

Pressure Driven Membrane Processes

Downstream Processing

Søren Prip Beier

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Pressure Driven Membrane Processes: Downstream Processing

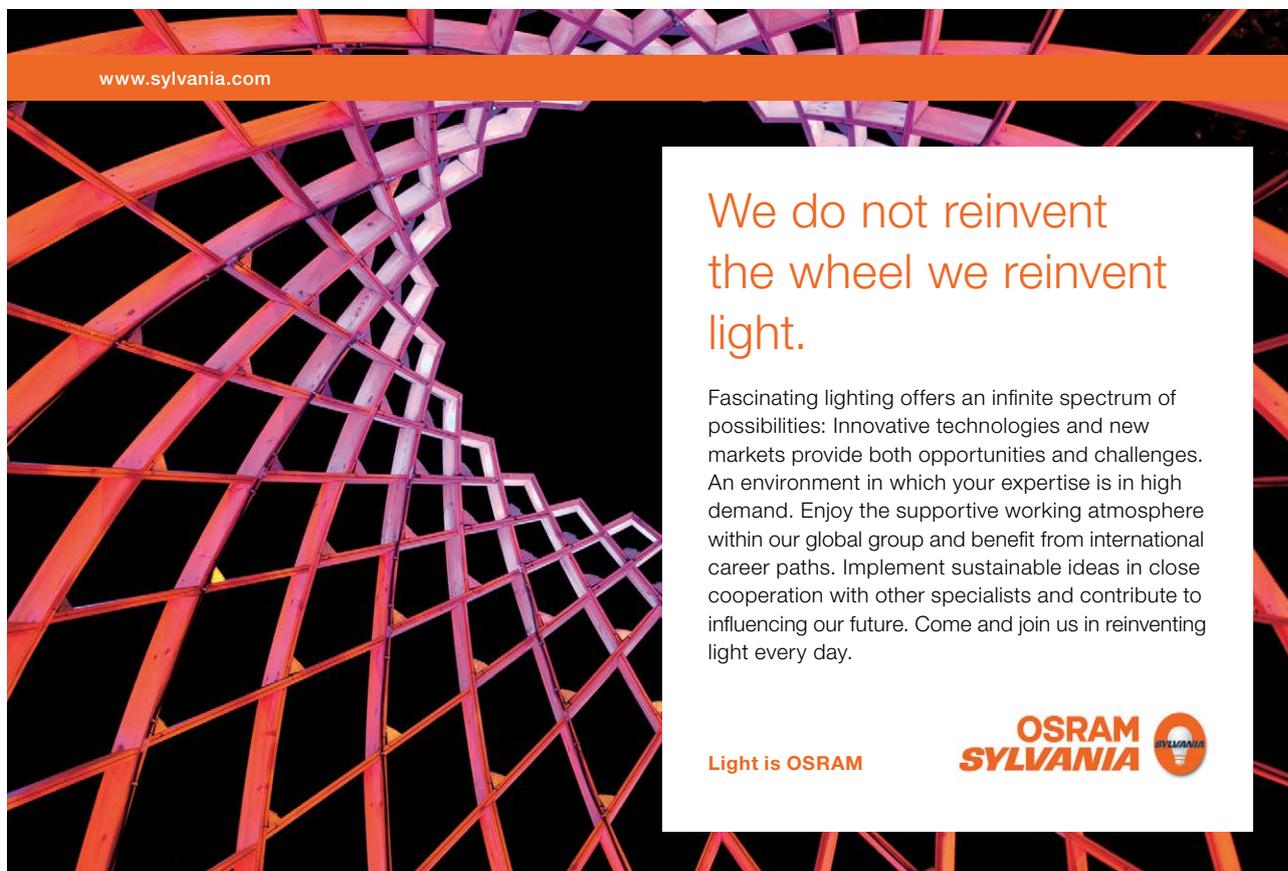
3rd edition

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ISBN 978-87-403-1158-7

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The world is moving fast. New products are constantly being developed, new technologies and concepts emerge. This calls for constant development of new production processes and education of skilled engineers.

This book is written to you who have an interest in natural science and especially in downstream production processes in which a separation between different phases is required. Pressure driven membrane processes are widely used in downstream processing in the chemical, biochemical and food industry, and in this book I will focus on the basic theory behind pressure driven membrane processes. You either i) study to become or ii) work as a chemist or an engineer. You can use this book as a supplement to your chemical engineering courses about downstream processing, membrane processes and/or membrane technology or you can use it if you wish to acquire basic knowledge about pressure driven membrane processes. You are supposed to have basic skills in mathematics and chemistry in general when reading this book.

The book will give you an introduction to basic principles behind pressure driven membrane processes. Relevant theory and models will be presented together with key terms widely within the area of membrane technology.

October 2015

Søren Prip Beier

1 Introduction

Pressure driven membrane processes are widely used in the chemical, biochemical, pharmaceutical, food and dairy industries. A membrane process is capable of performing a certain separation by use of a membrane. The core in a membrane process is a membrane that allows certain components to pass while retaining other components. Overall a very simple, clean and efficient concept but as you will realize when going through this book a handful of different phenomena will impact the process and make the scenario not that simple after all! Initially some of the most important terms used in membrane technology are shown in Figure 1.

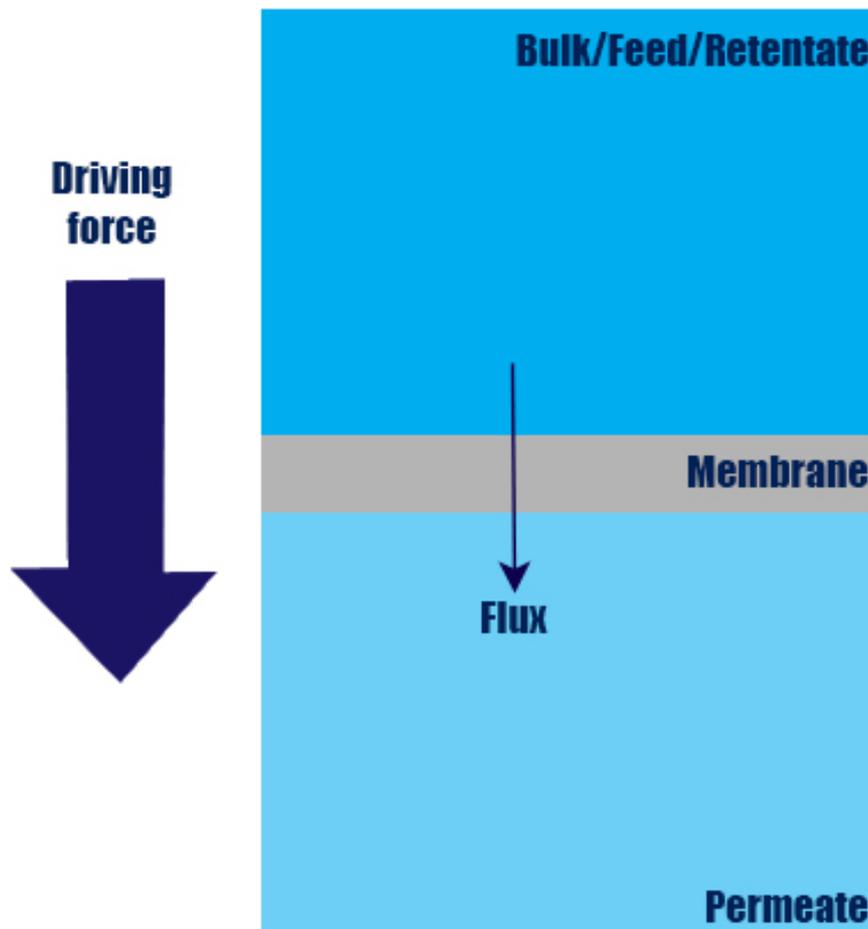


Figure 1: Membrane process
Sketch of a membrane process. The core is a membrane through which a driving force induces a flux from the bulk to the permeate side.

The feed side is often referred to as the *bulk solution*. The components in the bulk solution that are retained can also be referred to as the *retentate* after it has been in contact with the membrane. When a driving force is established across the membrane, a *flux* will go through the membrane from the bulk solution to the permeate side. The flux is often denoted with the letter “*J*” and is often reported in units of liter pr. m² pr. hour [L/(m²·h)]. The liquid going through the membrane is called the *permeate*.

A particular separation is accomplished by use of a membrane with the ability of transporting one component more readily than another. In other words, the membrane is more permeable to certain components because of differences in physical or chemical properties between the membrane and the components that are transported through the membrane.

- *Difference in size:* In many membrane processes (microfiltration and ultrafiltration for example) porous membranes with a given pore size distribution are used. Because of the pore size, some components will be retained by the membrane because of their size and some components are small enough to pass through to pores in the membrane.
- *Difference in charge:* In some membrane processes (electrodialysis for example) differently charged components are separated. This can be done by use of cation and anion exchange membranes which only allows transport of cations and anions, respectively. Cation exchange membranes are, for example, incorporated with negatively charged groups which will repel anions and allow transport of cations.

As seen in Figure 1, a driving force across the membrane induces a flux of permeate from the bulk solution to the permeate side. You can find a broad variety of membrane processes driven by different driving forces:

- Pressure gradient
- Concentration gradient
- Electrical voltage gradient
- Temperature gradient

In this book we will focus on pressure driven membrane processes, in which the flux through the membrane is induced by a hydrostatic pressure gradient between the bulk solution and the permeate side. Pressure driven membrane processes include microfiltration, ultrafiltration, nanofiltration, and reverse osmosis.

	Pore size [μm]	Applied Pressure [bar]	Typical applications
Microfiltration	10–0.05	0.1–2	Retention of particles
Ultrafiltration	0.05–0.002	1–10	Retention of macromolecules and/or colloids
Nanofiltration	0.002–0.001	5–20	Retention of low molecular weight solutes
Reverse osmosis	< 0.001	10–100	Retention of ions

Table 1: Different pressure driven membrane processes

Approximate pore sizes and typically applied pressures are given for the different pressure driven membrane processes together with some typical applications.

In microfiltration and ultrafiltration, porous membranes with the approximate pore sizes given in Table 1 are used. Membranes for nanofiltration and reverse osmosis can be considered as an intermediate between porous membranes with very small pores and dense membranes which are used, for example, in gas separation. The transition from microfiltration over ultrafiltration to nanofiltration and reverse osmosis is not sharp but lies in the areas of the pore sizes given in Table 1. Approximate pressure ranges are also given in Table 1. It is seen that as the membrane pores/structure becomes more open, the necessary applied operational hydrostatic pressure decreases. Thus only relatively small pressure levels are used in microfiltration whereas relatively large hydrostatic pressures are required to run reverse osmosis.

Proportionality between the flux and the driving force is often seen (at least when pure solvent permeates the membrane). The proportionality can be described by a phenomenological equation:

$$J = -A \cdot \frac{dX}{dx} \quad (1)$$

The flux J is proportional to the driving force, which is expressed as the gradient of X (pressure, concentration, electrical voltage or temperature) in the direction x perpendicular to the membrane surface. The proportionality constant A is called a phenomenological coefficient. Because the gradient is negative in the direction x of the flux, a minus-sign is placed on the right side of the equation. In pressure driven membrane processes the driving force is a pressure difference across the membrane. The term dX/dx in equation (1) can then be replaced by ΔP which is the difference between the hydrostatic pressure of the bulk side and the permeate side. *Darcy's law* is simply just such a phenomenological expression in which the driving force is the pressure:

$$J = l_p \cdot \Delta P \quad (2)$$

The phenomenological coefficient in *Darcy's law* is denoted l_p , which is the permeability coefficient of the membrane. The permeability coefficient in (2) is inversely proportional to the thickness of the membrane selective layer, and thus in order to achieve as high permeability as possible, asymmetric membranes with a very thin selective layer (skin layer) are often used. The skin layer is then attached onto an open porous support structure and thus the membrane is referred to as being asymmetric. The thickness of skin layers in asymmetric membrane is often in the order of magnitude of 1 μm . The permeability also depends on the dynamic viscosity of the fluid which is transported through the membrane and the resistance of the membrane towards mass transport. The permeability of microfiltration membranes are larger than for ultrafiltration membranes, and nanofiltration / reverse osmosis membranes have very low permeabilities. Therefore higher pressures are necessary to run reverse osmosis than for ultrafiltration and microfiltration, which again is seen in Table 1.

Two fundamentally different ways of running pressure driven membrane processes are sketched in Figure 2.

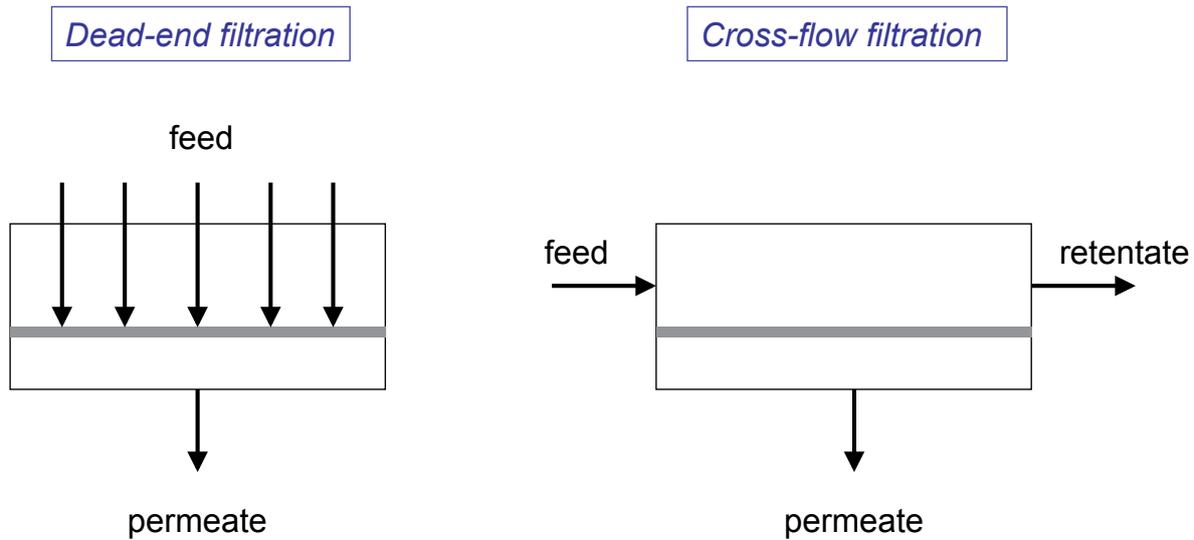


Figure 2: Dead-end and cross-flow filtration
Two different ways of running a pressure driven membrane process.

In dead-end filtration the bulk solution is pumped or pressurized through the membrane. That way the permeate will be forced through the membrane and the bulk solution will decrease in volume if the feed, for example, is contained in a batch cell. In dead-end filtration the pressure is constant throughout the whole membrane area. In cross-flow filtration, however, the bulk solution is pumped tangentially along the membrane surface. Again, the flux will be induced because of a larger pressure on the bulk side, but because of the tangentially flow over the membrane surface there will also be a pressure drop tangentially along the membrane surface on the bulk side. The pressure will, thus, not be constant throughout the whole membrane area which means that the driving force pressure difference across the membrane is also not at the same level throughout the whole membrane area. In Figure 2 the terms *feed* and *retentate* is visualized in the cross-flow case. The feed is introduced in one end of the membrane feed channel and the retentate is returned at the other end of the membrane feed channel. In dead-end filtration no retentate is continually removed. Cross-flow filtration has several advantages in comparison to dead-end filtration which will be described more in the *Concentration polarization* section.

If the membrane is semi permeable, the concentration in the permeate (of the components that are supposed to be retained) is close to zero, and the retention is close to 1 (100%). The retention is however often lower than 1 because the concentration increases close to the membrane surface (see the *Concentration polarization* section). The retention can be defined in different ways:

$$\begin{aligned}
 \text{Observed retention, } S &= 1 - \frac{c_p}{c_b} \\
 \text{True retention, } R &= 1 - \frac{c_p}{c_m}
 \end{aligned}
 \tag{3}$$

The concentration in the permeate stream is denoted c_p , the bulk concentration is denoted c_b and the concentration just at the membrane surface is denoted c_m . Because of convective transport of the retained components towards the membrane surface, the concentration at the surface c_m is often larger than in the bulk solution. This phenomenon is called concentration polarization. An enhanced surface concentration can lead to an increased permeate concentration. Because c_m is larger than c_b , the true retention is often higher than the observed retention. The difference between the observed retention and the true retention is very important to understand:

- The observed retention S describes what retention *the system* as a whole is able to deliver.
- The true retention R describes what retention *the membrane* itself is capable of delivering.

The observed retention is very dependent upon the pressure and the hydrodynamic conditions of the system in the membrane feed channels, whereas the true retention is more or less constant (except at low fluxes, at which the true retention can decrease).



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2 Osmotic pressure difference

The osmotic pressure difference between the bulk solution and the permeate stream is often an important factor to consider in pressure driven membrane processes. Therefore, before we go any further, the osmotic pressure concept will be briefly explained.

2.1 Introduction to osmosis

The terms “osmosis” and “osmotic pressure” can be explained in different ways. First we will look at Figure 3.

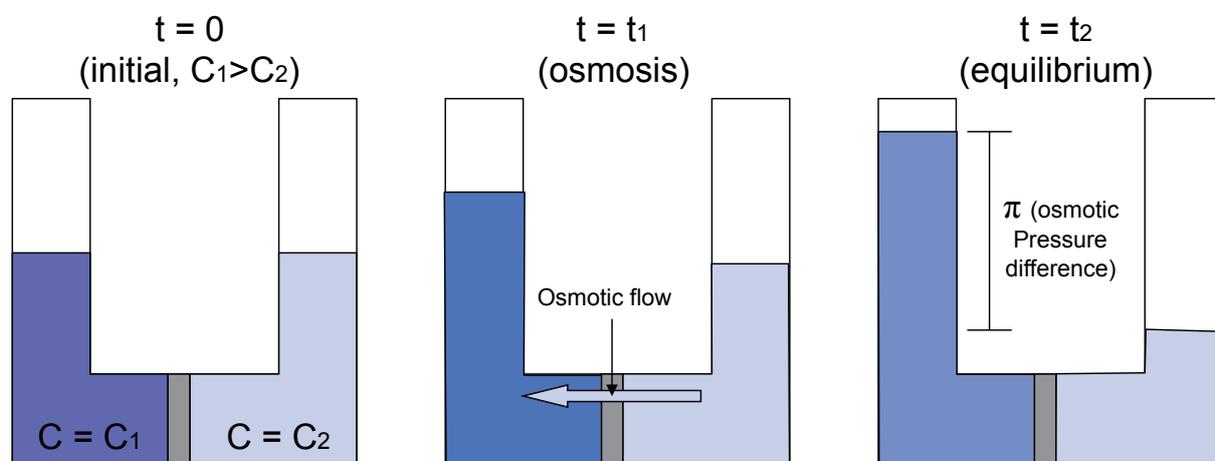


Figure 3: Osmosis and osmotic pressure

Two solutions with different solute concentrations are separated by a semipermeable membrane that allows only transport of solvent and not solute. As time passes, solvent will flow through the membrane as sketched at time t_1 . The solvent flow towards the concentrated side is called osmosis (osmotic flow). Because of the osmosis, the liquid level on the concentrated side increases, yielding a hydrostatic pressure difference build-up (osmotic pressure) between the two sides. Eventually, the osmotic flow stops at equilibrium. The hydrostatic pressure difference between the two solutions at equilibrium is called the osmotic pressure.

Initially two solutions at different concentration are separated by a semipermeable membrane that only allows transport of solvent and not solute. The solute concentration C_1 is larger than the solute concentration C_2 . As time passes, solvent will flow through the membrane from the lower solute concentration to the higher solute concentration, as sketched at time t_1 . That way the solvent pursues to dilute the more concentrated solute solution. This solvent flow is called osmosis. Because of the osmosis the liquid level on the concentrated solute side will increase resulting in a hydrostatic pressure difference build-up. Eventually, the hydrostatic pressure difference (liquid level on the concentrated solute side) reaches a certain level and equilibrium is reached. The hydrostatic pressure difference between the two solutions at equilibrium is called the osmotic pressure. If a hydrostatic pressure, just equal to the osmotic pressure, was initially applied on the solution side to the left (C_1) at time $t = 0$, the osmotic flow would have been prevented.

We have now learned that osmotic pressure is induced by the phenomenon of osmosis. The phenomenon of osmotic pressure can also be thought of as “osmotic suction”. The more concentrated solute solution (C_1) pursues to be more diluted. Thus, the more concentrated solute solution “sucks” solvent through the semipermeable membrane in order to become more diluted. During the “osmotic suction” the liquid level on the concentrated solute side will of course increase, causing a hydrostatic pressure difference build-up which, as mentioned above, is called the osmotic pressure. The “osmotic suction” is stopped when the hydrostatic pressure difference (osmotic pressure) between the two solutions has reached a certain equilibrium level.

As we have seen now, an osmotic flow of solvent through a semipermeable membrane is induced from the right towards the left on Figure 3. However, to go a bit deeper into understanding osmosis you might be asking yourself the following questions: Why does the concentrated solute solution pursue to be more dilute? Why does the diluted solute side pursue to dilute the concentrated solute side? Why does the osmotic flow or osmotic suction occur? And why does the osmotic flow stop at a certain equilibrium level?

The answers can be found by looking at the solvent concentrations (or solvent activities) or rather the chemical potentials of the solvent. We look at the solvent and not the solute because it is the solvent that is capable of passing the membrane. The chemical potential is denoted μ , and the chemical potential of the solvent is defined by the following expression:

$$\mu_{\text{solvent}} = \mu_{\text{solvent}}^0 + R \cdot T \cdot \ln(a_{\text{solvent}}) + V_{\text{solvent}} \cdot P \quad (4)$$

The chemical potential μ of the solvent is a function of the standard chemical potential μ^0 (at infinite dilution), the temperature T , the solvent activity a , the molar volume V of the solvent and the pressure P . Again, we look at Figure 3. The *solute* concentration (activity) is higher on the left side ($C_1 > C_2$), and therefore the *solvent* concentration (solvent activity) is higher on the right side. Thus, the initial chemical potential of the solvent is higher on the right side because of larger solvent activity. Since the system pursues to reach equilibrium (pursues to have equal solvent chemical potential on both sides of the semipermeable membrane), solvent will flow through the membrane from the higher chemical solvent potential towards the lower solvent chemical potential. This flow is called osmosis, and the flow is proportional to the solvent chemical potential gradient over the membrane, $-d\mu/dx$. Hence, the osmotic flow increases the solvent activity “ a ” and the pressure “ P ” on the left side of the membrane (Figure 3) resulting in an increasing solvent chemical potential on the left side. At the same time the pressure and solvent activity on the right side of the membrane decreases (liquid level drops and the solution gets more concentrated). The drop in pressure and solvent activity on the right side decreases the solvent chemical potential. The osmotic flow stops when the chemical potential of the solvent is equal on both sides of the membrane.

2.2 Osmotic pressure model

In order to obtain a flux through the membrane from the bulk side (with larger solute concentration) to the permeate side (with lower solute concentration), the applied hydrostatic pressure on the bulk side has to be larger than the osmotic pressure difference between the bulk and permeate side. If we again look at Figure 3, this corresponds to applying a hydrostatic pressure on the left side that is larger than the osmotic pressure. Thus, an osmotic pressure term $\Delta\pi$ has to be added to Darcy's law (equation (2)) in order to establish the flux equation. This is called to the osmotic pressure model:

$$J = l_p \cdot (\Delta P - \Delta\pi) \quad (5)$$

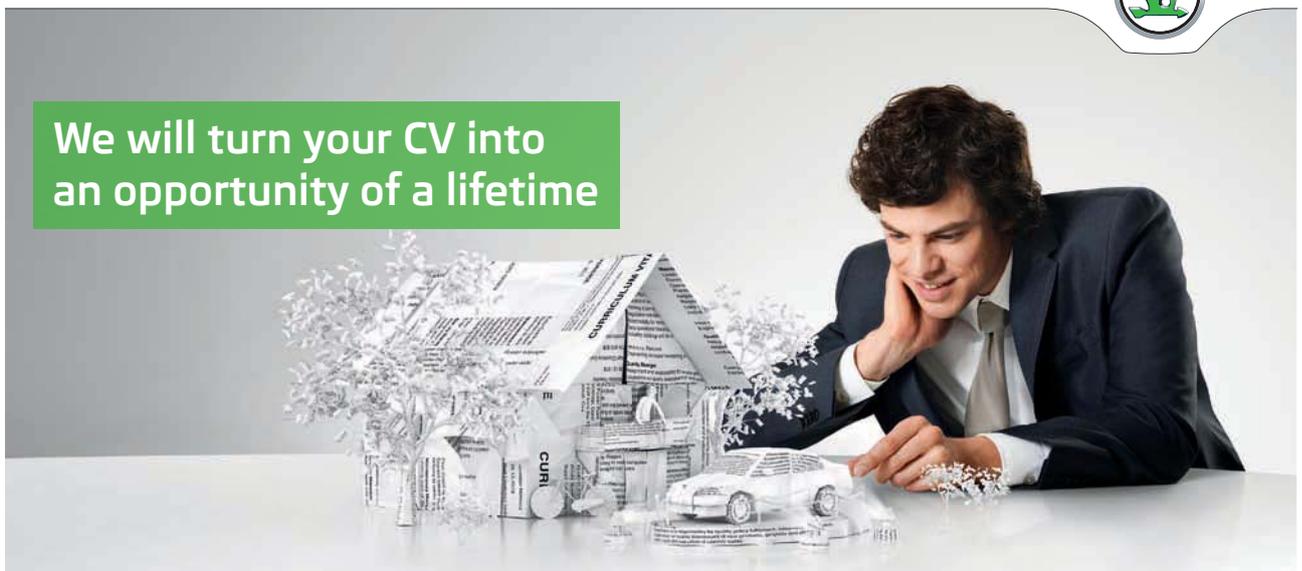
You can say that applying a hydrostatic pressure P on the bulk side increases the chemical potential of the solvent on the bulk side (according to equation (4)). This increase induces a gradient in the solvent chemical potential across the membrane. Thus, the system will “allow” or “facilitate” a flux of solvent from the bulk to the permeate in order to equalize this solvent chemical potential gradient (to pursue to reach equilibrium). However, as the bulk is often re-circulated and the permeate is often continually removed in pressure driven membrane processes, equilibrium is never reached and the flux is thus maintained.

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To exemplify the use of the osmotic pressure model, we can look at sea water. The osmotic pressure of sea water is around 30 bar. This means that when reverse osmosis of sea water is conducted, a hydrostatic pressure of 30 bar is needed in order just to overcome the osmotic pressure. Also in microfiltration and ultrafiltration the osmotic pressure can play a great role because the back diffusion of large molecules from the membrane surface into the bulk solution is often low and, thus, there will be a relative large concentration on the membrane surface giving a relative large osmotic pressure.

2.3 Calculation of the osmotic pressure

An osmotic pressure difference exists across the membrane, as described in the previous section, because of the solvent concentration (activity) difference between the bulk solution and the permeate side. The applied hydrostatic pressure difference between the bulk and permeate has to be larger than the osmotic pressure difference in order to obtain a flux through the membrane from the bulk side to the permeate side. These considerations are summarized in the osmotic pressure model, as we saw earlier. But how do we calculate the osmotic pressure of a solution?

The osmotic pressure π of a solution can be calculated by use of the van't Hoff equation:

$$\pi = \frac{R \cdot T}{M_i} \cdot c_i \quad (6)$$

In this equation, R is the gas constant, T the absolute temperature, M_i the molar mass of component i and c_i the concentration of component i . When the osmotic pressure is to be calculated for a sodium chloride solution, the concentration of NaCl has to be multiplied with "2" because of the dissociation into two ions (a sodium ion and a chloride ion). The proportionality between osmotic pressure and concentration given in equation (6) applies at low concentrations and for low MW molecules.

When the osmotic pressure is to be calculated for macromolecular solutions or high concentration solutions, a virial expansion expression can be used:

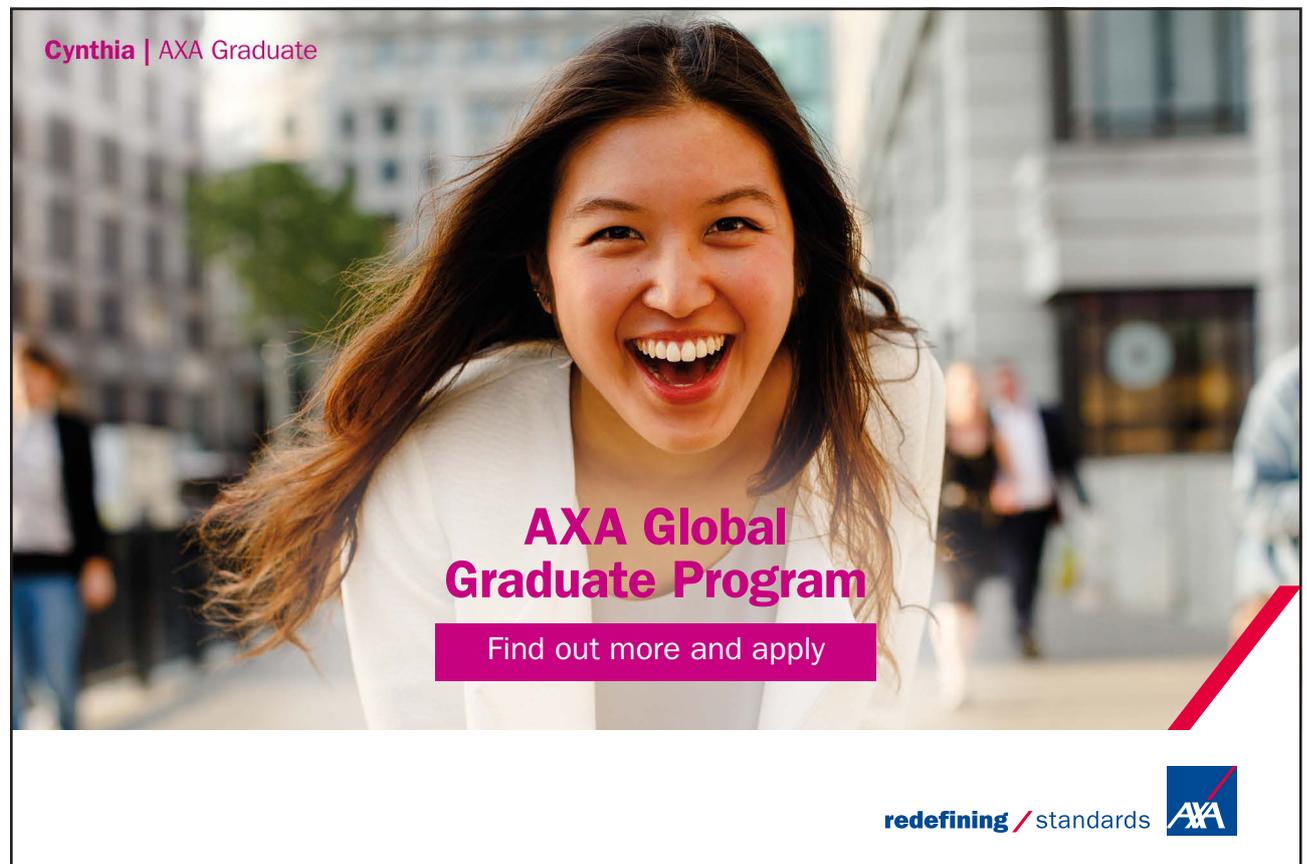
$$\pi = \frac{R \cdot T}{M_i} \cdot c_i + B \cdot c_i^2 + C \cdot c_i^3 + \dots \quad (7)$$

Here it is seen that the van't Hoff's equation is the first term of the expanded expression. It is also seen that when the concentration is low, almost only the first term contributes to the osmotic pressure. In that way, equation (7) is reduced to van't Hoff's equation (equation (6)). The terms B and C are constants for specific molecules.

For macromolecular solutions, a more simple exponential expression can, however, often be used for calculating the osmotic pressure:

$$\pi = A \cdot c_i^n, \quad n > 1 \quad (8)$$

The term A is a constant for a specific type of macromolecule and the exponential factor n has a value larger than “1”. The take home message is that macromolecules at high concentrations *can* constitute a significant osmotic pressure that need to be taken into consideration when designing a membrane based separation process in which macromolecules are to be retained.



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3 Resistance towards mass transport

According to Darcy's law (equation (2)) and the osmotic pressure model (equation (5)), the flux through the membrane is only dependent on the applied hydrostatic pressure and the osmotic pressure difference. In practice the flux will however decrease dramatically and can drop to a level as low as around 5% or less compared to the initial flux when solutions containing particular material and macromolecules are being processed. This can be due to a build-up of a concentration gradient in the laminar film layer over the membrane surface caused by the convective transport of solutes towards the membrane (concentration polarization), formation of a macromolecular gel layer on the membrane surface and other types of membrane fouling, which will be described more in the following sections. Thus, a term concerning the total resistance towards mass transport through the membrane R_{tot} has to be incorporated into Darcy's law (and the osmotic pressure model):

$$J = \frac{\Delta P - \Delta \pi}{\eta \cdot R_{tot}} \quad (9)$$

The total resistance increases with time due to different types of membrane fouling, leading to a decline in flux when a constant pressure is applied. From equation (9) it is also seen that the dynamic viscosity η is reverse proportional to the flux – meaning all other being equal, the flux of thick glucose syrup will be lower than the flux of pure water! The total resistance is the sum of all sub resistances towards mass transport:

$$R_{tot} = R_m + R_{CP} + R_f \quad (10)$$

R_m is the membrane resistance itself, which is a membrane constant, R_{CP} is the resistance caused by concentration polarization and R_f is the resistance caused by membrane fouling. The two latter terms will be explained in the next sections.

3.1 Concentration polarization

During membrane filtration, the convective transport of solutes towards the membrane will lead to a concentration increase in the boundary layer at the membrane surface, which is sketched in Figure 4.

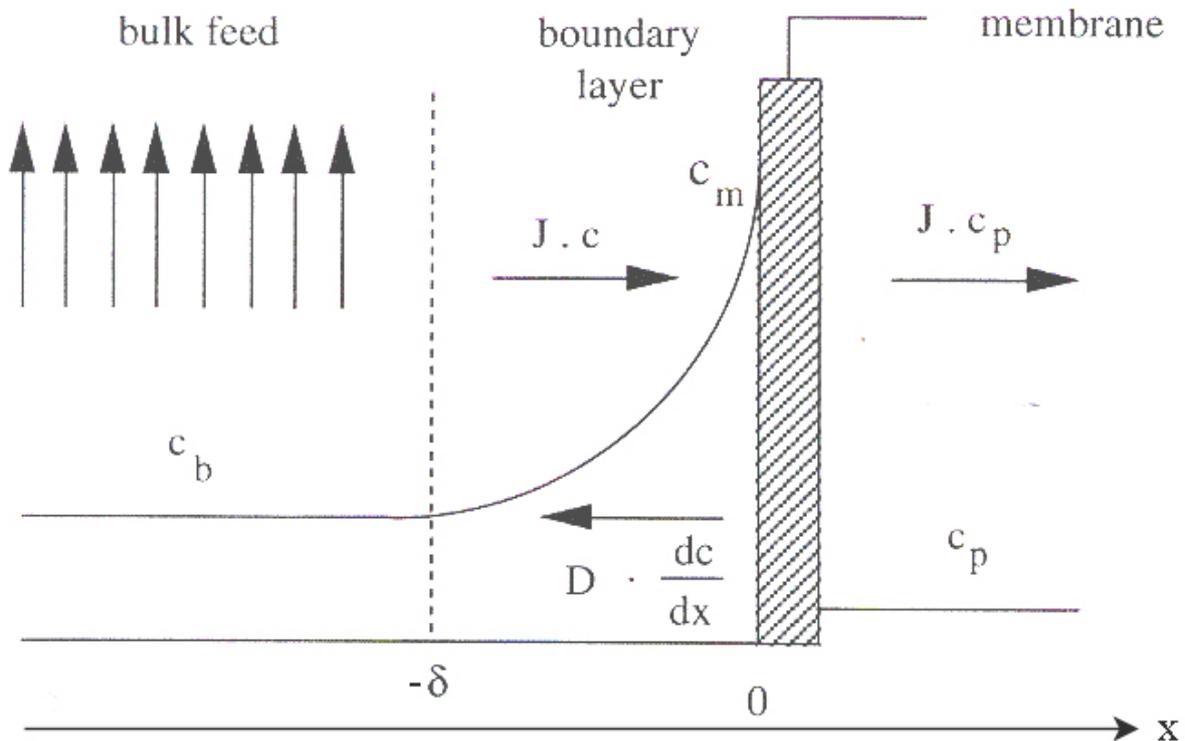


Figure 4: Concentration polarization
Sketch of the concentration profile in the boundary layer in a polarization situation.

In a distance δ from the membrane surface, complete mixing is assumed resulting in a constant bulk concentration c_b . This is sketched in the figure by the up-going arrows to the left showing the cross-flow along the membrane. In the laminar boundary film layer, with the thickness δ , the concentration c is increasing due to the convective solute transport in direction x of the flux. This convective transport is balanced by the diffusive transport of solutes back into the bulk solution and the part of the solutes that goes through the membrane to the permeate side. A solute mass balance in the laminar boundary film layer can be set up by these three terms (defined in the direction x according to Figure 4):

- Convective solute transport towards the membrane in the laminar film layer: $J \cdot c$
- Diffusive transport in the laminar boundary film layer back into the bulk: $D \cdot dc/dx$
- Transport of solutes in the permeate away from the membrane: $J \cdot c_p$

The diffusion coefficient is denoted D , and dc/dx is the concentration gradient in the laminar boundary film layer. Setting up a mass balance gives the following first order differential equation, which describes the concentration polarization in stationary conditions. The boundary conditions (BC) are also seen from Figure 4.

$$J \cdot c = D \cdot \frac{dc}{dx} + J \cdot c_p \quad BC: \begin{cases} x = -\delta \rightarrow c = c_b \\ x = 0 \rightarrow c = c_m \end{cases} \quad (11)$$

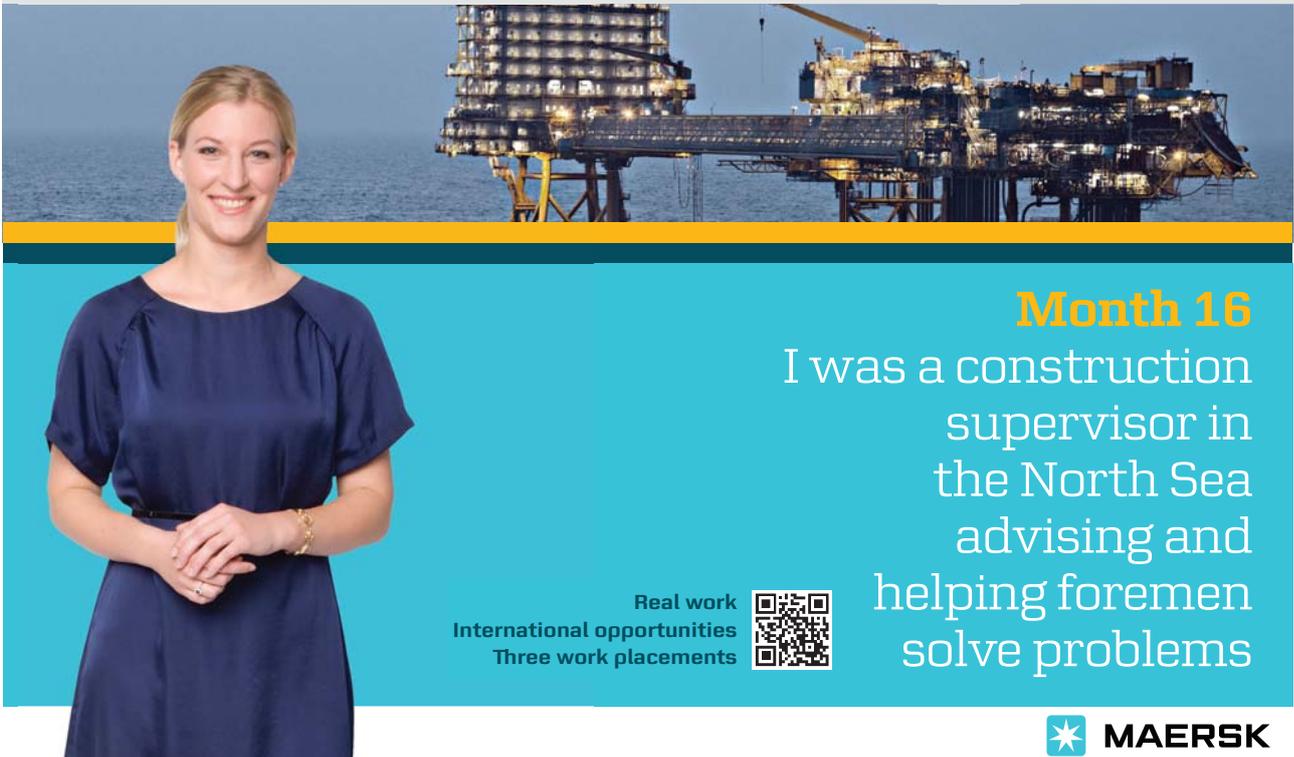
This differential equation is solved by integration over the boundary conditions:

$$\frac{c_m - c_p}{c_b - c_p} = \exp\left(\frac{\delta \cdot J}{D}\right) = \exp\left(\frac{J}{k}\right) \quad (12)$$

This film theory equation describes the correlation between the bulk, permeate and membrane surface concentrations and the flux. The term δ/D can be replaced by $1/k$, where k is the mass transfer coefficient of the system. Hence, the mass transfer coefficient tells something about the level of the back-diffusion of solutes from the membrane surface and boundary layer towards the bulk solution. It is seen that when the mass transfer coefficient is low, the concentration polarization can be large, resulting in a large surface concentration c_m compared to the bulk concentration c_b . A high concentration on the membrane surface is often not wanted, as it can lead to larger solute concentration in the permeate. Therefore it is often desirable to decrease the thickness of the laminar boundary layer δ , as it will increase the mass transfer coefficient and thus the back-diffusion of solutes into the bulk solution. An increased mass transfer coefficient will according to the film theory (equation (12)) result in decreased surface concentration and thus a relatively lower permeate concentration. A decrease in the thickness of the laminar boundary layer can be achieved by changing the hydrodynamic conditions on the bulk side. An increased cross-flow velocity along the membrane surface will decrease the laminar boundary layer thickness, for example. Therefore better filtration performance is often seen when cross-flow filtration is done instead of dead-end filtration (see Figure 2). Approximate estimates of mass transfer coefficients for a system can be determined based on literature correlations including the dimensionless Reynolds, Schmidt, and Sherwood numbers.

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Because of the difference in bulk and surface concentration due to concentration polarization, a quite large deviation between the observed and true retention (equation (3)) is often observed. As mentioned earlier, the true retention tells something about how large an amount of the solutes the membrane itself is capable of retaining, whereas the observed retention is the retention you actually achieve in the system during filtration. This means that a potential high true retention of a membrane will often not be utilized very much because of a high surface concentration due to concentration polarization. This can often be improved by changing the hydrodynamic conditions at the membrane surface.

3.2 Gel layer model

The gel layer model is often used when processing macromolecules, typically proteins. When the concentration on the membrane surface c_m reaches a certain level, due to concentration polarization, a gel can be formed at the membrane surface with a constant gel concentration c_g . This gel is then assumed to be impermeable to the macromolecules, it consists of, and thus the permeate concentration c_p is zero. Inserting this into the film theory model (equation (12)) gives the gel layer model, which can be used to calculate a limiting flux (J_{lim}) through the membrane when a gel layer is established.

$$\frac{c_g}{c_b} = \exp\left(\frac{J_{lim}}{k}\right) \Leftrightarrow J_{lim} = k \cdot \ln\left(\frac{c_g}{c_b}\right) \quad (13)$$

Again, the mass transfer coefficient is denoted k . The gel layer model can be quite useful, although some of its assumptions have been reported in literature not to hold. The gel concentration, for example, should be independent of the bulk concentration, which often not seems to be the case. Furthermore, the diffusivity ($D = k \times \delta$) is often not constant but concentration dependent to some extent. Finally, some macromolecules do not tend to form a gel as easy as other macromolecules. However, corresponding flux and concentration data can be used to estimate the mass transfer coefficient and gel concentration graphically from the gel layer model (for example during a concentration filtration run). This is done by rearranging equation (13):

$$J = k \cdot \ln\left(\frac{c_g}{c_b}\right) \quad (14)$$

The flux in equation (14) is then the limiting flux. Thus, flux (J) data and bulk concentration (c_b) data can be plotted in order to determine the mass transfer coefficient and the gel layer concentration. This is visualized in Figure 5.

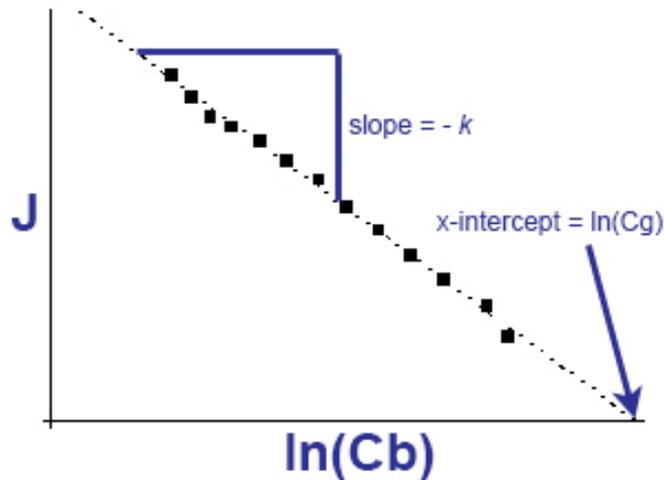


Figure 5: Gel layer model
Graphical estimation of the mass transfer coefficient and the gel concentration from the gel layer model.

From equation (14) and Figure 5 it is seen that the mass transfer coefficient can be estimated from the slope and the gel layer concentration can be estimated from the intercept with the x-axis. When doing this, the assumptions of the gel layer model have to be checked. As mentioned earlier, the assumptions not always hold, since, for example, the gel layer concentration is not always constant but dependent to some extent of the bulk concentration. Also, when the slope is relatively small, the uncertainty in the intercept with the x-axis increases, yielding large uncertainty in the determination of the gel layer concentration. Thus, you have to be aware when using the gel layer model to graphically estimate the mass transfer coefficient and gel layer concentration.

3.3 Membrane fouling

Under stationary conditions the concentration polarization gives a constant contribution to the total resistance towards mass transport through the membrane. This corresponds to a constant term R_{cp} in equation (10), page 12. Thus, the flux should be constant when the applied hydrostatic pressure is constant, but in practice the flux often keeps decreasing during filtration. This is due to membrane fouling, which is sketched in Figure 6.

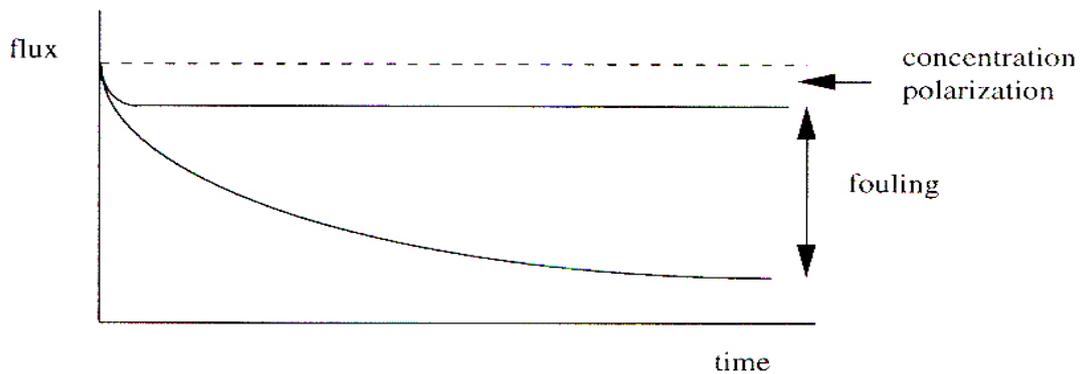


Figure 6: Flux decline during filtration

Flux decline at constant applied pressure during filtration. Concentration polarization contributes with a constant resistance towards mass transport through the membrane, whereas the fouling contribution continually increases resulting in a continually decreasing flux.

Membrane fouling is a complex phenomenon affected by many factors such as concentration, temperature, pH, ion strength, hydrophilic/hydrophobic interactions etc. Membrane fouling can, for example, consist of adsorption of different molecules, colloids or salts on the membrane surface and on the pore walls inside the membrane. Such adsorption will increase the resistance towards mass transport. Membrane fouling can also be blocking of the pores by different cells, bacteria or aggregated macromolecules, or it can be the build-up of a cake layer on the membrane surface. Membrane fouling can be divided into

- irreversible membrane fouling and
- reversible membrane fouling.

Often the irreversible membrane fouling is established first. This could be a rather tightly bounded adsorbed mono-layer of components on the membrane surface. Such a layer can act as a base for further build-up of a continually growing fouling layer, which is often removable by changing the hydrodynamic conditions or water rinsing. An easily removable outer fouling layer is categorized as reversible membrane fouling. The reversible fouling layer is often removed when the pressure is released or when the membrane is washed with water, whereas the irreversible fouling layer often has to be removed by cleaning the membrane with certain chemical cleaning agents. Since there in principle is no limit for the growth of a membrane fouling layer, the resistance towards mass transport caused by membrane fouling can, in principle, continually increase leading to the continually decreasing flux which is sketched in Figure 6. Thus, the term R_f in equation (10) on page 12 keeps increasing, leading to a continually decreasing flux, according to the extended version of Darcy's law (equation (9), page 12).

Because of the complex nature of membrane fouling no single equation is able to handle the phenomenon of membrane fouling. Different approaches including the description of the fouling layer as a filter cake has been tried with more or less success. The extent of membrane fouling and the nature of the fouling depend completely on the medium that is filtered and the hydrodynamic conditions in the experimental apparatus on the bulk side. Thus it is very difficult to generalize membrane fouling phenomena.

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4 Summary

Basic terms and equations used in membrane technology have been presented and explained in this book. The osmotic pressure term, which often plays a great role in pressure driven membrane processes, has been discussed and equations for calculating the osmotic pressure for different feed solutions have been presented and explained. The osmotic considerations lead to the osmotic pressure model which tells that in order to obtain a flux through the membrane from the bulk solution to the permeate side, the applied hydrostatic pressure has to be larger than the osmotic pressure difference between the bulk solution and the permeate side.

In the laminar film boundary layer at the membrane surface on the bulk side different phenomena lead to different kinds of resistances towards mass transport. The convective transport of solutes in the perpendicular direction towards the membrane surface leads to a concentration increase in the laminar film layer. This is called concentration polarization and it is often desirable to reduce this phenomenon in order to reduce the constant contribution to the total resistance towards mass transport through the membrane. When the concentration of certain types of macromolecules reaches a certain level in the laminar film layer, due to concentration polarization, a gel with a constant gel concentration can be formed. Thus the film theory model can be rewritten into a gel layer model, which is also presented and discussed in this book.

Concentration polarization can lead to the build up of a fouling layer on the membrane surface, which also contributes to the total resistance towards mass transport. However, membrane fouling also covers many other complex phenomena that can lead to a partly or completely clogging of the membrane. Membrane fouling is very dependent on the hydrodynamic conditions on the bulk side and the pH, concentration, temperature, ion strength etc. It is very difficult to generalize membrane fouling phenomena between different membrane filtration systems.