recovery unit in seawater desalination systems.

Multistage, low speed centrifugal pumps

The most commonly used type of pump is the multistage centrifugal pump. There seems to be an industry standard of up to 26 bar discharge pressure. Only few pumps of this type are rated higher than 26 bar.

Grundfos (Denmark) is a market leader in Europe for pumps with flows of up to 50 m^3 and pressures below 26 bar, but coming increasingly under competitive pressure, for instance from **Lowarra** (Italy). These pumps usually operate for years without maintenance.

KSB (Germany) produces a vast array of pumps, mostly for industrial applications, one type being large capacity multi-stage centrifugal pumps capable of delivering several hundred cubic meters per hour at very high pressure.

Multistage, high speed centrifugal pumps

Grundfos (Denmark) has an energy recovery unit, where a Pelton turbine is used to drive a submerged pump at approximately 5000 rpm using a flat belt drive. It will generate 70 bar pressure in only a few stages. As indicated above, overclocking to 80 Hz offers the possibility of generating high pressure in a few stages.

Generally feed pumps used in membrane filtration plants are frequency controlled in a range of up to 160% of the standard frequency on the site.

Positive displacement pumps

This type of pumps delivers an almost constant flow regardless of the pressure within a wide set of practical limits. There are several designs of positive displacement pumps, some are, comparatively speaking, more positive than others.

There are numerous suppliers of **piston pumps** with one or more pistons, but only few of them produce pumps of a suitable design for membrane filtration systems.

The homogenizer pump is a very expensive and also a very robust pump originally designed for homogenizing milk and other products containing fat. Since the pumps are designed for pressure up to 1,000 bar, even the pressure used for seawater desalination is in the lower design range. There are several modified homogenizer pumps available, modified to operate at higher flows and lower pressures.

Diaphragm pumps are comparable to homogenizer pumps, but tend to be even more expensive. Diaphragm pumps are mostly used for low flows and high pressures.

All positive pumps cause pulsation in the piping system. Pulsation dampeners are commonly installed and they help, at least as long as they function well. No matter the precautions, there will always be some pulsation tending to cause pipe breakage and leading to minor problems with loose bolts and nuts in the system. Positive displacement pumps are almost mandatory in laboratory test work. As a general rule, they should not be used in industrial membrane filtration systems.

Recirculation pumps for RO and NF systems

Multistage RO and NF systems with recirculation require specially designed booster/recirculation pumps. The main challenge is the high feed pressure to the pump, commonly up to 40 bar and in some cases more than 60 bar. Two types of pumps are used:

- Single stage centrifugal pumps
- Bore hole pumps

Single-stage centrifugal pumps

Ordinary single stage pumps are commonly used in connection with vacuum evaporators. The pumps differ from ordinary pumps in three construction details:

- The pump casing is thick and designed for vacuum and high pressure
- The bearings taking up the axial load are stronger than normal
- The mechanical seal are of a special construction

These construction details are well known and can be handled from a design standpoint. This type of pump is still preferred over the bore hole pump. The only disadvantage is the price for the pump and the cost of replacing the mechanical seal.

It is an advantage that many of the pumps available in this niche market are of a sanitary design.

Bore hole pumps

Bore hole pumps are multi-stage centrifugal pumps with submerged motors designed to work on cold drinking water deep underground. They can be positioned up to 200 meters below the surface and will keep pumping water for years without maintenance. The discharge pressure is generally higher than 20 bar with only a few meters of head on the suction side. Bore hole pumps should be used as recirculation pumps in high pressure membrane filtration only in water treatment systems at low temperature.

The main advantages to bore hole pumps are:

- They can operate at very high in-line pressure
- They are very quiet
- The price is relatively low
- They are standard pumps

The main disadvantages to bore hole pumps are:

- Limited operating temperature, typically a maximum of 50°C
- Little tolerance to viscosity
- The large number of gaskets between stages are vulnerable to damage when operating

on solutions containing particulates, sugar or sticky substances

- It is quite difficult to determine if the direction of rotation is correct
- Special observation of motor temperature and energy consumption is required
- The integrity of electric cables is a concern

Bore hole pumps have a limited market and they are getting outperformed by other pump types tolerating high in-line pressure.

General about pumps

Some issues are common for most pump types and attention needs to be paid to them, both in the process of selecting the best suited pump type for an application and from the standpoint of proper operation and maintenance with the purpose of avoiding production downtime and ensuring long pump life.

The **pump seal** has an essential function, but is an often overlooked detail because it is not very visible and forgotten as long as it functions correctly. There are two basic rules concerning pump seals: Only a mechanical seal will work.

It is highly recommended to flush (cool) the seal.

While flushing of the pump seal consumes water, experience shows that it eliminates many potential problems. Many liquids have a content of abrasive particulates, and if sugar is present it will migrate to the seals surfaces, burn and caramelize causing excessive wear of the sealing surfaces. Flushing prevents this.

The best suited material for pump seals is sintered carbide against sintered carbide. However, carbon against steel can also be used.

The seal in a high pressure recirculation/booster pumps must be able to tolerate a very high inline pressure. The solutions to this issue tend to be expensive.

There is a very simple rule to follow when choosing the **materials of construction** for pumps used in membrane filtration systems. Always choose pumps where the surfaces in contact with the liquid are made from 316L stainless steel or better, compromising this rule only if a robust polymer is available.

The pH may be as low as 1 and as high as 14 and the temperature as high as 80°C during cleaning-in-place (CIP). If the equipment is of a sanitary design it must be disinfected at certain time intervals, which is often performed with significant concentrations of sodium hypochlorite. Only very good materials will tolerate these conditions.

Pumps made from cast iron, bronze or aluminum should never be used in membrane filtration systems. These materials are subject to corrosion, which causes membrane problems to occur.

Control of pumps

A pump almost never delivers the exact flow and pressure needed, so it has to be controlled in some fashion. It is necessary to distinguish between centrifugal pumps and positive displacement pumps. Figure 2-12 provides information about the most important characteristics for the two types of pumps. A positive displacement pump provides, as the name indicates, an almost constant volume of liquid independent of the pressure.

A single stage centrifugal pump tends to deliver almost constant pressure which is largely independent of the flow it delivers when it operates close to its maximum efficiency.

A multistage pump is somewhere between the first two mentioned. The more stages a pump has, the steeper the pump characteristic. Consequently, the pressure varies significantly if the flow changes.

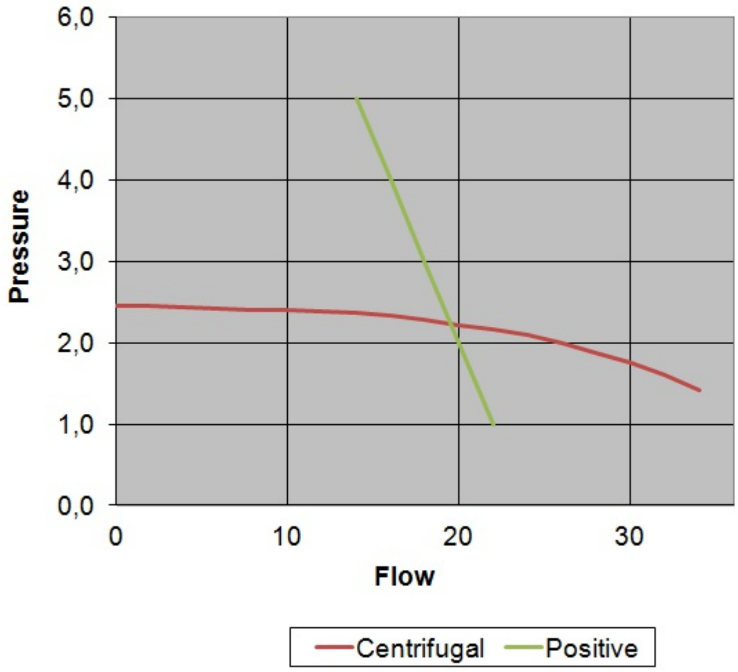


Figure 2-12. Pump characteristics

These statements are correct in principle, but a textbook should be consulted for a thorough description of pump characteristics.

With the above mentioned pump characteristics in mind, the following possibilities are available for controlling a pump. Table 2-2 represents practical rather than theoretical solutions.

Table 2-2. Control methods for pumps

Control method	Single stage centrifugal pump	Multistage centrifugal pump	Positive displacement pump
Frequency converter ((The best choice)	Yes	Yes	Yes
Throttling valve (Outdated)	Yes	Yes	
Mechanical variator (Outdated)			Yes

When using a positive displacement pump, never place a fully closable valve after the pump because if the valve closes, something will break. For many years, the only means of controlling flow and pressure were by mechanical variators by which the RPM of the pump can be changed. More recently, frequency converters have become available, offering an excellent way to control a positive displacement pump. Mechanical variators wear out faster than electronic converters.

Centrifugal pumps are simple and easy to control by means of a **throttling valve**. This method is very traditional. It is simple and inexpensive, but it has several drawbacks:

- It is noisy to the extent that the noise can be physically harmful.
- It wastes energy to the extent that several kWh every hour can easily be lost.
- It generates heat which may have to be removed by cooling, and cooling is an expensive process.
- Severe shear forces occur which can harm the product being treated.

Another often suggested way is to pass liquid from the discharge side to the suction side of a pump to regulate pressure and/or flow. However, experience shows that this method results in inherently unstable pressures and/or flows.

A **frequency converter** is the modern and most efficient way to establish pump control. There is no waste of energy, no noise and no shear forces. This method can be used in connection with all types of pumps.

The price of frequency converters have been dropping fast, partly because the number of users has reached a critical mass and partly due to the advancement in the area of electronics. The components have become so small and inexpensive that frequency converters are now factory installed in connection with smaller pump motors as standard, which means that eventually they will also become standard for bigger motors.

The energy savings from using a frequency converter can be substantial. If 1 kWh is saved, this corresponds to 8800 kWh in one year, which will quickly pay for the cost of the frequency converter.

In general, centrifugal pumps should not be used for shear sensitive products like egg white, but by exercising special care and consideration some centrifugal pumps can be found for this purpose. However, a slow piston pump is normally a better choice.

When high viscosity products are involved the Mohno-type pump is considered to be the better choice, although very special centrifugal pumps are available. Using a Mohno-type pump requires special control loops.

Energy recovery

The subject of energy recovery falls outside of the scope of this book. It will suffice to state that approximately 30% energy recovery is possible in large high pressure applications with low permeate recovery, seawater desalination being the prime example. Several energy recovery devices are commercially available.

Measuring devices

The control system of a membrane filtration system, be it manual or automatic, requires input concerning parameters allowing the plant to produce a product, permeate or concentrate as the case might be, with the right composition. The required input parameters may originate from a variety of measuring devices producing the required information in several different formats.

The most important control parameters are:

- Flow
- Pressure
- Temperature
- Dissolved solids (TDS)

Manually controlled systems are viable only for small scale production. With membrane filtration technology coming of age, the majority of the systems installed are automatically controlled. Manually controlled systems rely on the operator taking the appropriate readings of the control parameters and then making the required adjustments. Larger scale production systems need to be automatically controlled with continuous input covering the necessary control parameters.

The following is focused on automatically controlled membrane filtration systems, but the general principles of control apply equally well to manual systems.

Flow

The most common control parameter in membrane filtration is flow, although a volumetric concentration of the feed does not meet the requirements if the composition of the flow changes over time.

Several types of flow meters are available, but the rapid development in the areas of flow measuring devices and microprocessors renders it difficult to be entirely up to date on the capabilities of the combination of flow meters and microprocessor control.

The **rotameter** is a purely mechanical type of flow meter, which is not applicable to automatic control systems but provides a sound foundation for manual control and as a checkpoint for automatic control systems. Some types of rotameters are supplied with an electrical transmitter, but this is not common and better solutions for automatic flow control are readily available. Rotameters are sensitive to viscosity and density of the liquid and to wear and tear of the transparent housing, and the flow indication may deviate from the true flow values. A significant advantage of the Rotameter is that the reading can be observed from a distance making it easy for an operator to get a subjective feel for the plant performance.

The **magnetic flow meter** is the only type of flow meter providing good and reliable flow data for literally all products that will be encountered in a membrane filtration system with the only exception being ultrapure water.

The magnetic flow meter usually transmits a signal in the 4 to 20 milliAmp (mA) range, which is a standard for many control devices.

The magnetic flow meter has several significant advantages in the context of membrane filtration:

- The flow channels in the system are not impeded by the measuring devise
- There is virtually no pressure drop
- The diameter is generally identical to that of the pipe through which the liquid flows
- The measuring range is larger than that of most other flow meters

There are several manufacturers of magnetic flow meters. The following is a list of the manufacturers of magnetic flow meters commonly used in Europe, but the list is by no means complete:

- **Siemens** (Germany)
- **Danfoss** (Denmark)
- **F&P** (United Kingdom)
- **Bürkert** (Germany)
- **Endress & Hauser** (Germany)
- **Process Data** (Denmark)

It may be difficult to obtain a flow meter that can operate under the pressures and other essential parameters in an RO system. Another problem is sourcing magnetic flow meters operating in a strictly sanitary environment.

Flow meters are routinely delivered including a local display, a display in a control panel and providing a signal for control purposes. Additional features like temperature indication and flow totalization are commonly available.

The **turbine flow meter** will, in principle, perform the same job as a magnetic flow meter at a much lower price, but the bearings of turbine flow meters are often of a quality rendering them unsuitable for use in membrane filtration systems.

The **ultrasonic flow meter** is relatively inexpensive, but the measuring principle can only work well when there are particles reflecting the sound waves, and, generally, in connection with membrane filtration systems there are only few suspended solids and very little air in the form of air bubbles.

Mass flow meters are sophisticated instruments used to measure flow, density and mass simultaneously, their main purpose being the control of evaporators. The measuring principle encompasses inertia, mass and resonance damping. Externally they resemble a U-tube, often close to one meter long. The concentrate is conducted through the tube which is connected by a flexible joint to the evaporator. The weight of the product in the tube is measured on a weighing cell, and the density of the product is calculated. The faster the liquid flows, the more the tube will flex due to the force necessary to change the flow direction 180°. This flexing is measured, and based on the density of the liquid, the flow velocity is calculated. Knowing speed and density allows calculation of the mass flow. Viscosity can indirectly be determined by introducing a high frequency tone generator. Mass flow meters are excellent for fluids containing high solids. The biggest drawback is the price, rendering the use in membrane system questionable.

General about flow meters

The five types of flow meters discussed above rely on linear velocity, magnetic properties of the liquid, flow velocity, the reflection of sound waves, the density of the liquid and the inertia of the liquid. Many ingenious solutions to the measurement of flow are available based on these and other principles.

In general, it is risky to use flow meters containing moving parts. Suspended solids may contaminate and foul the mechanism, floats may get stuck, bearings may wear out and gears may deteriorate. The safest choice of flow meters for control of membrane filtration systems seems to be the magnetic flow meter.

Pressure

Bourdon type pressure gauges are the original and basic method of measuring pressure. In the context of membrane filtration they suffer from the lack of ability to be zeroed in an automatic control system. **Electronic pressure transmitters** can be automatically zeroed and provide extremely accurate readings of 0.1% accuracy over a large measuring range, which is beneficial in a membrane system, since it allows indication of the pressure drop over an element or a membrane housing, even at high operating pressures.

Electronic pressure transmitters are available with local displays, with display mounted in a control panel and providing an electrical signal for automatic control.

In the context of an automatically controlled membrane filtration system, Bourdon type flow devises are only suited for local indication to provide the operator with a visual estimate of the pressure at a point in the system, which has more practical than real value for control purposes with the general position of the indicator giving a snapshot of the present situation.

Using a Bourdon type flow meter, a diaphragm must be present to separate the meter from the product.

Temperature

The industry standard in connection with membrane filtration with respect to temperature measurement is **electronic temperature transmitters**, usually with the standard 4 to 20 mA signal for the measurement range of the devise.

The designs and the suppliers are legion. Safe and reliable temperature measurement is considered to be the state-of-the-art.

Total solids

An important control parameter in the operation of many membrane filtration systems is the content of total dissolved solids (TDS) in the concentrate.

The refractive index of an aqueous solution is considered to be representative for TDS, which is not entirely true, but which represents a practical and workable solution to obtaining a measured value representing TDS.

The scale commonly used for the measurement of TDS is degree Brix (°Bx), which is defined as 1 °Bx being equal to 1 gram of sucrose at 25°C dissolved in 100 grams of solution representing a weight/weight percentage. If the solution contains other solutes than sucrose, the measured result must be adjusted based on experienced values measured on the solution in question.

Other scales than °Bx are used to convert the refractive index to TDS in various industries, for instance in the brewing and wine industry where ethanol (alcohol) distorts the measured result, which needs correction to represent TDS or sugar.

Working out 'translations' of the measured values makes it possible, for instance in the dairy industry, to control a membrane filtration system for protein fractionation of cheese whey to produce predetermined levels of protein in a UF concentrate using an automatic control system based on an in-line output of an industrial refractometer. This translation is necessary to accurately control membrane filtration of several dairy streams containing fat and other suspended solids. The same consideration is valid for process streams origination in other industries.

The wine industry is a prime example. Ethyl alcohol has a refractive index vastly different from that of water. The content of sucrose can be measured accurately by measuring the refractive index of the starting solution. However, when fermentation has started and ethyl alcohol is formed, the results based on the refractive index are no longer representative of the sugar content.

In the same way, suspended solids in a solution are not detected by a refractometer. This goes for fat globules in milk and in concentrates of milk in the dairy industry, where a refractometer will produce wildly inaccurately readings of TDS for whole milk and part skim milk concentrates, unless corrections to the values delivered by the refractometer are made based on experienced actual values.

The refractometer must be positioned in the system in a way that ensures a reasonable and constant flow over the prism in all production phases. If the refractometer is placed in the concentrate line, flushing of the prism can be ensured by connecting a thin tube from the pressure side of the last recirculation pump to the refractometer.

Control systems

The last few decades has brought a rapid development of devices for control of processes and equipment encompassing every kind of simple mechanical control system to the more advanced systems using computers, which are so prominent today in their many forms and shapes.
The transition from analog to digital signals is almost complete although the 4 to 20 mA signal range from a measuring device is still a commonly used standard. However, there is a clear trend towards digital signals.

The older type of pneumatic controllers and relays have one virtue, they can literally be repaired with a Swiss army knife. There are still quite a few areas of the world where simple technology is preferable to the most up-to-date and advanced control technology. It seems that the human mind works against a simple solution since most end-users want the latest and greatest in the form of computer based control systems, and that the producers love to supply them.

Programmable logic controllers (PLCs) have been around for a number of years, and there are many manufacturers. The only preferences when choosing a PLC based control system should be choosing a well known and respected brand. It is not worth the saving buying one of the more obscure brands, if only a few people can service or reprogram it.

PLC programming has progressed greatly without becoming decidedly user friendly. This draw back seems to be overcome with the emergence of control systems based on **personal computers (PCs)**, which are offered by several suppliers and are fairly easy to program.

In very large operations like refineries and paper mills it is common to tie the control system of a membrane filtration plant and other equipment into the **main frame computer** at the location. Companies like **Siemens** and **Allen Bradley** have a good reputation in this area. This type of control system has a hefty price tag with but with the advantage that local and fast service is available. The operators cannot, in general, program main frame computer based control systems.

The end user may have several pieces of equipment and several processes requiring advanced control systems, and he may want to use the same type and brand for all new installed equipment.

As a general rule, money saved on control systems may be lost even before the system has been installed and will surely be lost the first time the plant is waiting for service in case of a control system failure.

Control loops

A well operating membrane filtration system is a well controlled system. Well thought out, accurate and reliable control ensures that the requirements to the final product of the operation are achieved. Although a membrane filtration system operates very much along the lines of other industrial processes, the membranes require a carefully controlled environment in order to function at their best performance. In other words, special considerations must be given to the way that the parameters in question are being controlled in a membrane filtration system.

Membrane filtration involves four different processes operating at widely different pressures and for widely different purposes with the product being the permeate in some cases and the concentrate in others. In general, but not always, the permeate is the desired product in reverse osmosis (RO), nanofiltration (NF) and microfiltration (MF), in seawater desalination, water purification and MF pretreatment for RO and NF, whereas the product is the concentrate in ultrafiltration (UF) and in most industrial NF applications.

Pressure

Pressure control (to control flow) of a membrane filtration system is used almost exclusively in NF and RO seawater desalination, water purification and wastewater treatment systems, where the operating parameters remain constant over long periods of time. There is an almost linear relationship between pressure and flux in RO and NF applications, making the control of the system pretty simple and straight forward. Pressure control may be applied to UF and MF applications, but in those cases the control objective becomes one of protecting the membranes, actually upsetting a primary production goal of constant capacity.

Flow

The function of a flow measuring device is, of course, to measure flow accurately. In membrane filtration systems this is particularly important in situations where the ratio between the volume entering the plant and the volume of concentrate exiting the plant has a constant predetermined value set by the operator with the purpose of arriving at a certain volumetric concentration ratio and a desired composition of the final product. In this situation there is one flow meter in the feed line and one in the concentrate line.

The actual control function is performed by a pneumatically or electrically driven concentrate valve with actuator and positioner. The signals from the flow meters travels to the controller which, based on the information received, sends a signal to the concentrate valve specifying the desired position as shown in figure 2-13.

A ratio control loop is relatively simple to design and operate.

It is a frequent suggestion to use the permeate flow for regulation instead of the concentrate flow. This scheme will work in some cases, but not always, and it has several inherent problems. Sometimes water is added during the filtration process to reduce the content of one of the dissolved species passing through the membrane in a process called diafiltration. In this case a control system based on the permeate flow will not work. Also, when the volumetric concentration ratio is high and the flow of feed and permeate become almost identical, even a small adjustment error may lead to disastrous results.

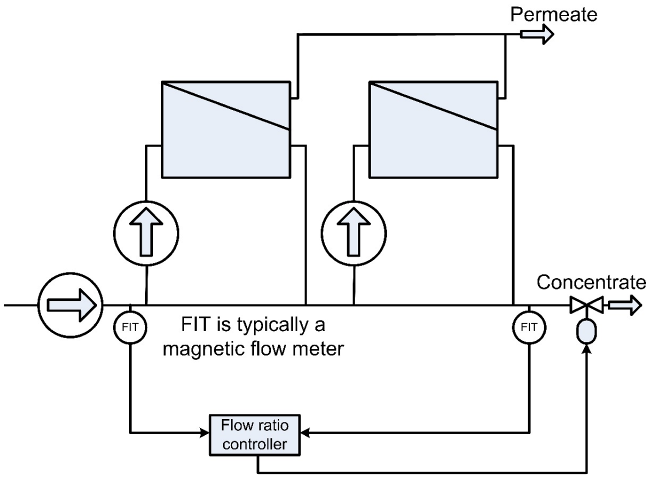


Figure 2-13. Flow ratio controller.

It is vastly preferable to measure the concentrate flow, and it always works.

When diafiltration is involved, there are two flow ratios to control, the volumetric concentration ratio and the ratio of diafiltration liquid to concentrate. It is tempting to design a system with only three flow meters as shown in figure 2-14 with the diafiltration volume being determined by the feed flow, but this is decidedly dangerous. Adjustment errors or operator error can lead to situations where the diafiltration volume exceeds the flow of concentrate from the previous loop, with the result that there is no concentrate flow. This leads to a buildup of solids and subsequent blocking of the membranes.

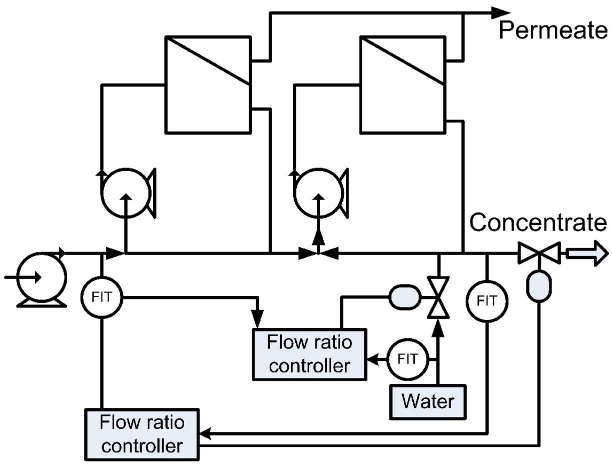


Figure 2-14. Flow ratio controller and diafiltration flow controller, 3 flow meters.

A safely operating system has four flow meters as shown in figure 2-15. This design assures that the flow of diafiltration water never exceeds the flow of concentrate from the previous loop.

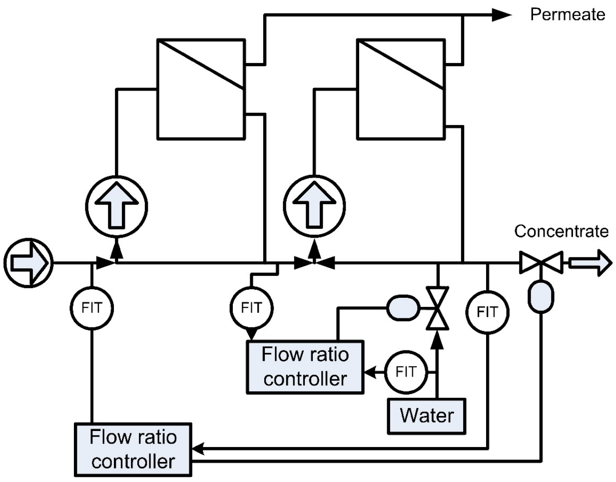


Figure 2-15. Flow ratio controller and diafiltration flow controller, 4 flow meters.

Total Solids

Total solids (TS) or total dissolved solids (TDS) are parameters that are not often used to control membrane filtration systems. An exception is in UF of whole milk where TDS is measured by a refractometer. The reason is that the UF milk concentrate most often is used for production of cheese and therefore it is essential that TS is correct. Another exception occurs in the pulp and paper industry where refractometers are sometimes used.

There are mass flow meters measuring liquid density (kg/m^3) and mass flow (kg/second), which enables a calculation of the volumetric flow (LPH). These instruments are primarily used in connection with evaporators, but they are becoming available for other types of equipment. The price is high but decreasing rapidly.

There are two correct positions for the placement of refractometers. Firstly, they may be placed in the concentrate line. However, this makes it quite difficult to start up a membrane filtration system. Very careful design and engineering are needed to ensure that the concentrate valve never closes completely. Secondly, they may to be placed in the last recirculation loop as shown in figure 2-16.

The drawback of the second option is that this loop must always be in operation for the control system to function properly.

An attractive feature of refractometers is that they contain no moving parts. A less attractive feature is that the reading can be distorted by fouling of the prism which is in direct contact with the liquid. Fouling of the prism is a distinct possibility because a rather powerful light source is needed to obtain a signal to be detected and transmitted for use by the control system. Local heating of the product takes place and that can cause the product to precipitate and adhere to the prism. A fairly simple method to minimize the problem to a manageable extent is to draw a very thin tube from the pressure side of the recirculation pump in the last loop of the plant, thus flushing the prism of the refractometer with a constant stream of liquid.

Another potentially serious problem is that the lamp in the refractometer can burn out. Alarms are needed to alleviate this situation and a quick response is essential to avoid that the membrane system moves outside of the control parameters.

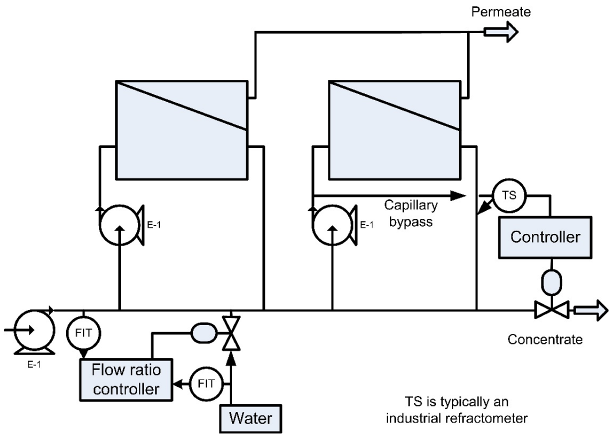


Figure 2-16. Controller for constant TDS in concentrate

The reading can be very diffuse, and it tends to become more diffuse at higher solids levels, especially on dairy products containing fat. Industrial refractometers have capabilities that the human eye does not. The electronic sensor integrates the diffuse signal simply because that is the nature of the sensor. A very diffuse signal is generally not a problem for an industrial refractometer, although it can become a substantial problem for the human operator.

An industrial refractometer does not tolerate high pressure. The pressure limitation is not of any consequence in a UF system, but it presents a serious problem in NF and RO.
Viscosity has no influence on the reading of a refractometer.

Temperature has some influence on the reading. Therefore calibration at the operating temperature is necessary.

It is common to control plants using diafiltration with refractometers as shown in figure 2-17. The control system is similar to the diafiltration process explained above.

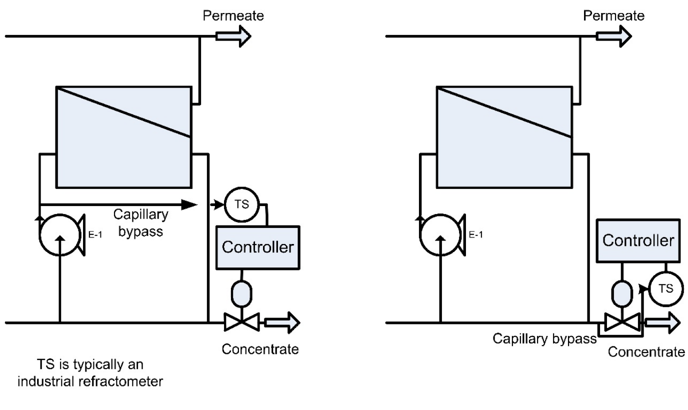


Figure 2-17. Controller for constant TDS in concentrate and for diafiltration flow

Only a few brands of refractometers used for membrane filtration purposes as shown in this probably incomplete list:

- **Anacon**
- **The Electron Machine Company**
- **Siegrist**
- **X-Control**

Pressure and Feed Flow Control

Pressure is a value which most often needs to remain constant or adjusted only slightly in a membrane filtration system to provide a desired level of performance during operation. This is most often the case in seawater desalination and water purification systems. In seawater desalination and water purification this is almost the only control method used and the only one needed. The same is the case for industrial RO and NF plants, but in some of these cases other control options than pressure control may be required, see figures 2-18 and 2-19.

For RO and NF plants an electrical signal from a pressure controller is in reality proportional to a feed flow and will adequately control the plant capacity.

For UF plants, feed pressure control is used as a way to ensure that the pressure does not rise above the maximum allowed or maximum desired value. It is also used to minimize the inevitable high flux occurring at production start up with clean membranes.

Figure 1-2 shows that pressure cannot be used to control the capacity in UF and MF systems, where the capacity is determined by the nature of the product and by the characteristics of the membrane and where the operating pressure is almost irrelevant.

The feed flow can only be indirectly controlled in UF and MF systems. It is common in a multistage system not to start all loops simultaneously in the production cycle. For instance, in a five stage system loops 3, 4 and 5 are typically started up initially. After a short time, maybe 30 to 60 minutes, the loop 2 is needed to reach plant capacity, and after a few hours loop 1 is needed, see appendix F.

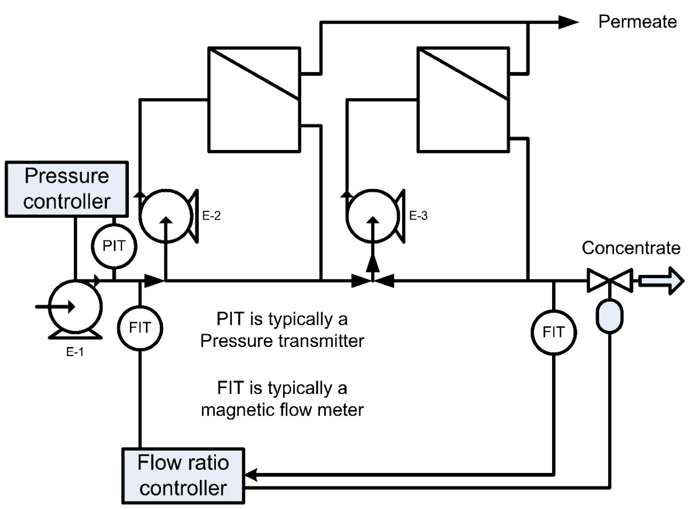


Figure 2-18. Ratio controller, feed and concentrate flow, at constant feed pressure

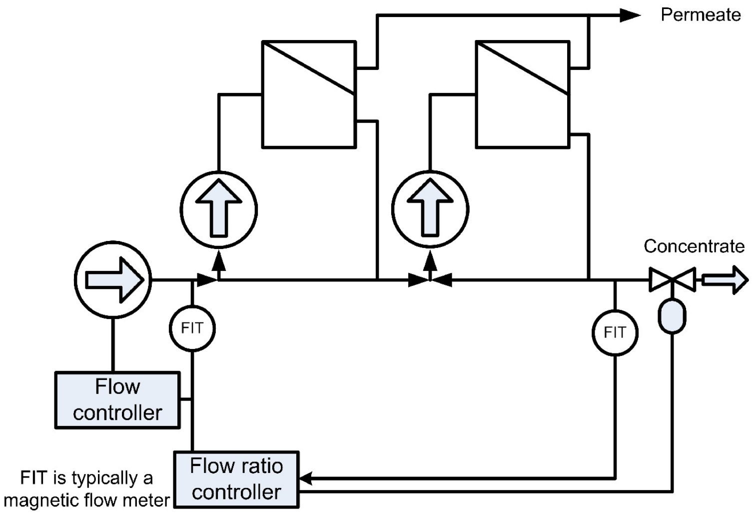


Figure 2-19. Ratio controller, feed and concentrate flow, at constant feed flow

Permeate Flow Control

In some situations in NF and RO systems a constant permeate flow is desired, see figure 2-20. This is accomplished by installing a flow meter in the permeate line and using the signal to control the feed pressure by (1) varying the RPM of the feed pump, which is best achieved using a frequency converter, or (2) using the signal to open or close the throttle valve between the feed pump and the system.

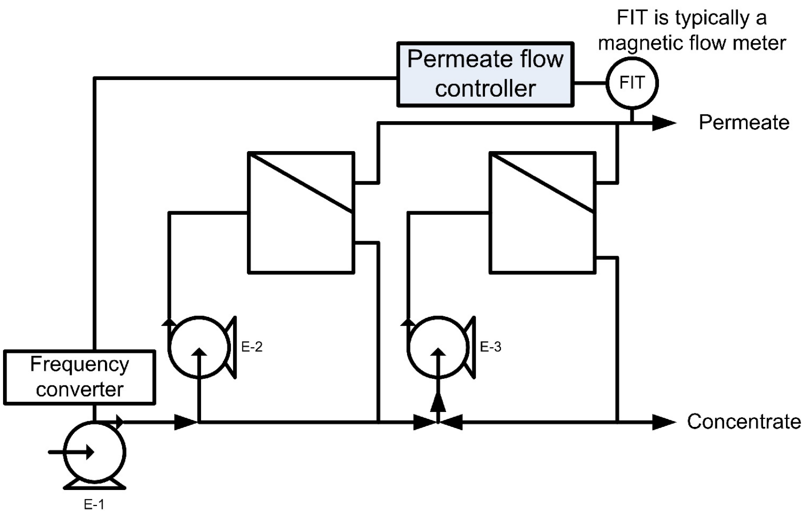


Figure 2-20. Permeate flow controller

In **batch systems**, if the feed pump is a positive displacement pump, the net result is that the concentration ratio is kept constant. If the feed pump is a centrifugal pump, the concentration ratio is undecided, which does not really matter.

In **continuous systems**, if the feed pump is a positive displacement pump the net result is that the concentration ratio is kept constant. If the feed pump is a centrifugal pump a ratio controller is needed.

Permeate flow control is somewhat controversial since there are several possible sources of error. Permeate flow control is, for instance, hardly useful in systems with diafiltration. However, it seems to work very satisfactorily in NF and RO systems with relatively non-fouling feeds and in batch systems.

Viscosity control

Viscosity can be a serious challenge when concentrating products like carrageenan and xantan. It makes very little sense to use solids as indicated by a refractometer or concentration ratio for control purposes because the relationship between the solids content and the viscosity is obscure. Consequently, a more indirect control method has been devised, see figure 2-21.

A positive displacement pump installed in the last loop provides a flow which is almost independent of the operating pressure of the pump, but there is a clear relationship between the pressure drop in the membrane element and the viscosity. When the viscosity increases, the pressure drop increases, thereby increasing the pressure which the pump has to deliver. The electrical current consumed by the motor is directly related to the pressure delivered by the pump when the flow is constant, although not by a linear relationship. There is consequently a clear relationship between the viscosity of the liquid and the electrical energy consumed by the pump motor. The information about the energy consumed can be used via a controller to regulate the concentrate valve and ascertain that the viscosity of the concentrate remains constant.

Centrifugal pumps cannot be used in the last loop.

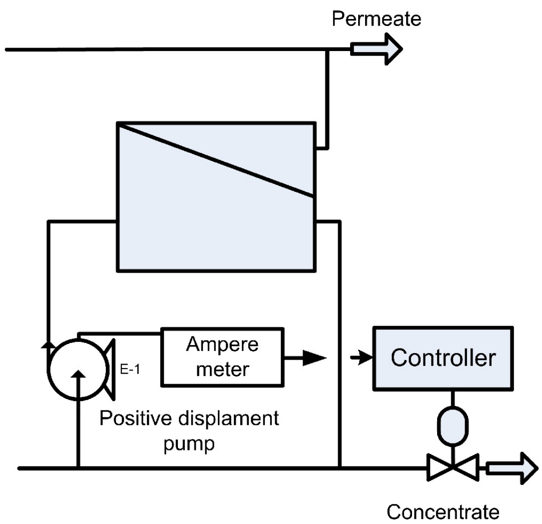


Figure 2-21. Viscosity control

Products and processes

Approximately 80% of all membrane filtration equipment is used for water purification and desalination of seawater. A large portion of the remaining 20% is employed by the dairy industry, mainly for processing of cheese whey. Other applications occupy only a small portion of the installed equipment, but the number of products and applications are legion. In some cases it takes only a minor amount of equipment to change the manufacturing of a specialized product or to significantly improve the situation with respect to contaminants in wastewater.

In the cases of purification the permeate is most often the product. If the purpose is concentration, the concentrate is the product, and it may also be purified in the process.

The table provides information about a number of general and specialized applications.

Table 2-3. Membrane filtration applications

	Product treated/process	Permeate	Concentrate
	Dyeing effluent	Clean water for reuse P	BOD, salt, chemicals, waste products W
RO	Water desalination	Low salinity water P	Salty water, waste product W
	Whey concentration	Low BOD water for reuse P	Whey concentrate P
	Antibiotics	Salty waste product W	Desalted, concentrated antibiotics P
NF	Water softening	Softened water P	Waste product W
	Whey desalting	Salty wastewater W	Desalted whey concentrate P
	Antibiotics clarification	Clarified antibiotics P	Waste product W
	Carrageenan concentration	Waste product W	Purified and concentrated carrageenan P
	Enzyme purification	Waste product W	Purified and concentrated enzymes P
	Milk protein concentration	Lactose solution P	Protein concentrate for cheese production P
UF	MSG	Clarified MSG P	Bacteria, suspended solids. Waste W
	Oil emulsion	Oil free water (<10 ppm) reuse or safe discharge P	Concentrated oil emulsion W
	Water clarification	Clarified water P	Waste product W
	Whey protein purification	Lactose solution P	Whey protein concentrate P
	Bio-gas waste clarification	Clarified liquid as fertilizer P	Microbes to be recycled P
	Produced water	Oil and particle free water for reuse or safe discharge P	Oily waste product W
MF	Membrane bioreactor	Particle free. P >log6 reduction of bacteria	Microbes and suspended solids remain in bioreactor (not wasted) P
	Milk sterilization	Cold sterilized milk P	Bacteria and fat. Reused after UHT treatment W

P in the right part of the cells denominates a process application

W in the right part of the cells denominates a wastewater application

Part 3

Membrane Filtration Systems

Fouling and Cleaning

Fouling

The term 'fouling' is the common denominator for all materials deposited in a membrane filtration system during operation which will impede the operation of the system, but with a special view to buildup of materials on the membrane surface decreasing the flux rate and/or impeding the rejection characteristics.

It is a general condition in membrane filtration systems that water is transported through the membrane. The flow of water in the direction of the membrane surface results in a concentration of dissolved solids, microorganisms, suspended solids and any other material, which are rejected by the membrane, for instance some organic macromolecules. It is common to use the silt density index (SDI) in water applications where prolonged periods of operation between cleaning cycles is required as a method to determined feed water quality.

Seawater and surface water are biologically active substances, where microorganisms such as bacteria and algae thrive. Bacteria can adhere to the surface of the membrane and to the surfaces of other materials in a membrane filtration system and form colonies, which continue to propagate. Some microorganisms produce metabolic products, which can deposit on the membrane surface and cause other particulates to accumulate. If dead microorganisms are present, for instance as the result of prior chlorine treatment of the water, intracellular substances, for instance triglycerides, may be released and adhere to the membrane surface. Also in this situation other particulates tend to accumulate on the membrane surface.

As mentioned, fouling mainly occurs due to transport of material to the membrane surface, and the transport of material to the surface of the membrane is more or less proportional to the flux rate of the membrane. The clean water flux can rarely be reestablished after the first use of a membrane, indicating that some irreversible adsorption or absorption phenomena take place. These phenomena should not be confused with membrane fouling during operation.

Four groups of membrane fouling must be considered:

- Inorganic scaling
  This is mostly carbonates, hydroxides and sulfates of metals, such as calcium, barium and strontium. It may occur if the chemical balance of the feed water is altered, for instance by a pH adjustment or addition of chemicals. It happens when the solubility product of a salt is exceeded and results in scales forming on the membrane and other surfaces in the system.
- Particulate fouling
  This kind of fouling is caused by the naturally occurring particles in the feed water. One of the purposes with pretreatment is to the highest possible degree to remove suspended solids, since they will foul the membranes in any membrane filtration systems. The goal is to deliver a feed with less than 3 SDI units in seawater desalination and water purification.
- Microbiological fouling
  Bacteria and other microorganisms can attach themselves to most surfaces, among them

the surface of a membrane. Colonies are formed, which continuously propagate. The metabolic products of microorganisms may also adhere to the membrane surface, as will the intracellular substances of dead microorganisms, resulting in a sticky layer, which is often called a biofilm. The stickiness of a bio-film causes small particles to be captured and can create serious fouling.

- Organic fouling
  This kind of fouling is caused by naturally occurring organic matter in feed, for instance humic and fulvic acid, which is the breakdown products from many plant parts.

It is difficult to generalize about industrial membrane filtration applications with respect to the potential for fouling, except that fouling is more prevalent in industrial applications and that cleaning may be required at frequent intervals with the purpose of maintaining a reasonable production flux of the system.

Industrial applications should always be pilot tested with the purpose of determining a reasonable operating flux, a satisfactory recovery rate and an expedient cleaning strategy. However, small scale batch pilot testing, where a small volume of the product to be treated is recirculated, may not provide the true picture of the fouling situation occuring in a full scale production plant, since the substances causing the fouling are present only in a limited quantity not being representative for continuous operation.

Pretreatment

As a general rule, all liquids entering a membrane system should be pretreated in some way, shape or form with the purpose of minimizing the potential for fouling and the risk of membrane failure. This renders the subject of pretreatment very broad, and it is not possible to treat it exhaustively in the context of this book. The following should be considered as a brief outline only with some useful recommendations pertaining to the most common methods of pretreating the liquids entering a membrane filtration system.

Bearing in mind that membranes are primarily designed to separate dissolved solids in aqueous solutions and that membranes only function properly, if they are free of chemical and physical deposits, three simple rules should be observed regarding liquids entering a membrane filtration system:

- Suspended solids should be removed
- Oxidizing agents are detrimental to thin-film membranes
- Precipitation of any material in the process must be avoided

Filtration

All membrane filtration systems benefit from protection against any kind of particulates or debris being present in the feed and some kind of filtration is mandatory. The less suspended solids present, the smaller the chance of physical blockage of the flow channels and for pore plugging, which may be a problem in connection with microfiltration (MF). The nature and shape of suspended material has a profound effect on the performance of a membrane filtration system. Small spherical particles are handled quite well by most systems, whereas thread like and fibrous material are problematic.

Fibers in connection with cellulose, cotton, asbestos and other materials deserve special attention. They tend to accumulate and form mats and balls, which can totally block even quite large flow channels in minutes or even seconds, rendering the operation of the equipment impossible. Tubular systems with a half inch or one inch diameter are capable of tolerating large amount of fibers, but for all other systems fibers must be removed from the feed.

Small and hard particles rarely cause problems. The most extreme example is electro-deposit (ED) paint forming the base layer of paint on, for instance, cars and refrigerators. ED paint contains close to 10% suspended solids, mostly titanium oxide (TiO_2) or aluminum oxide (Al_2O_3). ED paint is routinely treated with spiral wound elements, which is the membrane configuration most sensitive to suspended solids.

A curious case occurs when treating melting water in rivers, where very small chipped stone fragments are present and form deposits on the membrane totally blinding them. Once the deposits have formed they cannot be removed and the only possible pretreatment available is flocculation.

A vast array of suspended organic material may be present in the feed to membrane filtration systems, for instance in the food and dairy industry where many materials contain protein. If heat treatment is involved as a process step, part of the protein will be denatured and become insoluble. As long as a sufficient flow is maintained and they have no possibility to aggregate they are harmless. However, once deposits are formed they can be difficult to remove, even with chemical cleaning.

Several methods and kinds of equipment are available to remove suspended solids, some of the most common are:

- Cartridge filter for general purpose filtration
- Hydrocyclone to remove sand and oil in suspension
- Sliding screen to remove fibers and sludge
- Settlers to remove sand and clay flocks after flocculation
- Decanter centrifuge to reduce high contents of sludge
- A clarifier to remove fat, oil and precipitated organic material
- Vibrating screen as a coarse, high capacity filtration

pH adjustment

Calcium carbonate ($CaCO_3$) and calcium phosphates tend to form crystals and to precipitate as the concentration in a membrane filtration system progresses with membrane scaling as a result. It is very common to reduce the pH value slightly with the objective of increasing the solubility of the various calcium salts.

- In water treatment by addition of sulfuric acid to decrease pH by of 0,2 to 0,4 units.
- In the dairy industry several acids are used, most commonly lactic and citric acid.
- Addition of CO_2 is an ingenious but somewhat complicated way of reducing pH without adding chemicals.

Removal of oxidizing agents

Thin-film composite polyamide RO, NF and UF membranes do not tolerate oxidizing agents. The sensitivity to oxidizers is increased sharply when heavy metals like iron hydroxide ($Fe(OH)_3$) and manganese oxide (MnO_2) are present. Chloramines may also become detrimental to the membranes.

The most common method of removing oxidizers is addition of sodium bisulphite (Na_2SO_3) followed by a sufficient reaction time.

A less common method is using ultraviolet (UV) light, which destroys oxidizers efficiently.

Precipitation of heavy metals

Most water treatment begins with oxidation of iron and manganese, which can be a problem in membrane filtration, to form iron hydroxide ($Fe(OH)_3$) and manganese oxide (MnO_2). The oxidation can be performed with air or using sodium hypochlorite. The metal oxides can be easily removed by sedimentation or by several types of filtration, for instance microfiltration or conventional filtration.

Pasteurization

Many products in the food and dairy industry like milk and cheese whey are pasteurized at 72°C with a holding time at this temperature of 20 seconds, but several other combinations of temperature and time can be employed. Pasteurization ensures a vastly reduced microbial activity, which protects the membrane filtration system against excessive bacterial growth and subsequent fouling.

Softening

It is common to remove all divalent ions like calcium (Ca^{2+}) and magnesium (Mg^{2+}) in an ion exchanger where divalent ions are substituted by monovalent sodium (Na^{+}), which does not form insoluble salts and does not cause fouling in a membrane filtration system.

Cleaning-in-place

All membrane filtration systems need to be cleaned at certain time intervals, be it every few months or longer for seawater desalination systems and water purification systems or every day for food and dairy systems. Water systems may not have a built-in facility for CIP, but a portable cleaning skid, whereas all industrial systems are designed with built-in CIP facilities.

General

With the purpose of ensuring optimal performance of a membrane filtration system periodic cleaning is necessary. Cleaning should be performed whenever the capacity or the rejection drops below certain predetermined values. Due to the cost of cleaning in terms of downtime, chemicals and water, CIP should only be done when necessary.

Thorough pilot testing prior to the design of the system makes it possible to choose the optimal operating parameters to avoid system fouling, and good pretreatment of the feed alleviates the need for frequent CIP and helps reduce the overall operating costs.

If the system is a reverse osmosis (RO) system or if an RO system or an evaporator operates in the same facility, RO permeate or evaporator condensate should be used for CIP.

CIP of a membrane filtration system is relatively simple following a certain set of rules. The best CIP procedure and the best cleaning regimen vary from plant to plant depending on the product treated, the membrane employed and the system design.

Water treatment systems

CIP is performed occasionally at intervals of months or possibly years. If the performance of the system in terms of operating pressure, permeate flow or salt rejection deviate by more than 15% from the base line performance, cleaning is recommended.

CIP of a large water system, for desalination of seawater or general water purification, is a major undertaking. It is costly as well as time consuming, which is a good reason to choose the best possible pretreatment of the feed water.

Food and dairy systems

CIP at least once every 24 hours is standard operating procedure in the food and dairy industry with the purpose of avoiding excessive microbial growth because biologically active feeds are being treated. The flux rate may decrease by 50% or more over a day of operation, which is considered to be normal.

In some situations and on some sensitive products CIP is performed every 8 hours. Treating less sensitive products may require CIP only every 2 to 3 days.

CIP chemicals

The CIP protocol may be long and expensive. It is recommended to work with a reputable supplier of chemicals, who can provide advice and supply efficient chemicals for situations with standard products involved.

The CIP procedure in general

The cleaning regimen needs to be designed for each system and for each product treated, the membrane type and the system design. The following describes a complete CIP procedure, but can be modified for specific purposes. The values mentioned are valid for most systems operating with polymer membranes on biologically active products.

Table 3-1. General CIP procedure

1	Reduce the pressure to 1 - 2 bar for UF/MF and 2 - 8 bar for RO/NF.
2	Flush out the product until the concentrate appears reasonably clean.
3	An alkaline rinse comes first. Recycle permeate and concentrate. Heat to the specified temperature, between 45°C and 75°C. Add the alkaline detergent, such as DIVOS 100 from **Diversey** or Ultrasil 90 from **Henkel**, typically 1%. Recycle for 30 to 60 minutes or as specified by the supplier. Check pH carefully.
4	Flush out with clean water, e.g. tap water.
5	An acid rinse is second. Recycle permeate and concentrate and heat to the specified temperature between 45°C to 75°C. Add the acid detergent, such as DIVOS 2 from **Diversey** or Ultrasil 75 from **Henkel**, typically 1%. Recycle for 20 to 40 minutes or as specified by the supplier. Check pH carefully.
6	Flush out with clean water, e.g. tap water.
7	Then follows a second alkaline rinse. It is recommended to have an alkaline wash after an acid wash, which assists in restoring water flux and product flux. Recycle permeate and concentrate. Heat to the specified temperature between 45°C and 75°C. Add an alkaline detergent such as DIVOS 100 from **Diversey** or Ultrasil 90 from **Henkel**, typically 0.1%. Recycle for 20 to 30 minutes or as specified by the supplier. Check pH carefully.
8	Flush out with clean water, e.g. tap water.
9	Recycle permeate and concentrate. Heat to the specified temperature between 20°C and 50°C. Add a disinfectant such as Ultrasil Active from **Henkel** or Divosan Forte from **Diversey**, typically 0.1%. Recycle for 10 to 20 minutes or as specified by the cleaning agent supplier. The pressure may need to be increased to achieve a good flow of permeate which is necessary to disinfect the permeate side of the membrane system.
10	Flush out with clean water, e.g. tap water.
11	Measure the flux on tap water, the so-called water flux, at the temperature and pressure specified by the membrane manufacturer or at a temperature established for the system, commonly 25°C.

The CIP cycle for seawater desalination and water purification systems is similar but somewhat simplified. Basic chemicals are often used, such as caustic soda (NaOH) and nitric acid (HNO_3). The acidic cleaning is more important than the alkaline step, which is distinctly different from the food and dairy industry.

The necessity of steps 9 and 10 can be debated. It can be argued, that if the prior steps are performed well the membranes are already clean. However, experience shows that this may not always be the case.

At this point the membrane system should be squeaky clean. If the water flux is not reached there is an operational problem, which needs to be investigated. In the case of a problem it is often sufficient to soak a system for up to 48 hours in a neutral detergent. If the problem stems from protein deposits, add a liberal dose of a suitable protease such as papain, bromelaine or Alcalase®. Many polysaccharides can be broken down by alfa-amylase or more specialized enzymes.

It is often being debated whether alkaline-acid-alkaline or acid-alkaline sequence work better. The effect is largely product related. If the product contains reducing sugars and proteins, acid should be used first, thus minimizing the risk of a condensation reaction similar to the Maillard reaction taking place in an alkaline environment. The product of the condensation process is a reddish brown sticky deposit, which is difficult to remove from the membranes. The careful use of an oxidizer is a remedy. Alternatively, several cleaning cycles will gradually restore flux.

The appropriate pressures used during the CIP cycle are also being debated. For UF and MF systems, there is no doubt that pressure should be in the 1 to 3 bar range. For NF and RO systems it may be beneficial to keep the pressure around 10 bar, which is sufficient to ensure that the flow channels remain fully open. At lower pressure there is a risk that dirt blocking the flow channels can be kept in place by the membranes.

About cleaning chemicals

It is recommended to use formulated cleaning agents rather than basic chemicals like sodium hydroxide (NaOH) and nitric acid (HNO_3). Formulated products have better cleaning efficiency and are worth the added cost.

Simple sodium hydroxide and nitric acid or a mixed solution of nitric and phosphoric acid (H_3PO_4) may be sufficient in ample concentration and temperature.

Citric acid is surprisingly efficient in many situations having several advantages:

- It cannot be overdosed
- It is harmless to humans and the environment
- It complexes heavy metals, for instance Fe^{+3} improving cleaning significantly

Disinfection can be performed using heat or chemicals. The choice depends largely on the capability of the membrane elements installed. If the system tolerates heating to 80 °C the use of chemical can be avoided. Disinfection by heat is very efficient but somewhat costly. Commonly used chemicals for disinfection are sodium hypochlorite (NaOCl), hydrogen peroxide (H_2O_2), peracetic acid (CH_3CO_3H) and sodium bisulphate ($NaHSO_3$)

It is highly recommended to obtain information about cleaning and cleaning chemicals from companies with experience in the cleaning of membrane filtration systems.

Quality of water for CIP

Large volumes of water are used during CIP for flushing. The water can be tap water, softened tap water, RO permeate or evaporator condensate. The water should be of good quality and be low in hardness, humic acid, iron, manganese and silica.

The internal volume of a system with spiral wound membrane elements is typically 1,5 liters per square meter of membrane. When three chemical solutions and several flushings are employed a good supply of water as well as a good sewer system is mandatory.

Flushing out of product from the system calls for special attention. Low quality water and incorrect temperature may cause precipitation on the membranes and impede proper cleaning of the system.

The CIP tank

If a separate CIP tank is used it must be designed for this purpose with a slanted or conical bottom allowing complete draining, and the bottom outlet must have device to minimize vortex formation at the tank outlet.

All pipes returning CIP liquid to the tank must be submerged to avoid foam formation with spillover of foam and water and the potential for cavitation in the centrifugal pumps.

UF and MF systems require a large flow from the permeate tank to the CIP tank, preferably through a well designed overflow feature.

Heat disinfection

Disinfection of a polymer membrane system is a challenge, even for sanitary systems. Disinfection at elevated temperature is probably the most efficient method and is viewed by many as the only viable method with the advantages being that microbes cannot develop resistance to temperature and that all nooks, crannies and threads in the system are heated. Table 3-2 lists combinations of temperature and time commonly used in the food and dairy industry. Disinfection of a membrane system with polymer membranes commonly takes place at 70°C, but adequate time for the complete system to reach this temperature must be allowed, usually 20 to 30 minutes.

Table 3-2. Temperature conditions for disinfection

Temperature	Condition	Time	Designation
65°C	Wet	30 minutes	Low pasteurization
72°C	Wet	20 seconds	High pasteurization
140°C	Wet	2 seconds	UHT treatment
121°C	Wet	30 minutes	Sterilization
140°C	Dry	30 minutes	Sterilization
160°C	Dry	30 minutes	Sterilization including spores

Chemical Disinfection

Membrane filtration systems can also be 'sterilized' by chemical means. Achieving chemical sterilization has often proved to be difficult because microorganisms are very adaptable when it comes to protecting themselves and they often develop resistance, even to extremely harsh chemical environments.

Formaldehyde (CH_2O) is very effective, but the use is limited due to legislation.

Sodium hypochlorite (NaOCl) is effective but not very popular. It is a very aggressive chemical which most people prefer not to handle, and it indirectly causes pollution due to the fact that quicksilver (mercury, Hg) may be used in the manufacture of sodium hypochlorite. It can also form trihalomethane (THM) precursors, which are carcinogenic. Thin-film membranes do not, in general, tolerate sodium hypochlorite.

Ozone (O_3) is effective but expensive. It is rarely used in connection with membrane systems, since thin-film membranes are intolerant to it in almost any concentration.

Sodium hydrogen sulphite (sodium bisulphite, $NaHSO_3$) and **sodium hydrosulphite** (sodium dithionite, $Na_2S_2O_4$) are weak reducing agents which have some effect on microorganisms. They are popular because all thin-film membranes can tolerate these chemicals, but they are not very effective.

Hydrogen peroxide (H_2O_2) and **peracetic acid** (CH_3CO_3H) are used extensively in the dairy industry. Peracetic acid is an effective chemical, but thin-film membranes have limited resistance to it, thus the use of these chemicals must be strictly controlled.

Chlorine dioxide (ClO_2) can be used in connection with thin-film membranes, but only if it is free from chlorine which tends to be present in small quantities.

About Heating and cooling

Configurations with polymer membranes consist of several materials having different temperature expansion. The same is valid to a lesser degree for the array of system components. Heating and cooling of a membranes system should take this into consideration and take place at moderate rates.

Heating or cooling between ambient temperature and 50°C can take place quite rapidly.

Although most membrane manufacturers specify heating and cooling rates between 3°C and 8°C experience shows that 3°C per minute is by far the safer value.

Flushing out a system at high temperature with cold water may severely damage, for instance, a spiral wound element.

Heat disinfection of hot water sanitizable elements

A hot water sanitizable element is often referred to as HS, HWS or pHT elements. Heat disinfection can take place at 80 °C or slightly higher. The disinfection temperature is maintained for 30 minutes. Cooling can take place either using a controlled cooling cycle or by allowing the system to cool at its own pace while idle.

System storage

If a membrane system is not operating for prolonged periods of time the membranes should be protected against microbial growth and drying out.

For periods of less than a week special precautions are not normally necessary, except ensuring that the system is liquid filled at all times.

For periods up to several months the membranes can be chemically preserved in the system as follows:

1. Clean the plant
2. Flush the plant
3. Recirculate a solution of 0,1 g/l sodium meta bisulphite ($NaHSO_3$) using softened water
4. Adjust to 4,5 pH with a mineral acid, for instance hydrochloric acid (HCl) or sulfuric acid (H_2SO_4)
5. Recirculate at low pressure for 30 to 40 minutes
6. Leave the solution in the system
7. Check the strength of the solution every two weeks
8. Recirculate at low pressure for 30 to 40 minutes every two weeks

If the system is not used for a period exceeding some months it should be considered to remove the elements from the system and store them externally in a solution as mentioned above.

Part 4

Membrane Filtration

Processes

Process versus water applications

Membrane filtration can conveniently be divided into two main groups, process applications and water applications, based on their different purposes, the different elements used and the resulting different systems designs. However, the basic considerations when designing a membrane filtration system are similar for the two areas and are based on:

1. Volume
2. Flow conditions
3. Concentration factor
4. Pressure
5. Temperature

Water applications are fewer than process applications and they are easier to standardize. Process applications are many and varied, and it is impossible to describe all of them in detail as it pertains to system design and special operating conditions. The dairy industry is the oldest and largest area of process applications, and the dairy industry has been chosen in the following as being representative for process applications.

The fact that the permeate generally is the end product in water applications makes the systems design simpler than for process applications. Many special consideration complicate the system design for process applications, most importantly that the concentrate generally is the end product, that sanitary operation conditions are often required and that special consideration must be given to the cleaning regimen employed.

As described in the previous chapters, there are several possible membrane configurations, each with their own virtues and disadvantages. Describing all element configurations in process and water applications would render this book very long with some portions being redundant. Since more than 80% of all membrane used in process and water applications are spiral wound elements, this membrane configuration has been chosen to represent the membrane side of the equation.

The dairy industry

With the exception of seawater desalination and water purification, the dairy industry is the area where membrane filtration has made the largest impact on revolutionizing production methods, on providing new products, and on disposal of wastewater and other waste products. As in so many other success stories, it is partly coincidental, partly a question of timing and partly based on a concerted effort of a number of devoted individuals.

Several new membranes were developed in the 1960s and 1970s branching out from reverse osmosis (RO) into the ultrafiltration (UF) area, which was largely unknown and unexplored at the time. The mileposts were the development of polysulfone UF membranes in the early 1970s and of the polyamide thin-film composite membrane in the late 1970s. During this period the landscape of the dairy industry, and especially of the cheesemaking industry, changed vastly, going from a large number of small plants to a smaller number of larger plants by consolidation and rationalization.

Making 1 kilo of cheese requires 10 kilos of milk with 9 kilos of liquid being transformed into cheese whey, which literally had no value at the time except perhaps as a low grade animal feed. Prior to the process of plant consolidation, cheese whey was considered to be a bothersome wastewater, which was disposed of simply by leading it to the nearest stream or to the sewer. With the increased volumes from the larger plants this was no longer possible. It became obvious that other solutions had to be explored.

Like most other dairy processes, cheesemaking has as its main purpose to preserve the two most important constituents of milk, fat and protein, in a way that allows the product to be manufactured, stored and consumed at a later date. It is a curious fact that only 80% of the milk protein, the casein, is recovered in cheese. The remaining 20%, which are in fact the nutritionally most valuable protein fraction of the milk, is water soluble and escapes the cheesemaking process. This fraction, the whey protein, as the name indicates, ends up in the cheese whey, which traditionally was considered to be a wastewater with little or no value and potentially representing a disposal cost.

When membrane filtration was first evaluated by the dairy industry, two basic possibilities were investigated:

- Reverse osmosis (RO) of cheese whey with the purpose of concentrating all dissolved solids in the whey, mainly for drying and sale of the resulting product as animal feed with the RO permeate being fairly clean water representing no disposal problem.
- Ultrafiltration (UF) of cheese whey with the purpose of fractionating the whey protein and manufacturing it into a product suited for human consumption, hopefully selling at a price high enough to pay for the disposal of the remaining UF permeate, which, as a consequence of the milk sugar (lactose) content of the milk, has a biological oxygen demand (BOD) of approximately 50,000 mg/l.

Fractionation of cheese whey and marketing this product as a novelty was fairly successful and still is to this day. Egg white was considered for many years to be the ultimate nutritional protein product supplying the human body with amino acids that it cannot produce, but which are essential to human life. Egg white was assigned an index value of 100 with other food sources ranging from 40 to 90. When evaluating whey protein the result was 105, which is better than for egg white.

Whey protein isolates became an independent product very popular with athletes and other health conscious people, and for use in baby food formulations.

Soon an innovative scheme developed, suggesting that the whey protein could potentially be incorporated into the cheese. The cheese yield is largely depending on the capture of the protein fraction of the milk with the required fat being easily adjustable. The basic concept of the idea suggested that if only 80% of the milk protein was captured in the cheese, being able to incorporate the remaining 20% of the milk protein fraction would increase the cheese yield by 25%. The means was suggested to be UF of milk to a composition of the concentrate as close to that of the final cheese as possible.

This proved to be an impossible dream for most cheese types, but one stands out, feta cheese, where the concept has been employed and proven to be completely successful. The same concept has succeeded partly for other soft cheese types, but with respect to harder cheese types with less than 50% water content the deviations in composition and quality from the conventional cheesemaking process are so significant that it must be concluded that the composition and the quality of natural cheese product cannot be duplicated. This is valid for all yellow and hard cheese types.

However, the work on UF of milk led to protein standardization and preconcentration of cheese milk, procedures which are commonly used in the production of many cheese types, and this partly failed direction of development provided experience where UF concentrates with more than 50% totals solids and a significant viscosity were successfully made.

UF treatment of cheese whey continued to develop. The initial effort was directed toward making a UF concentrate with a composition as close to that of skim milk as possible. Later it changed to making whey protein isolates for general use in the human food chain, most noticeably in baby formulas where the whey protein brings the composition close to that of human mother's milk. This process resulted in a liquid product with almost 30% protein having a high viscosity.

The problem presented by the high content of lactose in the UF permeate found a solution. Many industrial processes, and particularly in the pharmaceutical industry, are based on fermentation, and eventually the UF permeate was made into a well suited substrate for many fermentation processes. This effort was aided by the emergence of the thin-film composite NF membrane in the 1990s, which allows a certain demineralization of the UF permeate and consequently a purification of the lactose fraction.

For cheese types that are heavily salted, for instance cheddar, a portion of the whey was almost useless due to the high salt content. NF turned the picture by demineralizing this fraction of the whey and enabling it to be treated in the same manner as normal cheese whey.

Most RO, UF and NF processes in the dairy industry take place at elevated temperature, mostly in the 35°C to 55°C range, but in order to ensure sanitary conditions cleaning should take place at temperatures around 70°C. It is a requirement in dairy processes that the membrane elements can withstand this temperature and the harsh cleaning agents employed. The spiral wound element soon became the membrane configuration of choice due to its price and versatility.

Other dairy applications like RO of condensate from evaporation of milk or skim milk place even higher demands on the temperature tolerance of the elements, not only during operation but during disinfection by heating up to 80°C.

With the host of applications in the dairy industry a high level of innovation with respect to further development of the spiral wound element and plant design was required. In retrospect, the developments in the dairy industry drove many other new and groundbreaking applications in other industries where special operating conditions were called for.

In the context of this book the dairy industry has been chosen as illustration of the development of the spiral wound element, the development of membrane systems operating under sanitary conditions and of special operating procedures employed in many aspects of membrane filtration.

The spiral wound element

There are several fundamental differences between water treatment and industrial applications using spiral wound elements. The most pronounced difference is that in water purification the permeate is always the product, while the concentrate is considered waste for disposal. This is also the case for some industrial applications, but more often the concentrate is the product and the permeate a waste stream, which may have some uses or just represents a disposal issue.

Another significant difference is the requirement for strictly sanitary conditions in many industrial applications, for instance in connection with food and dairy products. With the concentrate being the product, no dead zones can be tolerated in the system. In water purification there is no flow of liquid on the outside of the elements being blocked by a lip seal attached to the anti-telescoping device (ATD), resulting in a zone of stagnant water around the element. However, since the membrane is an excellent barrier for microorganisms the stagnant area is of no real importance in general water treatment, except for specialized applications, for instance water for kidney dialysis, and in some cases involving ultrapure water for the electronic industry.

While materials and the choice of patterns in the flow spacer and permeate carrier may vary, the basic design and manufacturing techniques are essentially the same for all spiral wound elements. The outer wrap and the design of the combination of the interconnector (IC) and the ATD determine, if an element meets the requirements for water purification or for sanitary industrial application.

The conventional outer wrap of an element for water purification is a layer of fiberglass reinforced plastic (FRP). The plastic component and the fiber material is applied in wet form and hardens to form a rigid shell, which assists in maintaining the shape of the element and the integrity of the flow channels during the intended use and also in preventing the phenomenon of channel forming between the membrane leaves.

Different solutions to the outer wrap issue are required in many industrial applications where sanitary conditions are required. The goal is to minimize or prevent deposits of microorganisms, particles and precipitates during operation, and of being able to remove such deposits and to sanitize the outer surface of the element during the cleaning cycle. This can only be accomplished by avoiding dead zones and allowing a portion of the feed to bypass the exterior surface of the element, thus keeping the outside of the element clean and free of microorganisms and particulate matter during operation. One solution is wrapping the element tightly with a net patterned material, which is glued or heat welded in a seam along the length of the element. A second solution is to insert the element into a prefabricated tube made of pliable plastic material with a suitable net pattern allowing a degree of feed bypass. A third solution is using a prefabricated tube of a hard plastic material with a suitable machined outside pattern, for instance grooves resembling threads, providing better control of the bypass volume.

There are a few inherent differences in the manufacturing procedure of elements used in water purification and elements used in industrial, sanitary applications. Water purification elements are taped tightly on the outside as part of the element rolling operation, and after curing of the glue holding the membrane leaves together the FRP material is applied to form a hard shell around the element. The outside diameter of a sanitary industrial element is critical and the element is not taped due to the need for trimming of the membrane leaves and feed spacer material after curing of the glue with the purpose of providing an exact diameter to fit the pressure housing. The element is re-tightened after trimming of the leaves and the feed spacer, often using rather complicated tightening machines, but it is difficult to attain the original tightness the element had immediately after the rolling procedure.

Feed Bypass

A spiral wound element must have a diameter slightly smaller than the inside diameter of the pressure housing.

In water purification applications the actual diameter of the elements is non-critical since an open annulus is allowed by design and the seal on the outer rim of the ATD prevent the feed from bypassing the elements. This results in a zone of stagnant water, which is of little or no consequence in this application. Tests have shown that this liquid is only exchanged by the feed flow through diffusion and that it may take up to one month for the liquid in the annulus to attain the same composition as that of the feed. The membrane is an excellent filter for microorganisms, and if an infection occurs, the membrane is relied upon to prevent a similar infection of the permeate which in this case always is the product.

In industrial systems the liquid treated by the spiral wound elements are often biologically active, for instance in the food and dairy industry. In many cases the concentrate is the product and the operating temperature is often dictated to coincide with the most advantageous range for microbial growth. The answer to this conundrum is a design, which allows a portion of the feed flow to bypass the element and flush all liquid touched surfaces during operation and cleaning.

The total feed bypass in sanitary industrial elements has mainly two components. The largest and most important is the flow through the annulus between the outer wrap or the shell of the element and the wall of the housing. The second component pertains to the portion of the feed volume, which to a small extent flows in and out of the feed spacer area between the membranes at the periphery of the element. The bypass is different for the different designs of elements. The basic designs are:

1. No-Wrap Elements
2. Net Wrapped Elements
3. Semi-Hard Wrap
4. Hard Shell

Hard shell elements is the most advanced design with the multiple purposes of achieving reduced bypass, better mechanical fit in the pressure housing and improved cleanability of the element. This type of element was designed and patented by **TriSep** under the name of TurboClean®.

Pressure drop and liquid velocity

Manufacturers of spiral wound elements specify a maximum allowed pressure drop over an element, usually 0,7 bar, but in a few cases up to 1 bar and also slightly higher. This translates into a certain liquid velocity over the membrane surface, which is imperative to keeping the membrane free of fouling and to maintaining a uniform and high flux rate. Some operating limitations arise from the element construction.

Using a standard 8040 element, 8 inch diameter and 40 inches long with a 30 mil 105° diamond pattern spacer as an example, the following operational limitations based on the warranty from most element manufacturers apply:

- A maximum applied pressure of 83 bar for elements for seawater desalination and 41 bar for RO water purification elements for RO and NF elements for industrial applications.
- A maximum pressure drop per element of 0,7 bar to 1,0 bar
- A maximum feed flow of approximately 16000 l/h resulting in a pressure drop of 0,7 bar per element.
- A maximum operating and cleaning temperature of 45 °C unless specified otherwise.

Most industrial process applications use a design with internal recirculation of the feed with the goal of bringing the linear liquid velocity over the membrane surface to the maximum permissible according to the guarantees provided by the element manufacturers. Calculating the highest permissible linear liquid velocity based on the maximum limits for feed volume as well as pressure drop results in a velocity of 0,4 meters per second.

Sanitary process spiral wound elements are designed to allow a bypass of feed liquid with the purpose of constantly flushing the space between the outside cylindrical surface of the element and the inside wall of the pressure housing.

Actual tests, experience and measurements show that the bypass volume for net wrapped sanitary spiral wound elements in many cases is 50% of the total feed volume and in isolated cases as high as 70%. In the case of elements featuring the TurboClean hard shell, the bypass volume is approximately 30% of the total feed volume.

The relationship between the bypass, the portion of the feed not going through the element, and the required feed volume of 16000 l/h at 0,7 bar pressure drop is typically as shown in table 4-1 for an 8 inch diameter element with a standard 30 mil feed spacer:

The additional and wasted annual energy expenditure per pressure housing using $0,15/kWh to compare the situation with an 'ideal' 10% bypass and a 50% bypass amounts to $650. Taking into consideration that the pump energy is being transformed to heat, and that the liquid in most cases must be cooled at an even higher cost, the wasted energy in terms of annual operating expense due to excessive bypass approaches the purchase price of the elements.

A side effect of the excessive bypass is that due to the commingling of the bypass volume and the concentrated product at the end of each pressure vessel, the elements must concentrate the feed to a point higher than the desired concentration in the discharge from a recirculation loop. At 50% bypass this effect amounts to a flux rate loss of 8% to 10%, which results in higher investment in equipment and lower obtainable total solids in the overall concentrate from a system.

Table 4-1. Housing, element and bypass flows (LPH)

Bypass, %	Flow to housing	Flow through the element	Bypass volume
0	16.000	16.000	0
10	17.600	16.000	1600
20	19.200	16.000	3200
30	20.800	16.000	4800
40	22.400	16.000	6400
50	24.000	16.000	8000

The strong points of the spiral wound element are numerous. Where specialized membrane configurations are typically being sold by the manufacturer to the end user, maybe with a single commissioned link in between, spiral wound elements are being represented and distributed by a multitude of business entities, among them original equipment manufacturers (OEMs), in a competitive fashion. Some of the commercial advantages of the spiral wound element are:

- A standardized product available from several manufacturers
- Interchangeable with products from other manufacturers
- Equipment available from numerous OEM companies
- Technical advice readily available for standard applications
- Competitive pricing
- Auxiliary equipment components readily available from many sources

Some of the technical advantages of the spiral wound element are as follows:

- High membrane packing density
- Small equipment footprint
- Relatively simple equipment design and construction
- Reusable pressure housings
- Relatively good cleanability
- The same basic element configuration for RO, NF, UF and RO and for a wide variety of applications

More about the spiral wound element

While the spiral wound element is the workhorse of most membrane applications today, this element configuration has some physical and mechanical limitations which must be observed in the operation of membrane filtration systems. In addition, several operating errors will result in element failure. It can sometimes be difficult to relate element failure specifically to an operating error or to an element manufacturing error causing lively discussions between the end user, the OEM and the membrane manufacturer.

The combination of liquid flow and pressure drop over the element exerts a substantial force on the end of the element, see table 4-2. This force is essentially taken up by the central tube (permeate collection tube), which is perforated to allow the permeate to flow from the membrane leaves into the tube. The central tube is normally sturdy enough to take up the force exerted. Only if the permitted feed flows are exceeded or in case of manufacturing errors will the central tube crack or break. The actual force for different elements and pressure drops are illustrated in table 4-2.

Table 4-2. Displacement force on membrane elements.

Element outer diameter, inch	Pressure drop, bar per element	Elements per housing					
		1	2	3	4	5	6
		Force on the central tube in kg					
2,5	1,0	32	63	95	1127	158	190
3,8	1,0	73	145	220	293	366	439
4,0	1,0	81	162	243	324	405	486
6,3	1,0	201	402	603	804	1006	1207
8,0	0,7	227	454	681	908	1135	1362

Since the central tube cannot budge, the hydraulic force is distributed to the entire end of the element, which consists of the edge of the membrane leaves and the flow channels with the feed spacer between the membranes leaves. The sandwich of membrane leaves and the feed spacer is more pliable than the central tube, and if anything has to give when excessive flows or pressure drops occurs it will manifest itself there.

Several other conditions can cause element failure.

It is tempting for the element manufacturer to aim at the lower end of the specification range for the outside diameter of the elements. This simplifies the manufacturing process, but may cause problems in operation in terms of feed spacer migration and channeling.

It is tempting for the end user to increase the operating pressure and flow of a system in the case of reduced capacity, which is the exact opposite of the proper course of action. If a system loses capacity, the reason for the loss must be established and corrected. If not, the condition is likely to be aggravated and cause serious operational problems in terms of element failure and associated further loss of production capacity.

The reasons for experiencing reduced capacity in a specific application in an end user's plant can be many and varied, some of which relating to the quality of the elements are outlined above. An equal responsibility should be placed on the end user for ensuring that proper operating procedures are being adhered to in his operation.

The following is not intended to place responsibility on any of the involved parties, only to describe the modes of failure, which mainly are:

- Telescoping
- Feed spacer migration
- Channeling
- Element buckling
- Blistering

These conditions are aggravated by insufficient cleaning and buildup of solids in the feed spacer of the elements and they are, to some extent, closely associated and difficult to assign to one explicit condition.

Telescoping and feed spacer migration are closely associated, although they may occur for several reasons. It is an inevitable condition for the operation of a membrane filtration system employing crossflow that it causes a pressure drop over the length of the element. With a pressure drop of up to 1 bar over the standard length, 38 or 40 inches, the pressure drop as shown in the table above results in a significant hydraulic force exerted on the feed end of the element.

The force increases with insufficient cleaning, which tends to cause blockage of a portion of the feed channels. The resulting increase in flow through the remaining open portion of the feed channels causes an excessive hydraulic force to be exerted on the end of the element with potential damage as a consequence. At the same time, the feed channels are subjected to this force and tend to be widened with channeling as the inevitable result. All of this causes element damage and result in inoperable elements.

Telescoping

In the case of telescoping the ends of the element are visibly deformed. Once experienced, this phenomenon is easily recognized.

Figure 4-1 shows the feed end of an element, where the leaves closest to the periphery are being displaced in the direction of the flow. Figure 4-2 shows the result of the membrane leaves displacement at the exit end of the element.

Telescoping is counteracted by a well constructed and strong anti-telescoping device (ATD). Many designs are available with stainless steel being a very safe and expedient choice of material allowing reuse when the elements need to be replaced. This type of ATD will hold up to high temperature and high pressure drop where polymer materials often fail.

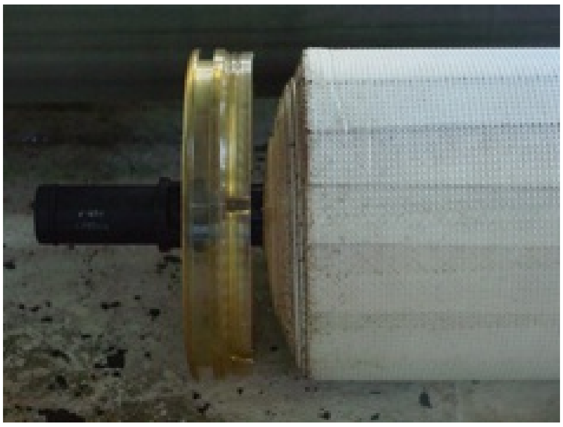


Figure 4-1. Inlet end telescoping

Figure 4-2. Exit end telescoping

Feed spacer migration

In the case of element telescoping, feed spacer migration is almost inevitable. The same hydraulic force that deforms the element tends to move the feed spacer from the feed end to the exit end, where it can be observed sticking out, sometimes several centimeters. It goes without saying that elements experiencing this problem either are or quickly will become inoperable, see figure 4-3.

This condition is aggravated by insufficient cleaning, which tends to block a portion of the feed channels and to push hard against the feed spacers in the remaining portion.

Figure 4-3. Feed spacer migration

Channeling

This condition is known unofficially as 'smilies' although there is no reason to smile when this condition is experienced, see figure 4-4.

If the elements are not rolled with sufficient tightness or if the outside diameter is not matched properly to the inside diameter of the pressure housing, the element will expand to the diameter of the housing and channels will form as shown in figure 4-4, which is a moderate example of channeling experienced in the field.

Figure 4-4. Channeling

This type of failure is fairly typical for sanitary elements, but rarely experienced in water applications using FRP wrapped elements. First of all, the FRP wrap holds the element together and, secondly, in the operation of a sanitary element a daily cleaning and sanitation occurs with fairly large temperature difference between each step of the cycle in addition to several pressure/depressurization events.

The life span of an element in a water application is most often 3 to 5 years, but 5 to 10 years is not uncommon. Elements used in process applications, where a daily cleaning cycle is required, commonly last for 9 months to 2 years, mainly based on the fairly harsh cleaning and sanitation regimen.

An element for water treatment may be cleaned 5 to 10 times it its life time. A process element for a sanitary application may be cleaned 300 – 700 times in it s life time.

Buckling

This is probably the final phase of the combination of several erroneous operational and manufacturing conditions with a collapse of the operational properties of a spiral wound element as the inevitable consequence, see figure 4-5.

With blockage of the flow channels in a spiral wound element for whatever reason, the end of the element must take up the total hydraulic force exerted on it. The result is an excessive force on the membrane leaves resulting in element buckling as shown in figure 4-5.

It is a surprising fact that the element shown in figure 4-5 was still operational, albeit not at full capacity.

Figure 4-5. Buckling

Blistering

This phenomenon will, in general, not cause a spiral wound element to fail, but blistering is not acceptable in sanitary applications in the United States. It is most likely caused by osmotic phenomena, which can occur at some points of the CIP cycle, resulting in migration and entrapment of liquid under the membrane. The result is that the membrane is locally lifted from the support layer, especially in cases where the glue has not penetrated the support layer and there is little or no adherence to the membrane, see figure 4-6.

The picture shows blistering of the side glue line of a nanofiltration element, which has been dyed with the purpose of identifying element defects. The impression of a parallel feed spacer can be observed on the membrane surface in the right side of the picture.

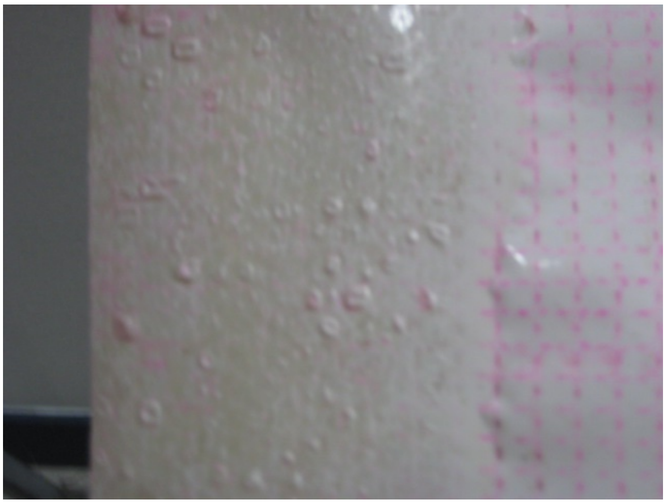


Figure 4-6. Blistering

How to avoid element damage

It is fairly easy to avoid the modes of damage of spiral wound elements described above.

- The elements must be rolled very firmly
- The ATD/IC must be well designed and support the element
- No buildup of solids can be allowed in an element due to insufficient cleaning
- Excessive feed flow and pressure drop cannot be permitted

The real problem is that the end user, the OEM and the element manufacturer must all do their part and not attempt to shift the responsibility for element failures onto the other parties.

Testing

One of the most important lessons learned during the almost half a century of availability of membrane filtration as a unit process in the treatment of numerous feeds is that testing of a process is not only beneficial, but also strictly necessary in many cases, and nowhere as much as in industrial processes.

Even when new membranes, equipment or operational parameters are introduced in well known applications like seawater desalination and water purification, testing has proven in many cases to pinpoint potential surprises, which would have been costly to correct in a full scale production plant.

But nowhere is thorough testing as strictly necessary as in the area of new industrial process applications, and even in known processes, if costly and potentially fatal surprises are to be avoided.

Full fledged testing consists of:

- Laboratory test
- Pilot test
- Small scale production test

All testing is costly in terms of time, labor and materials, but avoiding the impact of serious errors in the design and operation of a full scale production system is more than worth the cost and effort.

Laboratory testing

Numerous test cells using flat sheet membranes or small versions of the membrane configuration intended for the application are available.

The main purpose of a laboratory test is to establish the functionality of several membranes that may potentially be used in the application in question, and to establish the basic operating parameters of the most promising membrane(s) with respect to:

- Pressure
- Relative flux
- Separation characteristics

Laboratory testing suggests if the intended process is viable, but it provides little or no certain information about the feasibility of a full scale operation.

Pilot testing

The preferred membrane configuration in a format approaching the design of full scale version should, as far as possible, be used.

In the case of the spiral wound element, where the 8 inch diameter and 40 inch long element (8” element) is the standard for water and some industrial applications, a 2,5 inch diameter and 40 inch long element (2,5” element) is normally used.

Testing sanitary application, where the full scale version can be elements with 8” OD, 6,2” OD and 3,8” OD, each element 38 or 40 inch long it is common to use a 3,8” element due to the fact that a smaller sanitary membrane housing is hard to come by.

The setup is normally a batch system, see figure 4-7, with a feed pump, feed tank, membrane housing and concentrate valve, with the possibility of discharging the permeate or conducting it back to the feed tank as shown figure 4-7.

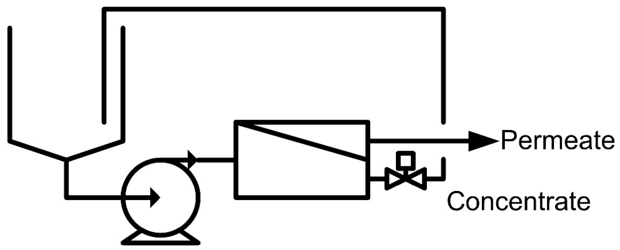


Figure 4-7. Flow sheet for laboratory and pilot testing

Only in a few industries has so much know-how and experience has been accumulated that industrial systems sometimes are sold without pilot testing. That is true in the dairy industry, but there are still so many variables, that only totally standardized processes can be predicted reasonably well.

Pilot testing a product has several objectives.

- Establishing if the process can be performed with the chosen membrane(s) with respect to concentration and/or separation
- Establishing the momentary and average permeate flux
- Determining the basics of cleaning requirements and cleaning regimen

There are some inherent pitfalls in pilot testing, which should be avoided.

1. **Test time**

   One of the most common errors is to accept the results of short time testing. An industrial system often operates 24 hours per day, and a representative pilot test should reflect that.

2. **Fouling**

   An industrial system treats a large volume of feed between cleanings. The material(s) causing fouling on the membranes and in the system may be present only in small concentrations, and the effect in terms of reduced system performance may be observed only after several hours of operation. Likewise, microbial growth is detectable only after several hours of operation and then increases exponentially.

3. **Operation**

   A pilot test begins with recycling of permeate and concentrate with the objective of conditioning the membrane and achieving a steady state condition in the system, typically between 20 minutes and 1 hour. The results are useless if the test is carried out without having reached a steady state condition.

4. **Volume**

   As mentioned, industrial systems process large volumes. If the volume used in a pilot test is small, only insignificant fouling can occur, which is, most likely, not representative for a production situation. In the same way, the observed permeate flux will be excessive and not representative for a full scale system.

5. **Feed**

Pilot testing should take place *in situ*, that is at the location where the feed is generated and/or where the production plant will be located, which ensures that fresh or typical feed is available. If the feed is stored or transported for any length of time it may change in some respect important to the results of the pilot test, for instance due to precipitation or microbial growth.

6. Data

As many data should be recorded as often as possible during a pilot test, more than are normally recorded in a production plant. This will assist in a better evaluation, also for parameters that were not thought to be important when the pilot test was designed and performed.

As a general rule, it is possible to obtain good flux data and information about the composition of the permeate and concentrate from pilot testing.

It is rarely possible to obtain good information about cleaning and disinfection. Suppliers of cleaning agents may be able to contribute with know-how about cleaning in the application in question from their accumulated experience in different industries.

Small scale production test

In the cases of large production systems, very costly production systems or processes that are essential maybe to the total operation of an entirely production plant, small scale production testing should be performed. This is equally true for water systems where a unique set of challenges can be foreseen, and for new industrial processes, where membrane filtration is a smaller part of the total production.

It is common to use the smallest possible version of the intended design for the production system. In the case of a single pass system with a 2:1 array, two membrane housing in the first stage and one in the last stage, with a pump that will be usable for other purposes can be designed. In the case of an intended multistage recirculation system, two recirculation loops each with one or two membrane housings should be used.

System design

Membrane housings are available in several materials and designs. Viewing the materials issue there are two main groups, polymers and metal. The material used for polymer housings is almost exclusively fiberglass reinforced plastic (FRP). The material for housing in metal is almost synonymous with stainless steel, although for instance titanium is used in a few cases for treatment of highly saline or acidic feeds.

The basic design of polymer housings has been almost unchanged for more than 30 years. It functions well for seawater desalination and water purification, but it entails several problems when used for other purposes than water applications. Most polymer housings have feed entry and concentrate exit going through non-centered ports in the end caps of the housings with the permeate exiting through a port in the center of the end cap. More lately it is being attempted to manufacture polymer housings with feed and concentrate side ports, similar to the design developed for industrial applications in general and for the dairy industry in particular. The basic design of polymer housings does neither allow sanitary operation nor adequate cleaning for food and dairy applications, see table 4-3.

The stainless steel housings were originally made exclusively for dairy use and they are designed with side ports as standard. Stainless steel tubes are available in a number of standard diameters, which largely determined the diameter of sanitary elements being 3,8, 4,3, 5,8, 6,3, 8,0 and 8,3 inches. The diameters originated in the United States and are therefore in US measurements. FRP housings can be made to any desired diameter with 2,5, 4,0, 8,0 16,0 and 18,0 inches being the most common.

Table 4-3. Housings comparison		
Parameter	Glass fiber	Stainless Steel
Pressure	Up to 200 bar	Rarely above 80 bar
Temperature	Up to 50°C	Up to 90°C
Side port entry	Available but not common	Standard
End cap entry	Standard	Non-standard
Sanitary	No	Possible
Price	Price = X	Price = 1,5X to 2X
2,5", 4,0", 8,0" for water	Standard	(Not used)
3,8", 5,8", 6,3", 8,0" for dairy	Not available	Dairy standard
6,0"	Military standard	(Not used)
4,3", 8,3"	Not available	Koch dairy standard

Stainless steel housings should be electro-polished on the inside to facilitate element replacement. A few stainless steel housings are designed similarly to FRP housings, which makes it difficult to remove the end caps.

The larger 16 and 18 inch diameter elements and housings are not considered to be standard. 16 inch diameter elements are gaining market share and may become a standard. 18 inch diameter elements were manufactured exclusive by Koch Membrane Systems but have been withdrawn from the market.

As mentioned, side ports are standard for stainless steel housings in two designs, the 4 port style, which uses the housing as a building block with no external product manifold, and the 2 port design, which requires an arrangement with external manifolds. Most systems are built with external manifolds.

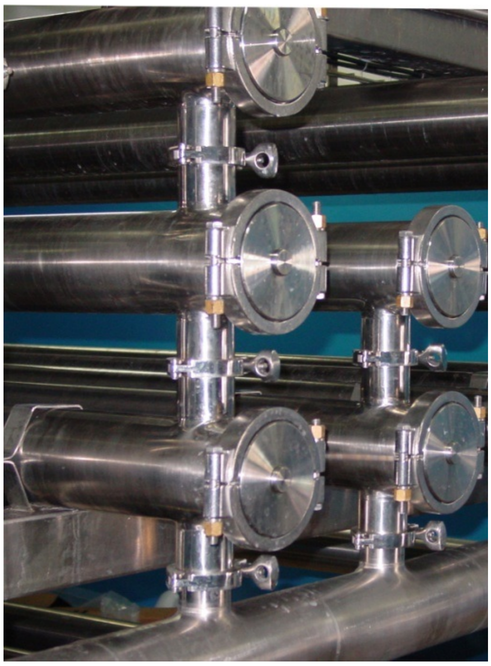


Figure 4-8. Sanitary plants, left with 2-port housings; right with 2 and 4-port housings.

The main advantage of side entry is that it allows for the high flow needed in sanitary systems.

The dimensions of sanitary elements and housings for them are not logically standardized, which makes it complicated to change element brand. Only elements strictly for standard applications are approaching this point. Although the diameters are fairly standardized, sanitary elements of the same diameter come in different lengths to accommodate custom built or older housings. This incompatibility issue sometimes creates problems for the users and the housing manufacturers.

4 side ports

2 side ports

End feed

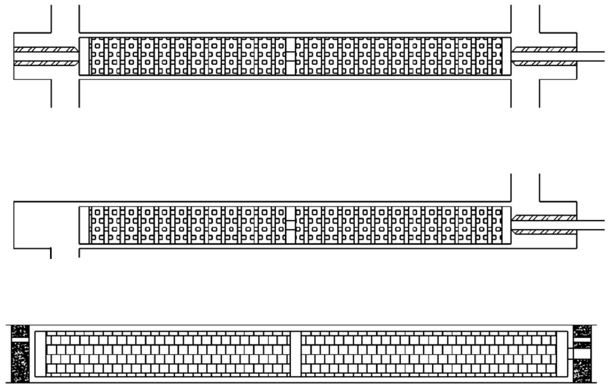


Figure 4-9. Different pressure housings

System design considerations

When it comes to designing and dimensioning a membrane filtration system several conditions must be taken into consideration. Projection programs are routinely supplied by the membrane element manufacturers for standard water applications, but in spite of the fact that the dairy industry has used membrane filtration for decades no such aid is generally available in the dairy industry, the main reason being that even small differences in the composition of feeds and manufacturing procedures may result in different sets of operating parameters for the system. As mentioned elsewhere, when designing a membrane filtration system consideration must be given to:

- Volume
- Flow conditions
- Concentration factor
- Pressure
- Temperature

The first consideration is the volume to be treated in relation to the concentration factor. Based on experienced values or values determined experimentally in pilot testing for the flux rate of the application, the necessary membrane area is calculated.

The next decision is choosing a suitable element design with respect to membrane area, diameter and length. This determines the number of elements required for the application.

The process employed, RO, NF, UF or MF, influences the design in several respects, which will be discussed in the following.

Single pass or recirculation design

The basic membrane technologies have different flux rates:

- RO – low
- NF – low
- UF – moderate

- MF - high

The required concentration ratio determines how much permeate will be removed from the feed and how much concentrate exits the plant, which again determines the flow velocity in the last element in a single pass, one stage design, whereas any desired flow velocity can be achieved in a recirculation design.

As a general rule, 50% permeate removal can be sustained in a one stage single pass system treating water. If water recovery, for instance in brackish water and wastewater applications are important, a single pass design with two stages can be used allowing approximately 75% water recovery. The permeate removal in a design with multiple recirculation loops is by design lower, typically about 10%. Since permeate removal and cross flow is not related in this design it renders permeate removal considerations superfluous.

Process applications generally work with higher permeate recovery than water systems, and the recirculation design is the preferred option for process applications.

Flow conditions

The manufacturers of spiral wound elements provide a maximum allowable pressure drop per element. This ensures that the elements are not subjected to an excessive hydraulic forces, which can damage the elements during operation or cleaning. It also limits the flow velocity over the membrane surface, which assists in keeping the membrane free of fouling and prolonging the periods between cleaning. With the purpose of limiting fouling it is advantageous to operate as close to the permitted pressure drop as possible.

Elements for water applications are equipped with a peripheral seal, which effectively blocks flow through the annulus between the outside of the element and the wall of the pressure vessel. In other words, the entire volume of the feed to a pressure housing has to pass through the elements in water applications.

A certain bypass of the feed flow between the outside of the element and the wall of the pressure vessel is allowed by design for sanitary applications with the purpose of keeping this area of the system clean during operation and being able to clean and sterilize it during CIP. The means to accomplish this is various designs of the outer wrap of the element allowing different degrees of bypass. Another factor, essentially outside of the control of the system designer, determining the volume of the bypass is the tolerance of the element diameter and the internal diameter of the pressure housing.

When designing a process system with sanitary elements, the bypass and the flow through the element providing the optimal liquid velocity must be added up to provide the feed flow to the system. As has been shown in a previous chapter, the actual feed flow may be significantly higher than that of the ideal feed flow in some situations.

Concentration factor

One contributing condition to determining the system design is the concentration factor or the permeate recovery rate, which are to some degree synonymous. The concentration factor is typically used when the concentrate is the product and permeate recovery when the permeate is the product.

In seawater desalination systems the osmotic pressure increases rapidly from the feed end to the concentrate exit, plus the net driving pressure is relatively high. 40% to 45% permeate recovery is technically and economically the optimum resulting in a concentration factor slightly below 2:1. The preferred design for seawater desalination systems is one stage single pass system, although one company, **GrahamTek**, promotes a 2 stage single pass system providing better overall performance than most other designs.

For membrane filtration of most waters other than seawater and in reuse of secondary treated wastewater 2 stage single pass systems with one feed pump are generally used having half as much membrane area in the second stage than in the first stage.

The concentration factor in most process systems, and certainly for most dairy systems, are in the range of 4:1 and up to 20:1, with the latter representing UF systems for whey treatment with diafiltration. Membrane filtration systems with a concentration factor of higher than approximately 3:1 favors recirculation systems with a number of recirculation loops commensurate with the total permeate removal.

Pressure

Membrane filtration is a process driven by the effective pressure difference between the concentrate side and the permeate side of the membrane, called net driving pressure (NDP), which should not be confused with trans-membrane pressure (TMP). It is easy to determine the TMP. NDP has several components and is more difficult to pinpoint, see figure A1. TMP is:

$$TMP = (PresF + PresC)/2 - PresP$$

Using ¶ as symbol for osmotic pressure NDP can be calculated as:

$$NDP = (PresF + PresC) / 2 – (¶_{feed} + ¶_{concentrate})/2 – PresP + ¶_{permeate} .$$

It can be complicated to accurately determine the osmotic pressure.

The NDP is different for the various membrane filtration applications:

- RO of seawater – approx. 30 bar
- RO of water and wastewater – 8 to 15 bar
- NF – approx. 10 bar
- UF – less than 5 bar
- MF – 0,3 to 3 bar

The feed to be treated may contribute to the resulting operating pressure in two ways. In RO applications, where salt rejection is the objective the feed has a certain osmotic pressure, which must be added in order to arrive at a realistic operating pressure as shown in the formula.

The same is the case for NF applications where the objective is to concentrate or purify sugar, which is rejected to the membrane. In situations where the concentrate has significant viscosity this factor will also add to the required operating pressure necessary to make the membrane perform at its most efficient.

The operating pressure is a technical problem only in seawater applications, where it typically is at or close to 70 bar.

Pressure as such is not a limitation for spiral wound element, with seawater elements tolerating up to 90 bar. This is actually slightly above the recommended and guaranteed limit for standard FRP pressure housings. If stainless steel pressure housings are used, 40 bar is the upper limitation for the operating pressure.

The following list provides examples of the operating pressure, which is close to the TMP for some common applications:

- RO of seawater – 60 to 80 bar
- RO of water and wastewater – 15 to 40 bar
- RO in dairy applications – 25 to 35 bar
- NF of seawater – approximately 30 bar
- NF in dairy applications – 20 to 30 bar
- UF in dairy applications – 2 to 7 bar
- UF in general – 1 to 5 bar
- MF – 0,3 to 3 bar

Elements per housing

With the total membrane area for a system calculated and the basic design determined, 1 stage single pass, 2 stage single pass or a recirculation system, based on the nature of the application, the main remaining consideration is the number of elements per pressure housing. One set of considerations is valid for RO and NF applications, while the system design for UF and MF applications follows different rules.

It was said earlier that the pressure drop over a spiral wound element according to the manufacturer should not exceed 0,7 bar. In a few cases a higher pressure drop is used in the dairy industry and for other process applications based on the general element construction and on the thickness of the feed spacer used. In some cases 1,0 bar pressure drop per element is permissible and in rare cases 1,2 bar.

In RO seawater desalination the average osmotic pressure in the concentrate is approximately 40 bar at 45% permeate recovery, with a required NDP of 30 bar, resulting in an operating pressure of approximately 70 bar. The pressure drop in the system, even with a large number of elements in series is insignificant compared to the operating pressure. Consequently the number of elements per pressure is chosen as high as practically possible, which is, more or less the practical limit for manufacturing of FRP pressure vessels. The maximum number of elements per pressure vessels for seawater desalination is 8, resulting in a system pressure drop of not more than 5,6 bar, which is less than 10% of the operating pressure and the average NDP is hardly affected.

Viewing a situation for RO purification of brackish water with 2 bar osmotic pressure in the feed, 75% permeate recovery and a required NDP of 10 bar, the operating pressure will be approximately 15 bar. The pressure drop over each element corresponds to 4.6% of the operating pressure with the following result:

- 8 elements per housing – 38% or the operating pressure
- 6 elements per housing – 28% of the operating pressure
- 4 elements per housing – 17% of the operating pressure

Assuming that the operating conditions for the first element in a housing were chosen to fall as close to the specifications for the element as possible, the percentages above designate the deviations from the specified performance in terms of flux rate with an associated deterioration of the specified salt rejection. Consequently, 4 elements per housing is the technically best solution, but other conditions, mainly economical, have made 6 elements per housing the most common design for this application.

NF pure water applications follow the consideration stated in the point above.

When it comes to RO and NF of cheese whey with a high content of milk sugar (lactose) and an associated relatively high osmotic pressure, a solution with 4, 5, or 6 elements per housing can be employed viewed from a purely technical standpoint. However, the solution of 4 elements per housing is more commonly used in the dairy industry.

Entering the area of UF applications the conditions described above become even more pronounced.

As an example, the best NDP in an application for UF of cheese whey has been determined to be approximately 4 bar and the design is a recirculation system with parallel element housings in multiple recirculation loops, where the booster pump in each loop compensates for the pressure drop over the pressure housings. With a pressure drop of 1,0 bar per element the pressure drop over a housing and the NDP at the exit of the housing with different numbers of elements will be as shown in table 4-5.

The sum of the feed line pressure and the booster pressure should add up to 6 bar, and the elements should operate as close to this pressure as possible, with the purpose of maximizing the flux rate of the system, since the flux in this pressure range is largely proportional to the NDP.

Table 4-4. Pressure drop and TMP, at 6 bar inlet pressure.

No. of elements	TMP at inlet	TMP at exit
1	6,0	5,0
2	5,0	4,0
3	4,0	3,0
4	3,0	2,0

The conclusions are:

- A high number of elements per housing results in higher pressure drop, lower average TMP and lower flux, lower capital cost and lower cross flow.
- A low number of elements per housing means lower pressure drop, higher TMP, higher flux, higher capital cost and higher cross flow.

In other words, a compromise must be decided on to achieve satisfactory operating conditions.

In real life situations four (recommended) to six elements per housing is used in RO and NF. In UF applications three elements is recommended but four is sometimes used, the latter sometimes resulting in over-fluxing of the first element.

MF for water applications can be performed at a low 0,3 bar NDP, while process applications require up to 2 bar NDP. With the pressure drop over a 40 inch long spiral wound element being up to 1,0 bar, the use of standard dimension spiral wound MF elements for process applications is problematic and spiral wound MF elements are few and far between, especially since other MF element configurations offer different and much more optimal operating conditions.

The spiral wound element configuration with MF membranes has been successfully adapted to seawater pretreatment in a dead ended operating mode, but other configurations are far more voluminous in this and other water applications. One MF element manufacturer, **Parker Hannifin**, offers spiral wound elements shorter than the standard 40 inch length, obviously with the purpose of alleviating the decreasing NDP over the element.

Housings per recirculation loop

The number of membrane housings in each recirculation loop is largely determined by the capacity and availability of suitable booster/recirculation pumps and the required capacity of the system. As mentioned previously, it is common to experience a 50% bypass of the feed to a housing, and this number can be even higher in case of the internal diameter of the housing falling in the high end of the specification range and the outside diameter of the elements falling in the low range.

The commonly used type of centrifugal booster has a very flat pump characteristic, which more or less makes it self-adjusting with respect to volume, but the number of housings fed by the pump must be chosen to fall comfortably within the pressure and volume range of the pump, preferably with capacity to spare.

Recirculation loops per system

A recirculation loop in a multistage system essentially consists of a number of membrane housings arranged in parallel, a booster/recirculation pump and the necessary piping to connect the loop to the feed line, which is pressurized by a feed pipe common for all the loops.
The booster pump increases the pressure in the feed line by the pressure drop over the membrane housings.

The recirculation loop is repeated and a system can consist of any number of recirculation loops. In figure 4-10 the system contains two recirculation loops. Control of the system is essentially performed by a regulating valve in the exit end of the feed line (not shown).

A batch system is the most efficient system with respect to membrane flux because the membrane operates on the ideal flux curve. This is the yellow curve in figure 4-11.

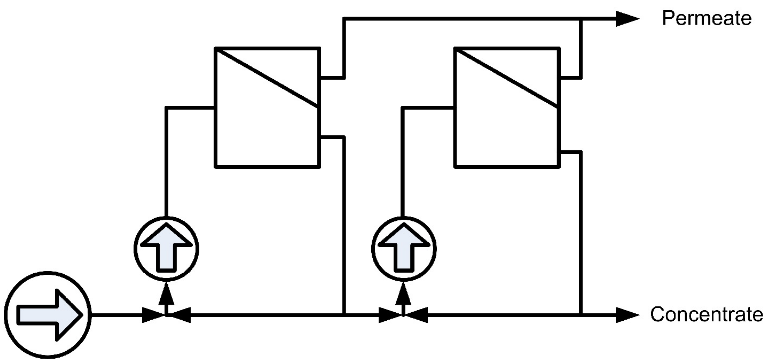


Figure 4-10. Two loop membrane system

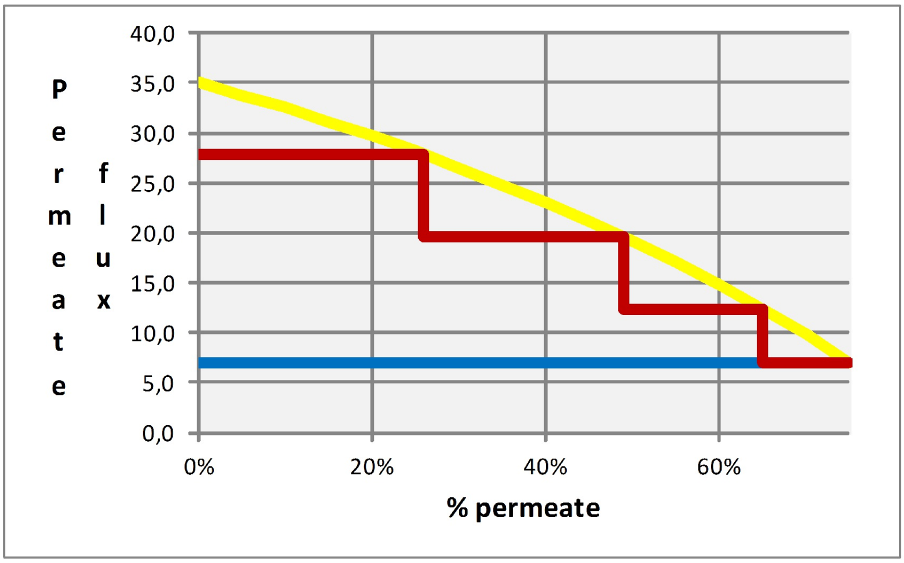
The least efficient system is a 1 loop recirculation system, represented by the blue line in the figure, because the system always operates at a concentration corresponding to the composition of the end product. The flux point is the intersection between the yellow curve for the batch system and the blue line.

The efficiency of the batch system is proportional to the area under the yellow curve. The much smaller efficiency of the 1 loop recirculation system is proportional to the area under the blue line, with the efficiency loss represented as the area between the yellow curve and the blue line.

The efficiency in terms of average membrane flux increases by introducing several loops into a recirculation system. The red step curve represents a 4 loop recirculation system with the loops operating at the intersection points with the yellow curve for the batch system and the area between the yellow and the red curves representing the loss of efficiency.

The decision with respect to the number of loops in a system is not only based on technical aspects. With the dairy industry moving from plate-and-frame and tubular membrane configurations to almost exclusively using spiral wound elements, the membrane price has been reduced by 90% over the last few decades.

In the past, it was quite common to build recirculation systems with up to 10 loops with the main purpose of gaining operational efficiency and reducing the cost of membrane replacement. With the presently much lower membrane prices, the point of compromise between operational efficiency and the capital cost of the system is 4 loops for most standard applications in the dairy industry and elsewhere.



The yellow line represents the flux development of the batch system
The red line shows that the flux in each of the 4 loops are 19, 15, 11 and 7,5 LMH
The blue line shows that the flux in a single loop system is 7,5 LMH

Figure 4-11. Flux for a batch, a 4 loop and a 1 loop system.

Part 5

Appendices

List of appendices

When writing this book some material was deemed to contain material too specialized for general use, being of a commercial nature not meeting the technical content and scope of the text although helpful to the reader, or in other ways to be of a general nature containing practical guideline instructions and advice. This material has been placed in the following appendices.

Appendix A – Definitions: A comprehensive list of terms, expressions and definitions commonly used in connection with membrane filtration.

Appendix B – Pump manufacturers: A partial list of manufacturers of pumps commonly used and accepted as components in membrane filtration systems.

Appendix C – Do not . . . : A list of common reaction to operational problems, which tend to lead to further deterioration of the performance of membrane filtration systems.

Appendix D – A and B values: An explanation of the transport mechanism for water and salts through reverse osmosis (RO) membranes.

Appendix E – Wagner units: A useful tool for evaluation an application in relation to the need for standard or special elements.

Appendix F – How to avoid TS surges on start up: A description of the best start up procedure for multi-stage recirculation ultrafiltration (UF) systems treating feeds with high content of total solids (TS).

Definitions

A-value	A peculiar but standardized unit for pure water flux. Unit: g/(cm^2*sec*bar) at 25 deg C. Be aware that the A-value is usually stated as A-value times 10^5, which is the case in the following examples. Multiply with 0,36 to get LMH at 1 bar NDP 1,02 to get GFD at 70 PSI NDP 1 to get approx. GFD at 70 PSI NDP (2% error)
Alfa. Alpha α	1 The first letter in the Greek alphabet. 2 Percent water recovery in water desalination systems.
Array	An arrangement of membrane housings with a number of parallel housings feeding (usually a smaller number) of other parallel housings.
Ash	Whatever is left after heating a material sample to 550 °C until constant weight is achieved.
ATD	Anti-Telescoping Device which prevents the leaves in a spiral wound element from being displaced due to the force of the flow of liquid.
Backflush	A process where the flow occurs from the permeate side through the membrane and lifts dirt and deposits off membrane surface lasting seconds or minutes. The liquid forced through the membrane can be permeate, clean water or water with addition of miscellaneous chemicals.
Back pulse	Back flush for a very short time (seconds or milliseconds), typically at frequent intervals.
Base line pressure	See: Pressure, feed
B-value	Salt flux. Similar to A-value. Unit [cm/sec] or written differently cm^3/(cm^2 * sec). When the density of salt is known it can be re-written to g/(h*m^2)
Beta value	Concentration polarization factor. Multiply the salt concentration in the bulk solution with the beta value to get the concentration at the membrane surface.
Blister	*(Specific for spiral wound elements).* Under special conditions liquid filled bubbles form over the glue line or at the fold reinforcement in a spiral wound module, mainly due to osmosis.
Booster flow = FlowB	Water applications: The flow exiting a stage to be re-pressurized before entering the next stage, see figure A2. Process: The flow exiting a booster pump in a recirculation loop, see fig. A3.

Booster pump	The term has two meanings. Water application: A pump increasing the pressure between stages in a single pass system, see figure A3. Process: A pump in a multistage recirculation system compensating for the pressure drop over a stage and ensuring the correct cross flow, see figure A3 and A4.
Brine	Water with high salt content, used as synonym for the concentrate in water applications.
Buckling	Occurs when excessive force is exerted on a spiral wound element and causes deformation in the longitudinal direction, an accordion effect, see picture in 'More about the spiral wound element'.
Central tube	The perforated tube around which the membrane leaves of a spiral wound element is rolled, also called a permeate tube.
Channeling	Occurs when a spiral wound element is rolled too loose, when it is subjected to frequently changing pressure and temperature, in case of ineffective cleaning leaving deposits, or with excessive annular space between the element and the wall of the pressure vessel – often a combination of these causes – resulting in enlarged space between the membrane leaves and poor flow conditions in the element. See picture in 'More about the spiral wound element'.
CIP	Cleaning-in-place, meaning cleaning a system without dismantling it.
Concentrate flow = FlowC	Several different meanings, bearing in mind that concentrate is always the liquid not going through the membrane, see figure A1. a. The flow exiting an element. b. The flow exiting a pressure housing. c. The flow exiting a stage or a recirculation loop. d. The flow exiting a membrane system (final concentrate). Also known as retentate.
Concentration	Many units are used for instance mg/l, g/l, parts per million (ppm) and percent. Although common, percent (%) is troublesome unless clearly defined. For very dilute solutions it is acceptable, but for more concentrated solutions it must be defined if the percentage is weight-weight (W/W%), volume-volume (V/V%) or a combination. Non-water soluble components, for instance fat, oil, grease and suspended solids can distort a mass balance without proper precaution.
Concentration ratio	Refers to volumetric concentration or mass concentration. Volume: FlowF/FlowC = VolF / VolC (See figure A1) Solute: (solute X in concentrate)/(solute X in feed) When the permeability of a solute is zero then Solute Concentration Ratio is equal to Volumetric Concentration Ratio.
Core tube	Central tube in spiral wound elements.
Cross flow	The volume of feed liquid flowing tangential to the membrane surface reducing concentration the risk of polarization and deposits.
Dalton	Used synonymously for molecular weight.

Dead ended operation	Operation similar to conventional filtration, either pressure or vacuum driven, mostly for microfiltration.
Dead end plug, DEP	Device plugging one end of the permeate tube of a spiral wound element, typically employed at the inlet end of the elements in a housing.
Diafiltration	Addition of water to the concentrate with the objective of reducing the content of one or more low molecular weight solutes. Examples: Lactose in whey and cephalosporin in fermentation broth.
FlowD	The volume of water added during diafiltration.
Fast forward flush	Cleaning mode of a dead-ended operated system. The concentrate valve is opened and an influx of feed flushes concentrate and deposits out for a short period of time. Used in tubular and inside-out fiber systems
Feed-and-bleed	Another name for a multistage recycling system.
Filtrate	The same as permeate.
Flow, feed = FlowF	The volume of feed to a membrane system.
Flow, booster = FlowB	This term is used almost exclusively in a multistage recirculation plant, referring to the exit flow out of a booster/recirculation pump, see figure A1.
Flow, recirculation = FlowR	FlowR is the volume of concentrate returned to the suction side of the feed pump in a single pass system or to the recirculation pump in a multistage recirculation system, see figures A1 and A5.
Flux, instantaneous and average	The instantaneous flux is the flux at any given moment. Average flux is the average flux from the process is started until any point in the filtration process. Instantaneous flux can be measured, while average flux is calculated.
Flux, unit	Mostly Volume of permeate per unit area and time (see A-value). LMH = liter per m^2 and hour liter/(hour*m^2) GFD = US GALLONS per ft^2 and day US Gallon/(day*ft^2) LMH = GFD * 1.7 Flux is sometimes used synonymously for permeate flow.
Flux, water	The flux of water through a membrane under well-defined conditions. Water flux has a definite meaning in reverse osmosis and nanofiltration, while only indicative for ultrafiltration and of little use for microfiltration. It is commonly used to verify that a membrane system is clean and performing well.
Formula mass	See Molecular Weight.
Fouling	Common denominator for materials accumulating on the membrane surface during operation tending to reduce flux.
GFD	See Flux, unit.

Glue line	In a spiral wound element the membranes are glued together to form closed envelopes or leaves where only permeate can enter through the membrane. The membrane leaves are glued on three sides, while open to the central tube. The side glue line is exposed at the end of an element. The end glue line runs parallel to the central tube.
H-value	The resistance of permeate flow through the permeate carrier. The unit can be [BAR]*[Second]/[ml] with a typical value of 0,15. H equals 0 when there is no resistance, H equals infinite, when no permeate can flow.
Hyperfiltration	Synonymous with reverse osmosis.
Housing	The pressurized component of membrane filtration equipment holding spiral wound elements or other membrane configurations, also referred to as pressure vessel. The housing is for all practical purposes a tube with membrane elements inside.
HF	Synonymous with Reverse Osmosis.
Interconnector, IC	A device connecting two spiral wound elements allowing permeate to flow from one element to the next through the central part of the interconnector.
Inside-out	A membrane configuration with the membrane on the inside of a fiber and the permeate flowing to the outside.
Kjelddahl, nitrogen	The nitrogen content determined according to the Kjelddahl method, often used with a multiplier for specific purposes. a. N*6,25 is used to get the protein content in most industries. b. N*6,38 is used to get the protein content in the dairy industry.
Langelier index	Index for the tendency of $CaCO_3$ to precipitate and create scaling. If positive, $CaCO_3$ scaling is likely. If negative, $CaCO_3$ scaling is unlikely. See also SDSI.
Leaf	Two membranes glued together in a spiral wound element.
LMH	See Flux, unit.
Loop	A building block in a feed and bleed system consisting of, as minimum, one pump, one housing and piping, see figure A1.
MF	Microfiltration, typically 0,1 to 10 micron pore size.
mil	US and UK unit of length, 1 mil = 1/1000 inch = 0,0254 mm.
Molecular weight	A more modern expression is “Formula Mass”. Used synonymously with Dalton.
Multistage recirculation system	Also referred to as a feed and bleed system.
MW	See Molecular Weight.

MWCO	Molecular Weight Cut Off, defined as the molecular weight of a solute which is rejected 90% under test conditions. It is well defined for RO and NF, poorly defined for UF and it has no meaning for MF.
Nanofiltration	A process similar to RO, but high rejection of di- and polyvalent negative ions (anions), while the permeability for monovalent anions and most cations are high. NF membranes are characterized by rejection of NaCl and $MgSO_4$, not by pore size.
NDP	See Pressure, net driving.
NF	See Nanofiltration.
NPN	Non Protein Nitrogen. Common abbreviation for nitrogen containing solutes which do not precipitate with trichloroacetic acid.
Outside-in	A membrane configuration with the membrane on the outside of a fiber and the permeate flowing to the outside.
PEA	The Product End Adapter is a device connecting a series of spiral wound elements to the end cap of a housing allowing the permeate to exit thought a common port.
Permeability, apparent, P_{app}	Multiply the concentration of a salt, for instance NaCl, in the feed with P_{app} to get the concentration of salt in the average permeate. P_{app} is a number, which can be calculated from the membrane permeability and the volumetric concentration ratio.
Permeability, membrane	Permeability relates to dissolved solids, commonly referring to a specific solute, for instance NaCl. An RO membrane typically has between 0,5 and 2,0% permeability for NaCl.
Permeate flow, FlowP	The liquid passing through a membrane, also called filtrate or in water purification product.
Permeate carrier	The drainage layer under the membrane or membrane sandwich conducting the permeate to the exit of the system.
Permeate tube	See Central tube.
Pi, Π	Pressure, osmotic, the Greek letter Π.
ppm	Parts per million, mg solute per 1000 gram solution, equivalent to mg per liter (mg/l).
Pressure drop	Designated several different pressure drops in a membrane filtration system. The pressure difference from the inlet to the outlet of: a. A spiral wound element b. A housing with several spiral wound elements c. A single pass system d. A membrane configuration of any design

Pressure, feed = PresF	This expressions have several meanings: a. The pressure of feed entering a membrane system b. The exit pressure of a feed pump c. The exit pressure of a high pressure pump d. The common line pressure in multistage recirculation plant e. The entry pressure to a housing
Pressure, net driving	Net driving pressure = TMP_{av} $-\Pi_{conc.,av}$ + $\Pi_{perm.,av}$ NDP may refer to: a. The average pressure in a plant b. The average pressure in a housing c. The average pressure in an element
Pressure, osmotic	The osmotic pressure is a function of the content of salt and other low molecular weight solutes. Osmotic pressure is sometimes written with the Greek letter Π (Pi). $\Pi = f^* \, i * m * R * T$ where f is activity factor For dilute solutions Π is 1 i = number of ions by dissociation m = molality R = gas constant T = degree Kelvin
Pressure, trans-membrane, differential (TMP)	Trans Membrane Pressure is the difference between the pressure on the feed side and the permeate side of a membrane. Trans-membrane pressure (TMP) may refer to the average in a plant, in a housing and over an element.
Pressure vessel, PV	See Housing. Pressure vessel is commonly used, but housing is a better expression.
Product	An expression with many and conflicting meanings, as product may refer to the permeate, in water purification applications and to the concentrate in process applications, or to a component in either of the two streams.
Product end adapter	See PEA.
Product spacer	See Spacer.
Recovery	Water applications: The fraction of the feed becoming permeate. Process applications: The portion of a particular solute recovered.
Reject	Synonymous with concentrate.
Rejection	In water desalination the rejection of NaCl is used as a standard number to characterize a membrane. Permeability is a better value, where: Rejection = 100 - Permeability.
Retentate	Synonymous with concentrate.

RO	Abbreviation for reverse osmosis using the tightest possible membrane, in principle allowing only water to pass through, also called HF. RO membranes are characterized by rejection of NaCl and not by pore size.
Salt	Commonly meaning table salt, sodium chloride (NaCl). More widely meaning inorganic or organic solutes dissolving as ions.
SDI	Silt Density Index, which is a standardized unit characterizing the amount of suspended solids in water.
Scaling	Deposits of inorganic salts on a membrane. See Fouling.
SDSI index	Stiff-Davis Saturation Index, attempting to overcome the limitations of the Langelier index, mainly used for high salinity water.
Spacer	Also referred to as product spacer. The netting forming the gap between opposing membrane surfaces forming a well defined flow channel and assisting in creating turbulence in the flow channel.
Spacer, height	Spacers in many dimensions and heights are used. a. 30 mil is most common and standard for water treatment. b. 47 mil is less common, mainly for processes applications c. Higher spacers are used in process applications, for instance 60, 80, 100 and 120 mil.
Spacer migration	Displacement of the spacer in spiral wound elements in the direction of the feed flow.
Telescoping	Displacement of the membrane leaves in the direction of the feed flow, eventually causing element failure.
TFC, TFM	Acronyms for Thin-Film Composite Membranes.
TMP	See Pressure, Trans Membrane.
TRP	True Protein, a common abbreviation in the dairy industry designating protein precipitating with trichloroacetic acid.
TS, TDS	TS is Total Solids TDS is Total Dissolved Solids. TS is higher than TDS when suspended solids are present.
UF	Ultrafiltration. Pore size typically in the range 0,005 to 0,1 micron.
Ultra osmosis, UO	Another expression for nanofiltration.
VCR, VCF	Volumetric Concentration Ratio. Volumetric Concentration Factor. See Concentration ratio.
Vexar	Trade name for the feed spacer in spiral wound elements.
Vol	Commonly used by the author for volume.
VolC	Volume Concentrate in a batch process.

VolF	Volume of feed to be treated in a batch process.
VolP	Volume Permeate in a batch process
Volume Fraction Concentrate	Volume of concentrate divided by volume of feed, often called X.
Volumetric Concentration ratio	See Concentration ratio
Water recovery	See Recovery.
X	Se volume fraction concentrate.
Yield	See Recovery.

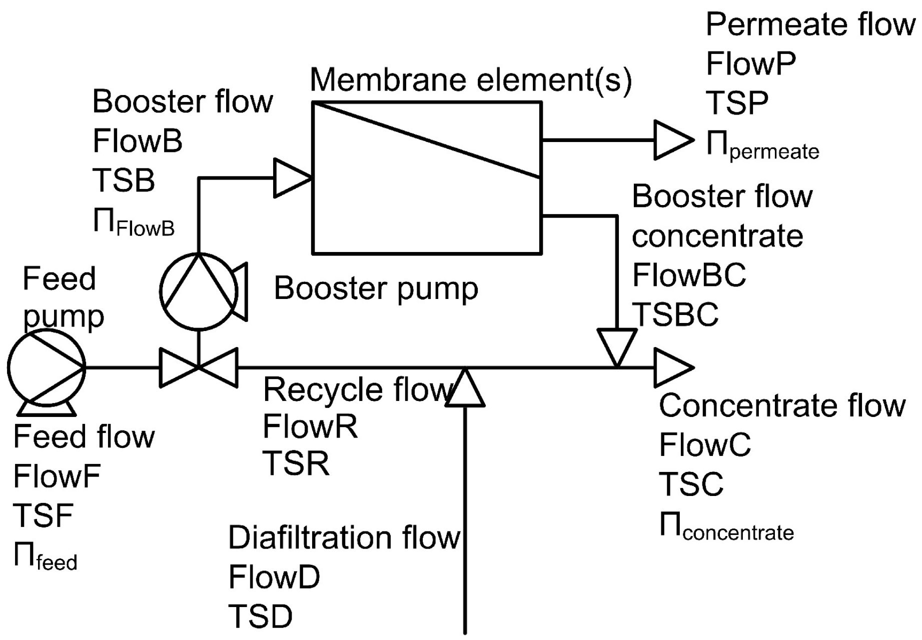


Figure A1. Nomenclature

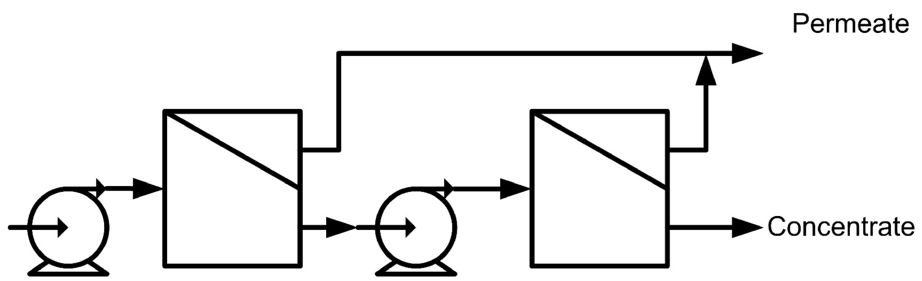


Figure A2. Single pass system with booster pump between stages

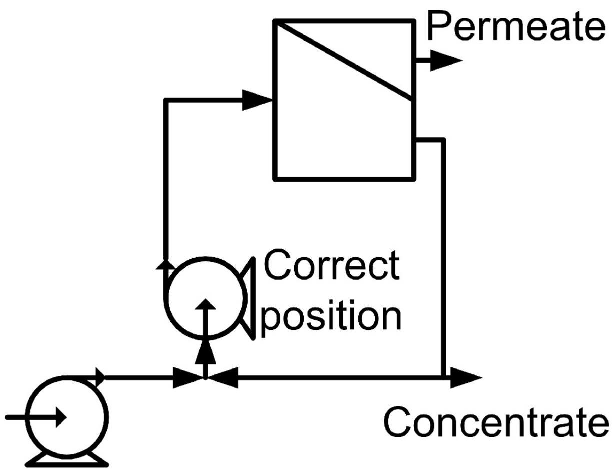


Figure A3. Correct position of booster pump

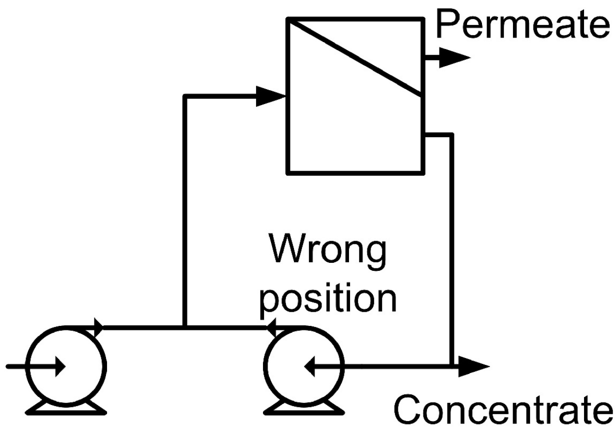


Figure A4. Incorrect position of booster pump

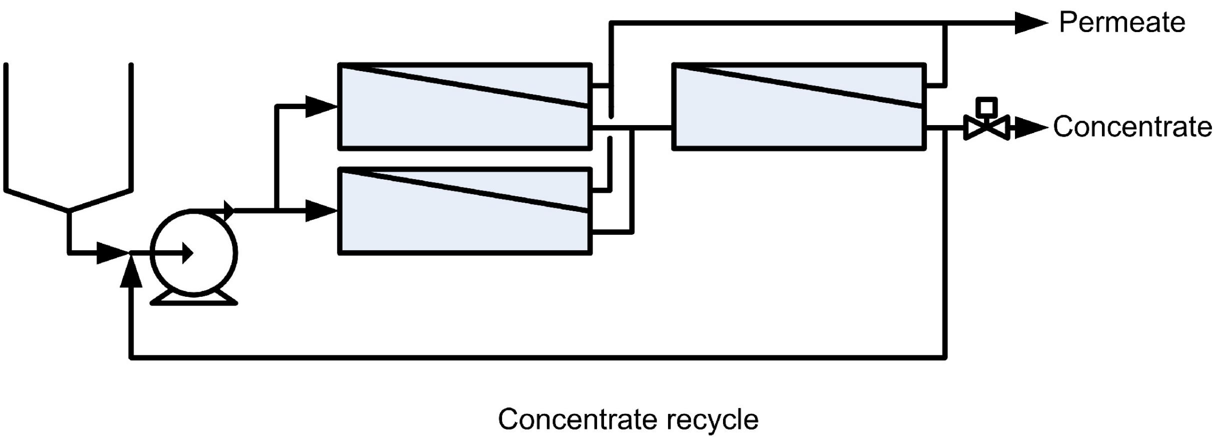


Figure A5. Single pass system with concentrate recycle

Pump manufacturers

Pumps form an essential component in the operation of membrane filtration systems. The pumps used in water treatment systems are considered to be standard pumps, while the pumps required for process applications, and especially in multistage process systems, must meet an entirely different set of operating conditions, far from standard specifications.

There are a limited number of pump suppliers with experience and know-how of membrane filtration systems and of the requirements to low and high pressure pumps used in industrial multistage membrane systems.

European pump suppliers were faced with these requirements at an early stage and developed sanitary booster pumps. These pumps tolerate an inlet pressure up to 60 bar. The same type of pump is as a three stage pump used as high pressure pump. To this day, this market segment is dominated by European companies.

A few general rules when choosing or applying a pump in a membrane filtration system:

- Always use mechanical seals. It is recommended to flush the seal with low pressure water to cool it and to wash away product coming out.
- It is highly recommended always to use pumps in stainless steel (316 or better) ensuring that corrosion is not a problem during production and during CIP.

High quality and local service are important parameters when choosing a pump. There is a large number of excellent pump manufacturers around. One that stands out is **Grundfos** (Denmark) supplying pumps used extensively in RO water treatment systems as high pressure pumps. A specialty from Grundfos is multistage pumps in Titanium.

Overview of selected pump manufacturers

The list below is not intended to be complete, nor does it imply specific recommendations of the brand and companies mentioned. It is solely based on practical experience and observations.

- Centrifugal. Sanitary. Single stage. <5 bar pressure increase. <16 bar feed pressure:
  Alfa Laval
  APV
  Hilge
  Stamp
- Centrifugal. Sanitary. Multi stage. >5 bar pressure increase. <16 bar feed pressure:
  Alfa Laval
  APV
  Stamp
- Centrifugal. Sanitary. Single stage. <5 bar pressure increase. >16 bar feed pressure:
  Alfa Laval
  APV

Stamp

- Centrifugal. Non-sanitary. Single stage. <8 bar pressure increase. <16 bar feed pressure:
  KSB
  Grundfos
  Numerous others
- Centrifugal. Non-sanitary. Single stage. 70 bar pressure increase. <16 bar feed pressure:
  Sunstrand,
  Rotojet
- Centrifugal. Non-sanitary. Multi stage. >5 bar pressure increase. <16 bar feed pressure:
  Grundfos
  Lowarra
  KSB
  Numerous others
- Positive displacement. Sanitary. 60 bar pressure increase:
  Rannie
  Gaulin.
- Positive displacement (piston), non-sanitary, 60 bar pressure increase (Marginally suitable for membrane systems, but used due to low price):
  Speck
  Numerous others
- Positive displacement (diaphragm). Non-sanitary. 60 bar pressure increase.
  Wanner

External or submerged motor

An external motor is standard and it is the chosen type used in the vast majority of the membrane filtration systems.

The disadvantage is that it generates noise and heat.

The advantage is that it is totally standardized and easy to service.

A submerged motor is non-standard. However, it is used in bore hole pumps. If mounted inside a pipe it can be used as a high pressure and booster pump.

The disadvantages are that it is not standardized, that it tolerates only relatively low product temperature and that service is complicated.

The advantages are that it is very quiet and automatically cooled by the product.

Do not ……

The membrane is the essential component, which determines the performance of a membrane filtration system with respect to separation and flux rate. Attempting to force a membrane to function outside of its performance envelope always leads to deterioration of the overall system performance, immediately or later. The instinctive reaction of an operator to deviations from the expected system performance often aggravates the situation. The following is a list of situations with advice on what not to do.

Do not:

- - force a membrane filtration system to deliver excessive permeate flux, since it will always increase membrane fouling.
  The flux for spiral wound elements should in general not exceed 35 LMH.
  The flux in most other systems should not exceed 50 to 70 LMH
  The flux for ceramic membranes and the CR filter may in rare cases exceed 500 LMH.
- - believe promises of higher than 100 LMH permeate flux for process applications. As far as it is known, only the CR filter from Metso and a few systems with ceramic membranes have consistently exceeded 100 LMH flux rate without frequent cleaning.
- - exceed limits set by membrane manufacturer. Certain rules can be broken, but it requires a lot of experience, insight or knowledge.
- - expect to exceed the total solid levels in the following applications:

Solute	Example
Monosaccharide	15% glucose
Disaccharide	25% ordinary sugar
Polysaccharide	4% Xantan
Low MW ionic solute	5% NaCl
Di-di-valent solute	15% $NiSO_4$
Protein	25% egg white or whey protein
Milk concentrate	42%, for feta cheese production
Oil emulsion	70% mineral oil in water

  The literature often quotes values higher than stated here, which may be possible in laboratory tests or for short periods of time for industrial applications, but most of this kind of information borders on fiction.
- - expect or ask for unreasonable performance guarantees. A guarantee is a kind of insurance and insurance costs money. It is better to perform thorough pilot testing and work with the membrane and system supplier to optimize the design and operation of a membrane filtration system.
  When negotiating a warranty it should be kept in mind that:
  - the product may change in the future
  - the plant operator is the most knowledgeable concerning the product

A-value and B-value

The A-value and B-value are used for theoretical calculations, mostly by membrane scientists and in connection with seawater desalination and water purification.

A-value

The A-value is a constant used to characterize the flux of water through a membrane in a standardized manner. The A-value makes it possible to compare the water flux of widely varying membrane types.

The A-value has the unit 10^{-5} [gram/(cm²*second*bar)]. The conversion factor from [gram/(cm²*second*bar)] to [liter/(m²*hour*bar)] is 36000. Notice the constant 10^{-5} in front of the A-value, which is usually given with this constant included: 10^{-5} * 36000 = 0,36

Therefore:

[liter/(m²*hour*bar)]	= 0,36 * [gram / (cm²*second*bar)] or
LMH/bar	= 0,36 * A-value
GFD at 70 PSI	= 1,02 * A-value (* 10^5) or simply ≈ A-value (* 10^5)

B-value

Similar to the A-value, the B-value is a constant describing the flow of salt (solute) through the membrane. It describes the mass of salt transferred through the membrane per unit of membrane area and per unit of concentration difference. The B-value is independent of pressure.

The unit of the B-Value is [cm/sec] or written differently $cm^3/(cm^2$ * sec). When the density of the salt is known, multiply the B-value with density and get a B-value with the unit gram/(cm^2 * sec)

General

The A-value describes flow water through the membrane, which is a pressure driven process with the flux rate being largely proportional to the net driving pressure (NDP) for RO and NF processes. Since the transport of salt through the membrane is a diffusion process the B-value is independent of pressure.

A consequence is that in an idle RO plant, if not properly flushed, the concentration of salt will eventually equalize to be the same on the two sides of the membrane.

Another consequence is that when estimating or calculating the concentration of salt in the permeate, the diffusion of salt is constant, but the water transport is pressure dependent. If the NDP can be doubled and the flux rate increased correspondingly, the salt content in the permeate will decrease to half.

It is important to find the optimal operating point for a membrane filtration system to get the best performance of the membrane with respect to rejection characteristics.

Wagner units

The Wagner unit, named after one of the authors of this book, is a number used to evaluate the stress on a membrane or a membrane filtration system with respect to temperature and pressure. The Wagner unit is valid for polymer membranes only and primarily valid for spiral wound elements.

Background

The original version of the spiral wound element with thin-film composite membranes has the following specification:

- Temperature: Max. 45°C
- Pressure: Max. 41 bar

In spite of this clear set of specifications, operation at all combinations of temperature and pressure is not possible because they affect the membrane and the membrane configuration in different ways for instance, operation at 45°C and at 41 bar is not possible. This is due to the fact that temperature influences the membrane more than pressure.

Spiral wound elements were developed for seawater desalination at an early stage with the following specifications:

- Temperature: Max. 45°C
- Pressure: Max. 82 bar

Again, operation at the combination of 45°C and 82 bar may not be possible, but the seawater desalination element became the prototype for high pressure spiral wound elements.

In the area of process applications, the requirements of the dairy industry were satisfied with respect to operating temperatures of approximately 50°C. Other process applications require even higher operating and/or cleaning temperatures, and a new class of elements was developed with the following approximate specifications:

- Temperature: Max. 80°C
- Pressure: Max. 41 bar

Here the combination of temperature and pressure becomes even more tenuous, and the element specifications only provide a guideline to the viability of a process application.

The Wagner unit is intended to predict the viability of an application and to assist in selecting the right type of element.

Definition

The basis of the Wagner unit is pressure measured in bar multiplied with the temperature in °C (bar*°C). The relationship between pressure, temperature and Wagner Units (Wu) is provided in table 5-1 for some common applications.

Table E1. Sample Wagner units			
	Common operating pressure, bar	Common operating temperature, °C	Wagner Units
Tap water applications	10	15	150
Standard water applications	15	Approx. 30	450
RO of cheese whey	30	50	1500
Seawater desalination	70	30	2100
Separation of mono and di-saccharides	40	60	2400

Based on experience from known applications and plants in actual operation the Wagner unit can be used to specify four sets of operating conditions.

- Standard conditions: Up to 1200 Wagner units and up to 50°C.
- Medium severe conditions: Up to 2000 Wagner units and up to 50°C.
- Severe conditions: Up to 2000 Wagner units and up to 80°C.
- Extreme conditions: Above 2000 Wagner units and up to 80°C.

Other parameters, like pH and the presence of oxidizing agents are in this context considered to be conditions relating to the chemical resistance of the membrane in question.

The Wagner unit is useful in evaluating RO and NF applications. The lower pressure means that the Wagner units never get above 1200 in UF and MF.

Figure E1 shows the general specification ranges for the three main groups of commercially available elements.

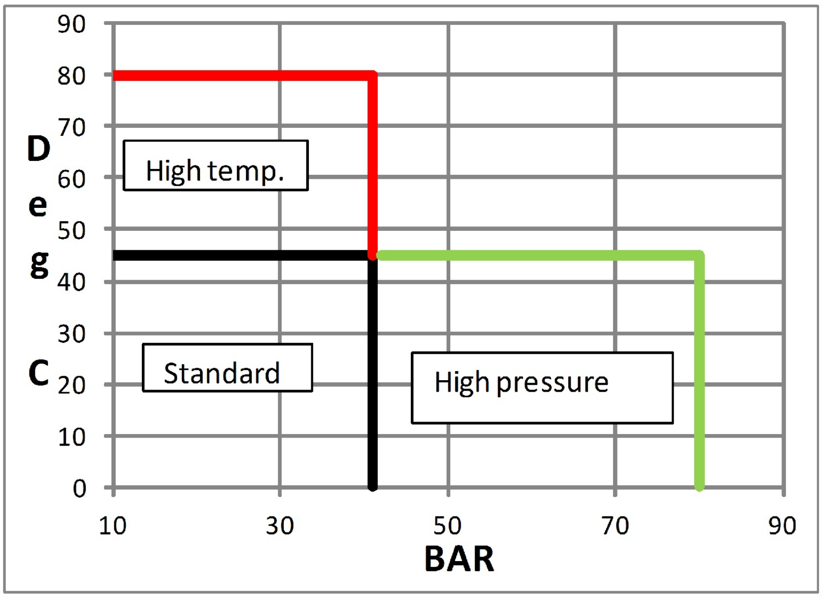


Figure E1. Standard element specifications

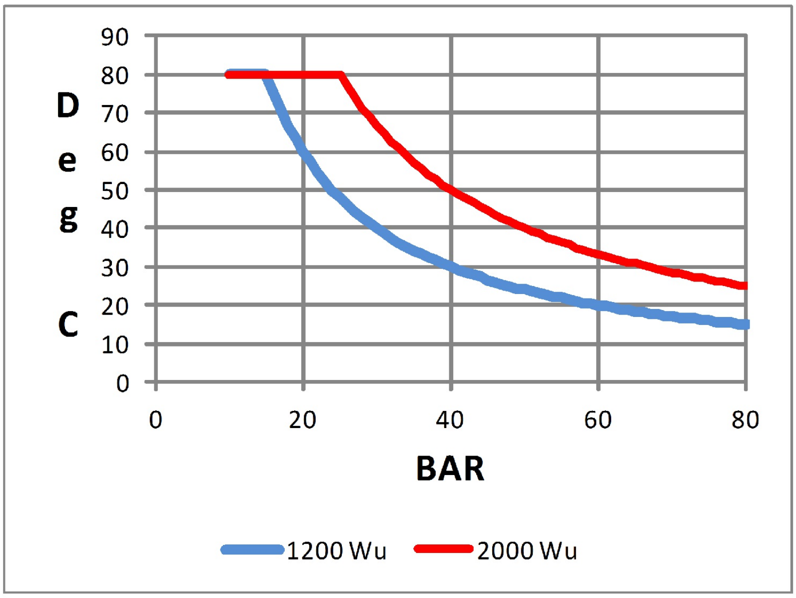


Figure E2. Wagner units

Figure E2 shows the boundaries for operation as defined by the Wagner units.

In figure E3 the two previously shown figures are combined.

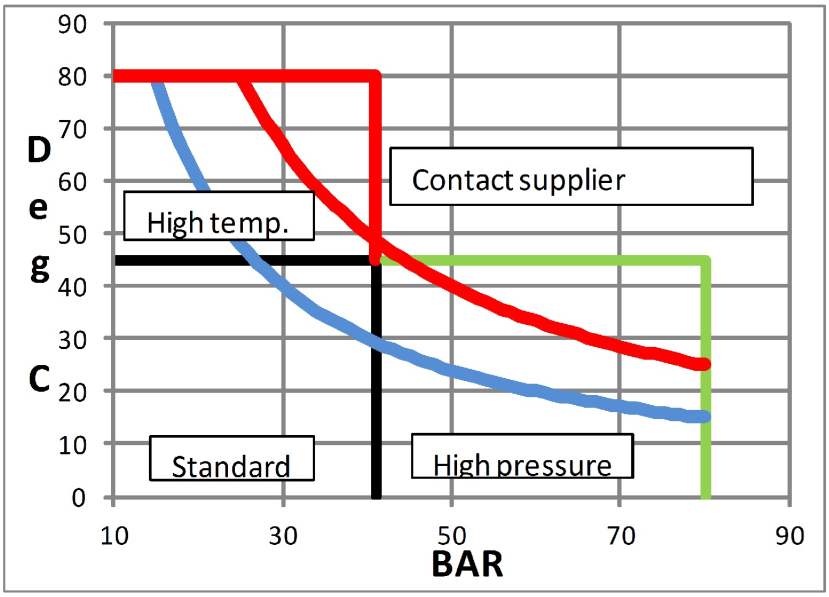


Figure E3. Combining Wagner units and element specifications

Spiral wound RO elements for seawater desalination are high pressure elements using special construction materials allowing them to operate at, for instance, 70 bar and 30 °C, meaning 2100 Wagner units and falling in the range 'severe conditions' bordering on 'extreme conditions'. This point of operation is slightly above the maximum recommended value of 2000 Wagner units. The main reason that seawater desalination can be performed relatively problem free is that a seawater desalination system operates for months, if not years, in a steady state without start up, shut down or cleaning. If the same element is used at 80 bar and 45°C, which technically is within the specification range, it is likely to fail within a relatively short time frame, especially if frequent cleaning is required.

The boundaries between the various sets of conditions are not firm, but the Wagner unit will provide a good guideline for the stress that an application places on the elements and an indication of the operating life, which can be expected from the elements. The operating conditions for the elements and the membrane filtration system can be exceeded in some cases, if a reduced element life is acceptable.

In general, temperature exerts more stress on the elements than pressure. With sufficient date available, the definition of the Wagner unit can be refined to applying an exponent to the values for temperature and pressure, where the exponent for temperature will be higher than 1 and the exponent for pressure lower than 1 or exactly 1.

Consequently, extreme care needs to be exercised when operating at high temperature using spiral wound elements, see the section on operational limits. For instance, the rate of heating and cooling at any point in the operation or cleaning of the system is extremely important to the element life. The need for carefully performed pilot testing of a sufficient longevity is paramount in all areas of process applications, but especially in the case of high temperature applications.

Other variables may come into play, for instance:

- Frequency of heating and cooling above 50°C
- Speed of heating and cooling
- Presence of lubricants, e.g. butter fat
- Start/stop procedure

How to avoid TS surges on start up

This appendix is highly specialized and relates only to the start up large multistage UF or MF systems using polymer membranes. The comments are primarily valid for systems which do not tolerate pressure on the permeate side, mostly plate-and-frame and spiral wound systems, but also referring to ceramic and hollow fiber membrane configurations.

Ceramic and fiber membranes

These systems are capable of operation with the permeate valve shut off, which is an advantage during start up. In addition, the permeate can be throttled during operating enabling a reduction of the flux to minimize fouling and maximize operation time.

The permeate valve can be completely shut before start up, which allows the flow conditions in the system to be stabilized prior to shifting into production mode. During operation the permeate flow can be adjusted not to exceed a preset flux value known to cause fouling.

Start-up of a system is relatively uncomplicated compared to spiral wound and most plate-and-frame systems.

Spiral wound elements and flat sheet configurations

In these systems the permeate flow cannot effectively be controlled.
The most common start up procedure is to start loop 1, then loop 2 and so on, in quick succession. This can cause blockage in large UF systems by precipitation of protein or other matter.

A careful analysis of the profile of the solids buildup occurring at the time of start up of a water filled plant to the time a steady state has been reached has led to several interesting discoveries, which in retrospect are logical.

A five stage system as shown in figure 5-4 with an internal volume of 800 liters is being representative for an industrial size system designed to treat 30000 liters of cheese whey per hour at a volumetric concentration ratio of 30:1, meaning that in a steady state the plant will produce 1,000 liters per hour of concentrate and 29.000 liters per hour of permeate. The system is controlled by a ratio controller and a feed pressure regulator. Under ideal conditions 15 * 800 equal to 12000 liters need to be fed into the plant before a steady state is reached.

If all pumps are started at the same time, this procedure will result in a spectacular power surge because 5 motors will be started simultaneously each drawing 18.5 kW.

Even when using a gentler start up procedure the result is a large feed flow to the plant. The water in the plant starts mixing with the feed and concentrate, the result being that the solids in the plant will be pure protein which is pushed from the first stage to the subsequent stages.

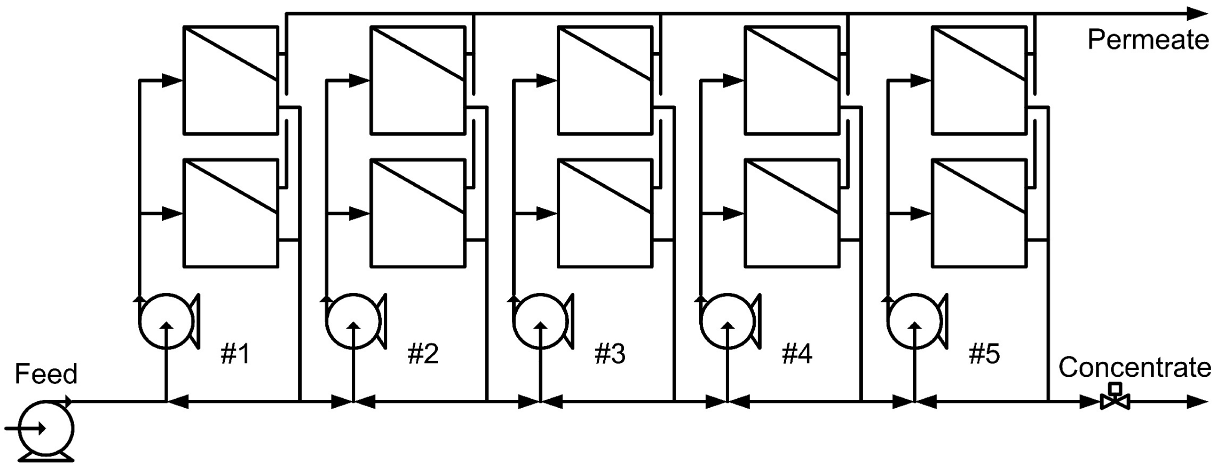


Figure F1. 5 loop continuous system

Due to the high initial flux of pure water, the concentration in the first loops will be higher than during normal operation. When the over-concentrated product moves through the system and reaches the last stage chances are that the protein level gets so high that gelling occurs, which can lead to a disastrous situation. Total blocking of all or the majority of the flow channels can occur, and it can be next to impossible to clean and recover the performance of the elements. A total exchange of elements may be the only remedy of getting the plant up and running again.

The best way to start a multistage plant is as follows, using a 5 stage system as an example:

- Loop 5 is started first while loops 1 through 4 are valved off.
- When the flux in loop 5 gets close to the normal production value, loop 4 is started.
- When the flux in loop 4 gets close to the normal production value loop 3 is started and so on.

The general idea is to attain a buildup of solids throughout the plant to the point of normal operation with particular attention to the last stage.

The conventional start up procedure results in a fivefold higher initial feed flow than during normal production. In many cases the pretreatment equipment, cannot even handle this excessive flow and function properly. As a general rule, it takes about 30 minutes for a system to settle down and to adjust to normal production conditions.

Figures and tables

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