LAB EXPERIMENTS

Nanofiltration

Framework
This module explains the lab experiment on nanofiltration.

Contents
This module has the following contents:

1. Objective

Nanofiltration can be used in drinking water supply for different reasons. Iron and manganese ions are retained by nanofiltration when treating anaerobic groundwater. Nanofiltration is also used when anaerobic groundwater has a high value of organic matter. By nanofiltration the organic molecules are retained. Nanofiltration can also be used when the hardness of the water is too high, calcium and magnesium ions are retained by nanofiltration. Even surface water can be treated with nanofiltration.

Membrane filtration is for most people an advanced treatment process. In contradiction to the conventional drinking water treatment processes, water is not visible when flowing through a membrane filter. In this experiment we will introduce the basic principles of nanofiltration and the possibilities to operate the system are demonstrated.

Figure 1 - Nanofiltration installation in the laboratory

2. Experiment set-up

The membrane module (A) is the central part in the installation (Figure 2). This module contains 45 capillary nanofiltration membranes with inner diameter of 1.5 mm and a length of 1 m. The module is positioned vertically. Feed water is added to the module by a pump (B). Permeate is collected and weighted by means of a balance (C). The cross-flow velocity inside the membranes is measured by means of a flow meter (D). The operating pressure is measured at three different places in the system, in the feed flow (P_1), in the concentrate flow (P_2) and in the permeate flow (P_3). The water quality (conductivity and temperature) is monitored by conductivity measurements. The conductivity of the feed flow (EC_1) and of the permeate (EC_3) is measured. On top of the system a special air release device (R) is placed. The system is flushed by opening valve W. A valve (E) is used to adjust the desired flow and pressure.

Permeate mass, flow and pressures have to be determined in this experiment. Values of the conductivity meters have to be written on the measuring form.

3 Theory

3.1 General theory

In membrane filtration processes in water treatment the driving force is pressure. The productivity of membrane filtration is expressed in the parameter permeate flux:

$$J = \frac{K_w}{\mu} \cdot (TMP - \Delta\pi) \qquad [1]$$

where:

J	= flux	$(m^3/(m^2 \cdot s)$
K_w	= membrane water permeability	(m)
TMP	= trans membrane pressure	(Pa)
μ	= absolute viscosity	$(Pa \cdot s)$
$\Delta\pi$	= osmotic pressure difference	(Pa)

3.2 Membrane water permeability

The membrane water permeability is dependant on the size of the pores in the membrane, the

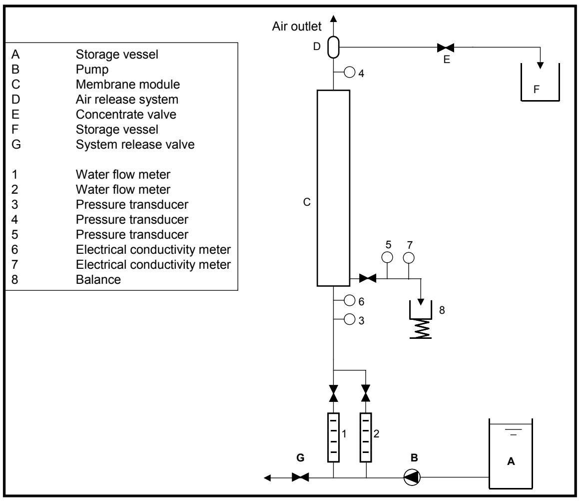

Figure 2 - Schematic drawing of test installation

porosity of the membrane and the thickness of the membrane. The membrane water permeability is constant over time. The membrane water permeability is used to see whether fouling or concentration polarization of the membrane has occurred.

3.3 Trans membrane pressure

The trans membrane pressure is the hydraulic available pressure in the membrane system and is defined as:

$$TMP = \frac{P_1 + P_2}{2} - P_3 \qquad [2]$$

in which:

P_1	= pressure of feed	(Pa)
P_2	= pressure of concentrate	(Pa)
P_3	= pressure of permeate	(Pa)

3.4 Osmotic pressure difference

The osmotic pressure is a liquid property dependant on the salt concntration and temperature of the liquid. The osmotic pressure is defined as:

$$\pi = \sum \frac{R \cdot T \cdot c_i \cdot z_i}{M_i} \qquad [3]$$

in which:

π	= osmotic pressure	(Pa)
R	= gas constant	(J/(K·mol))
T	= temperature	(K)
c_i	= concentration of salt i	(g/m³)
z_i	= valency of ion i	(-)
M_i	= molecule mass of ion i	(g/mol)

For the calculation of the osmotic pressure it is sufficient to use the ions in water which occur in high concentrations. These ions are HCO_3^-, SO_4^{2-}, Cl^-, Na^+, Ca^{2+}, Mg^{2+}.

Because salts are retained by the membrane a concentration difference over the membrane exists. At the concentrate side the concentration is much higher than the concentration in the permeate (which is almost negligible). The osmotic pressure difference over the membrane is:

$$\Delta\pi = \pi_{membrane} - \pi_{permeate} \qquad [4]$$

in which:

$\pi_{membrane}$	= osmotic pressure at membrane surface	(Pa)
$\Delta\pi_{permeate}$	= osmotic pressure of permeate	(Pa)

3.5 Concentration polarization

During filtration a pressure difference across the membrane is applied. Water passes the membrane, while solutes are partially retained by the membrane. These solutes accumulate close to the membrane surface in a so-called boundary layer. The flow close to the membrane surface is laminar and a reduced exchange between salts in the laminar boundary layer and feed is possible. A difference in salt concentration in the feed and the boundary layer is found, this phenomenon is called concentration polarization. The increased concentration in the boundary layer results in a higher osmotic pressure difference and thus a lower flux.

The thickness of the boundary layer is dependant on flow hydrodynamics. At turbulent flow conditions the effect of the concentration polarization is small. At laminar flow condition the effect of the concentration polarization becomes considerable, resulting in a lower permeate flux.

3.6 Relation between salt concentration and electrical conductivity

The salt concentration in feed and permeate is indirectly deduced form electrical conductivity measurements. Herefore an empirical relationship between salt concentration and electrical conductivity is used. The measurements used for the derivation of this relationship are given in figure 3. The relationship is given by:

$$EC = -7.6486 \cdot \left(c_{MgSO_4 \cdot 7H_2O}\right)^2 + 516.24 \cdot \left(c_{MgSO_4 \cdot 7H_2O}\right) \quad [5]$$

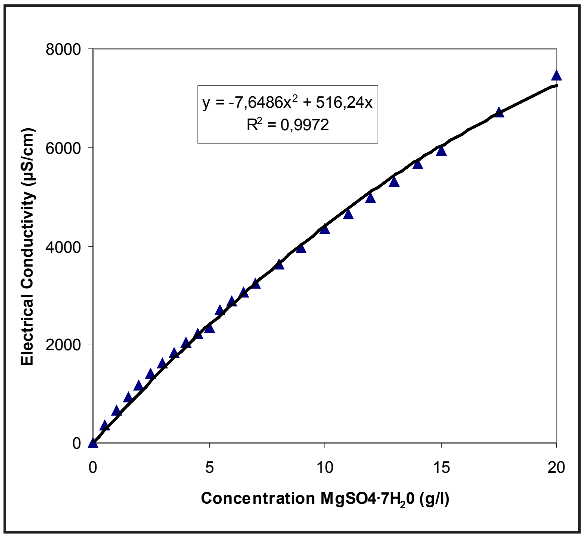

Figure 3 - Electrical conductivity as function of salt concentration

3.7 Absolute viscosity

The absolute viscosity is calculated with:

$$\mu = \nu \cdot \rho_w = \frac{497 \cdot 10^{-6}}{(42.5 + T)^{1.5}} \cdot 1000 = \frac{497 \cdot 10^{-3}}{(42.5 + T)^{1.5}} \quad [6]$$

in which:

μ	= absolute viscosity	(N·s/m²)
ν	= kinematic viscosity	(m²/s)
ρ_w	= density of water	(kg/m³)
T	= temperature	(°C)

4. Experiments

4.1 Experiment 1: Determination of the water permeability of the nanofiltration membrane

The permeate produced in 15 minutes when filtering demineralised water is collected and weighted. The feed pressure is 3.0 bar, the cross-flow velocity is 1.25 m/s.

Procedure

- calculate the flow rate to obtain a cross-flow velocity of 1.25 m/s in the membrane module
- fill the feed vessel with demineralised water
- apply a feed pressure of 3.0 bar (P_1) and the calculated flow by opening valve E and changing the pumps number of revolutions (Effect: Permeate is produced).
- wait until permeate concentration is constant (this can take some minutes).
- check if the feed pressure is still 3 bars and if the flow rate is as desired, if not adjust feed pressure or flow rate.
- start experiment by loging data on data sheet. Write down conductivity of feed and permeate and the temperature manually every minute for 15 minutes on empty result sheet.
- stop the experiment after 15 minutes of filtration by shutting down the pump.
- depressurize the system by opening valve E.
- remove all water in the membrane installation by opening valve W (Effect: The water is flushed from the system).

Questions/Elaboration

- present the experimental results graphically and give comments on the results.
- calculate the flow rate to obtain a cross-flow velocity of 1.25 m/s in the membrane module
- calculate the TMP of the experiment.
- why is the electrical conductivity of the feed water and the permeate low?
- determine the membrane water permeability from the experiments.
- why is the permeability constant?

4.2 Experiment 2: Filtration of water containing bivalent ions

Use water from the vessel with c = 12 g/l $MgSO_4 \cdot 7H_2O$. Water is filtrated at a pressure of 3 bars during 15 minutes and the cross flow velocity is 1.25 m/s. The permeate mass, the conductivity of feed and permeate and the temperature of the feed are noted every minute.

Procedure

- fill the vessel with water containing 12 g/l $MgSO_4 \cdot 7H_2O$.
- apply a feed pressure of 3.0 bar (P_1) and the calculated flow by opening valve E and changing the pumps number of revolutions (Effect: Permeate is produced).
- wait until permeate concentration is constant (this can take some minutes).
- check if the feed pressure is still 3 bars and if the flow rate is as desired, if not adjust feed pressure or flow rate.
- start experiment by loging data on data sheet. Write down conductivity of feed and permeate and the temperature manually every minute for 15 minutes.
- stop the experiment after 15 minutes of filtration by shutting down the pump.
- depressurize the system by opening valve E.
- remove all water in the membrane installation by opening valve W (Effect: The water is flushed from the system).

Questions/elaboration

- present the experimental results graphically and give comments on the results.
- calculate the recovery of the system.
- calculate the retention for $MgSO_4$.
- calculate the concentration of salts in the concentrate.
- calculate the theoretical osmotic pressure of the feed, concentrate and permeate with the equation given in the hand-out. Give comments on the result.
- calculate the theoretical osmotic pressure of the feed, concentrate and permeate by means of the spreadsheet.
- calculate the concentration polarisation.

4.3 Experiment 3: Influence of recirculation velocity on system performance

Use water from the vessel with c = 12 g/l $MgSO_4 \cdot 7H_2O$. Water is filtrated at a pressure of 3 bars during 20 minutes and the cross flow velocity is 0.35 m/s. The permeate mass is recorded by the computer, the conductivity of feed and permeate and the temperature of the feed are noted every minute.

Procedure

- fill the vessel with water containing 12 g/l $MgSO_4 \cdot 7H_2O$.
- apply a feed pressure of 3.0 bar (P_1) and the calculated flow by opening valve E and changing the pumps number of revolutions (Effect: Permeate is produced)
- wait until permeate concentration is constant (this can take some minutes).
- check if the feed pressure is still 3 bars and if the flow rate is as desired, if not adjust feed pressure or flow rate.
- start experiment by loging data on data sheet. Write down conductivity of feed and permeate and the temperature manually every minute for 15 minutes.
- stop the experiment after 15 minutes of filtration by shutting down the pump.
- depressurize the system by opening valve E.
- remove all water in the membrane installation by opening valve W (Effect: The water is flushed from the system).

Questions/Elaboration

- present the experimental results graphically and give comments on the results.
- calculate the recovery of the system.
- calculate the retention for $MgSO_4$.
- calculate the concentration of salts in the concentrate.
- calculate the theoretical osmotic pressure of the feed, concentrate and permeate with the equation given in the hand-out. Give comments on the result.

- calculate the theoretical osmotic pressure of the feed, concentrate and permeate by means of the spreadsheet.
- calculate the concentration polarisation.
- explain why the pressure P_2 in this experiments is higher than in the previous experiment.
- explain why the flux in this experiment is lower than in experiment 2.

Data Forms

Data Form 1

Experiment 1

Date			
Time			
EC in feed vessel (μS/cm)			
P1 (bar)	t=0min	t=5min	t=10min
P2 (bar)			
P3 (bar)			
Qre-circulation (l/h)			

Time (min)	Permeate mass (g)	EC1 (μS/cm)	EC3 (μS/cm)	Temp1 (°C)
0				
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

Data Form 2

Experiment 2

Date				
Time				
EC in feed vessel (mS/cm)				
P1 (bar)	t=0min	t=10min	t=20min	
P2 (bar)				
P3 (bar)				
Qre-circulation (l/h)				
Time (min)	Permeate mass (g)	EC1 (µS/cm)	EC3 (µS/cm)	Temp1 (°C)
0				
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				

Data Form 3

Experiment 3

Date				
Time				
EC in feed vessel (mS/cm)				
P1 (bar)	t=0min	t=10min	t=20min	
P2 (bar)				
P3 (bar)				
Qre-circulation (l/h)				
Time (min)	Permeate mass (g)	EC1 (μS/cm)	EC3 (μS/cm)	Temp1 (°C)
0				
1				
2				
3				
4				
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