



Influence of NOM and Membrane Surface Charge on UF-membrane fouling

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Abstract

In literature NOM-fouling of UF-membranes is described due to the deposition of mostly high molecular weight organics, bigger than the MWCO-value of the membrane, like polysaccharides. A former PWN study indicated that the low molecular weight organics and metal complexes rather than the high molecular weight organics were responsible for the acceleration in film formation of these HMW fractions and therefore fouling. In this study experiments on bench-scale were carried out to reduce the fouling potential of IJssel Lake water by:

- removing HMW organics like polysaccharides, with enhanced coagulation, according to literature;
- removing LMW organics like acids and humics, with ion exchange, according to hypothesis PWN;
- reducing the negative surface charge of the membrane or using opposite charge to promote electrostatic exclusion.

From this study can be concluded that the removal of LMW organics (lower than the MWCO-value of the membrane) with the same amount of HMW organics leads to a much lower fouling potential than the removal of HMW organics alone. The combination of a relatively high positively charged hydrophilic membrane and the removal of LMW fractions with an anion resin (MIEX) results to a high gross flux rate at almost no fouling. However results have been achieved during a relatively short time on bench-scale. Therefore extended pilot research is recommended.

Keywords

NOM-fouling, surface charge, surface water, ultrafiltration

INTRODUCTION

Since the end of 1999 20 Mm³/year (15 MGD) pre-treated IJssel Lake water is subjected to an integrated membrane system (IMS) at water treatment plant Heemskerk. This surface water treatment plant is based on combined application of ultrafiltration (UF) and reverse osmosis. During the pilot phase it became clear that the IJssel Lake water had a very high fouling potential for ultrafiltration. Extended pre-treatment (coagulation, sedimentation, rapid sandfiltration and activated carbon filtration) was needed to achieve a stable operation at a relatively high gross flux rate (113 L/h.m²).

Since start up of the Heemskerk plant research into the fouling mechanisms is continued to enable reduction of the pre-treatment for the IJssel Lake water not only for the Heemskerk plant but also for additional direct treatment of the IJssel Lake water in Andijk. In 2001 pre-coat (EPCE) experiments were carried out in parallel with in-line coagulation experiments, both treating the raw water directly with UF-membranes (Galjaard, 2002). This study resulted in the hypothesis that irreversible fouling is not caused by pore blockage but by attachment of the deposited material including colloidal polymers. These polymers seemed to be formed by natural organic matter (NOM) of the IJssel Lake and organic metal complexes. The interaction of these polymer films with the membrane material (hydrophilic negatively charged) made it difficult to reverse fouling.

In literature NOM-fouling of UF-membranes is very often attributed to the deposition of high molecular weight organics (HMW), like polysaccharides and polyhydroxyaromatics on the membrane surface, organics larger than the MWCO-value of the UF membrane (Laine, et al., 2002). In some cases rejection of smaller organics like carboxylic acids and humics was measured and attributed to the deposition of polysaccharides on the membrane surface making the "pores" of the membrane smaller, reaching the cut off value of the acids and humics (Amy et al., 2001)

Our hypothesis proposes that the larger organics interact at high concentrations (at the membrane surface) forming long polymers. The low molecular weight (LMW) organics like carboxylic acids and humics combine with the HMW organics by electrostatic forces and accelerates the formation of a film the same way organic metal complexes do. The membrane may become irreversible fouled rapidly, if the formed film and the

membrane are oppositely charged, since then the film is adsorbed by the membrane. According to our hypothesis two solutions exist to reduce the fouling potential of IJssel Lake water being:

- remove LMW organics like the hydrophilic acids and humics and avoid organic metal complexes (by not using coagulants like ferric or alum) to prevent fast polymerisation and adsorption to the membrane surface (with ion exchange);
- reduce the surface charge of the membrane or increase opposite charge to promote electrostatic exclusion of the formed film.

Considering that UF is a promising solution for future treatment of IJssel Lake water, it is necessary to study the presence and nature of NOM in the raw water, and to find a relationship between the properties of the membrane and the NOM, so that the fouling problem can be better understood and the most suitable membrane material can be proposed for further study.

BACKGROUND

Natural Organic Matter (NOM)

NOM describes the complex mixture of organic material, such as humic and hydrophilic acids present in all drinking water sources. NOM might be harmless in itself but it can cause major problems in the water treatment by reacting with chlorine to form disinfection by-products (DBP's), lowering the UV-transmission, etc. This leads to higher regeneration frequencies of activated carbon filters, to membrane fouling, etc.

NOM can be characterized according to size, structure, and functionality; the important characteristics that affect its interaction with the membrane include molecular weight distribution, hydrophobic (aromatic/cyclic) versus hydrophilic (aliphatic) character, and functional group content.

With regards to its solubility in water, NOM can be categorized into three large groups: hydrophobic, transphilic, and hydrophilic. A hydrophobic species tends to be electrically neutral and nonpolar, and thus preferring neutral and nonpolar solvents or molecular environments. Hydrophobic is used interchangeably with "lipophilic". A hydrophilic molecule is electrically polarized and capable of H-bonding, enabling it to dissolve more readily in water than in oil or other "non-polar" solvents. Transphilic represents a group of NOM with neutral charge (Amy et al., 2001).

NOM and membranes

As a heterogeneous mixture, NOM represents a complex solute that interacts with the membrane surface and pores. For UF membranes, there are three possible interactions with NOM: steric exclusion (rejection), electrostatic exclusion (rejection), and adsorption onto membrane surface/pores (fouling).

In relation to membrane operation, NOM plays an important role in membrane fouling. NOM properties can be represented by various parameters such as dissolved organic carbon (DOC), UV absorbance at 254 nm (UVA_{254}), specific UVA_{254} ($SUVA = UVA_{254}/DOC$), molecular weight (MW) distribution by size exclusion chromatography (SEC), and humic (hydrophobic) content by XAD-8 resin adsorption. Meanwhile, the membranes also have properties that affect their interactions with solutes. Important membrane properties include molecular weight cut-off (MWCO), hydrophobicity, and surface/pore charge (Amy et al., 1999).

Amy and co-workers (1999) found that electrostatic exclusion plays an important role in NOM rejection. It was concluded that the rejection increased with humic content, while a clear trend was not found for molecular weight (MW). It was also noteworthy that there was a preferential rejection of UVA_{254} over DOC, suggesting an effective removal of hydrophobic acids (humic and fulvic) as measured by SUVA.

The lack of a clear trend between NOM rejection and MW supported the assumption that *electrostatic exclusion* plays a more significant role than *steric exclusion*. This conclusion was made based on the fact that the MW range of the NOM is lower than the membrane's MWCO. This leads to the concept of *effective MWCO*, which describes the specific NOM MW corresponding to 90% rejection. This means UF membranes with relatively high manufacturer-reported MWCO values are able to achieve significant NOM removal by exhibiting an 'effective MWCO' significantly lower than manufacturer-reported MWCO.

Membrane properties

Most ultrafiltration membranes for large scale water applications are hollow fibres made of polymers. These fibres need very low trans membrane pressure to produce relatively high amounts of water. The modules of these membranes contain a lot of membrane surface, are chemically resistant and relatively cheap to manufacture, making them suitable for large scale applications in drinking water treatment. Most of these fibres are made by phase inversion processes.

Phase inversion is a process whereby a polymer is transformed in a controlled manner from liquid to a solid state. The process of solidification is very often initiated by the transition from one liquid state into two liquids. At a certain stage during demixing, one of the liquid phases (the high polymer concentration phase) will solidify so that a solid matrix is formed. In most cases water is used to demix the polymer from a solvent. The solvent more or less dilutes into the water phase solidifying the polymer at the same time. Since the polymer has to dilute into the solvent and the solvent into the water, the solvent and the polymer are electrically polarized. This creates a surface charge that is mostly negative. The hydrophilicity is caused by the polymer itself.

Polymers used as membrane material are (listed in order of most hydrophilic to most hydrophobic), (Mulder, 1991):

- Cellulose esters;
- Polycarbonate (PC);
- Polyacrylonitrile (PAN);
- Polyether sulphone blended with 1% polyvinylpropylene (PES/PVP);
- Polyether sulphone (PES);
- Polysulphone (PS);
- Teflon (PTFE);
- Polyvinylidene fluoride (PVDF);
- Polypropylene (PP);

The hydrofobicity starts already more or less with the polyether and polysulphone membranes. The surface charge of most of the hydrophilic membranes is negative but can be made positive for special purposes like paint recovery by adding certain positively charged compounds. For our study we used our standard PES/PVP membranes with slight alterations and PAN membranes since they are more hydrophilic at a surface charge closer to zero.

EXPERIMENTAL SET-UP

The pilot consists of two independently treated feed streams, fed into the small bench scale UF-unit consisting of 4 parallel tested UF-membranes (see figure 1).

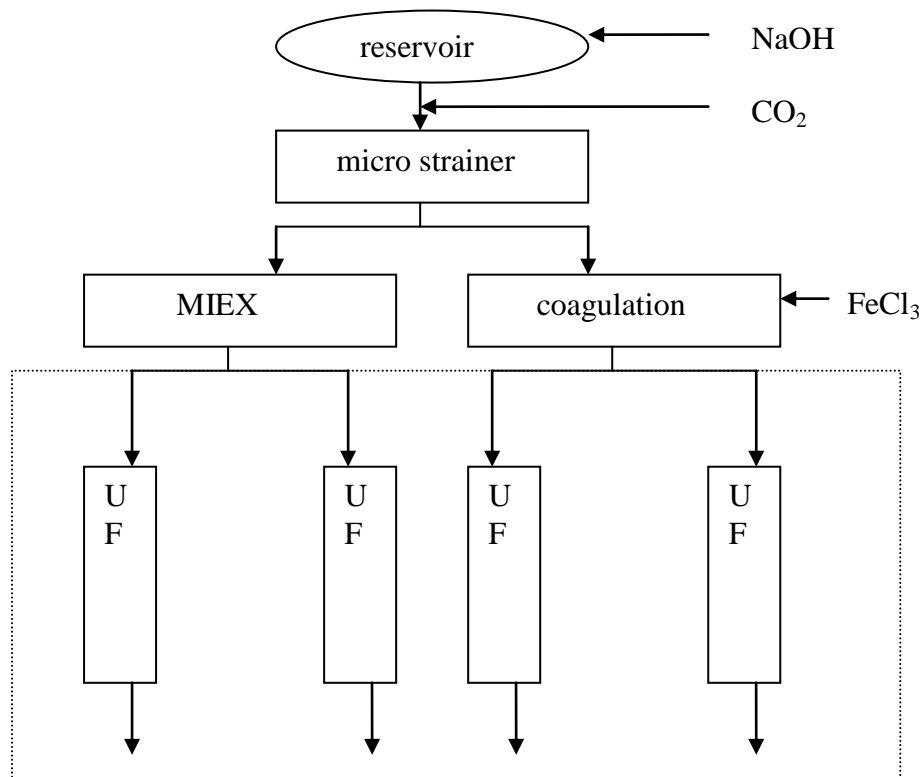


Figure 1 Treatment scheme pilot

IJssel Lake water is stored into a reservoir and chemically softened with NaOH. After storage of several days pH is adjusted from 9,3 till around 8 by a CO₂-dosage and the water is led over micro strainers with a pore size of 30µm. Up till here water from the existing full-scale treatment plant is used. In the pilot facility the stream is split into an ion exchange unit (MIEX pilot) and a coagulation tank. The product of both treatment steps are then fed into a bench-scale UF-installation, the so called Quick-Scan. Each stream is treated by two membranes which differ in material or charge or cut off.

Coagulation

From a jar-test experiment it can be concluded that the coagulation should take place between a pH of 6,5 - 7 to achieve the lowest zeta potential and the highest UV-transmission after filtration. The FeCl₃ dose must be 15 mg Fe/L with a minimum contact time of 5 minutes. Therefore the micro strained water is fed directly into the feed pump of the UF-unit. HCl is injected in the feed line equipped with a static mixer. FeCl₃ is injected downstream of the acid dosage using a second static mixer creating a fully mixed suspension within a second. The FeCl₃ is dosed as a fixed amount whereas the acid is controlled by pH. The FeCl₃ is dosed approximately one meter in front of the feed pump creating a contact time of 5 minutes before the micro flocs reach the membranes. When the UF-unit is not in filtration mode a valve will by-pass the feed flow towards a drain insuring a continuous feed water quality.

Ion exchange MIEX

The chosen ion exchange resin is an anion resin called MIEX. The name MIEX[®] comes from Magnetic Ion Exchange, because the ion exchange resin beads contain a magnetized component within their structure which allows the beads to act as weak individual magnets. In a settler these magnetic particles form rapidly settling resin flocs. The MIEX[®] DOC resin has been designed specifically for the removal of DOC from drinking water. The very small resin bead size of around 180µm (80 mesh) provides a high surface area densely populated with the strong base active sites allowing rapid exchange of negatively charged DOC with the counter-ion chloride released into the water. The MIEX[®] DOC resin is utilised in a continuous ion exchange process. The resin has been developed to enable removal of DOC in a stirred contactor, much like a flash mixer in a conventional water

treatment plant. It is 2-5 times smaller than conventional ion exchange resins. This allows for rapid DOC exchange in the contactor vessel at very low resin concentrations used (10 mg/l). Because of the “open” process design, MIEX[®] DOC Resin is not affected by suspended solids (i.e. turbidity), hence this process can be used as the first treatment stage in a water treatment.

Quick-Scan and membranes

A semi-pilot scale UF Unit known as the Quick-Scan was used to carry out the UF-experiments. It can test up to four elements simultaneously. The membranes were fed by one or by two feed pumps creating the possibility to experiment with two different feed water types. The controls and the data-acquisition are fully automated.

In total 6 different membranes were tested. In table 1 a summary is given of the membrane characteristics.

| Mem. | Material | MWCO [kD] | ID/OD [mm] | Permeability [l/(h.m ² .bar)] | Comments/expected or measured charge by manufacture |
|------|----------|-----------|------------|---|---|
| 1 | PES/PVP | 150 | 0,8/1,3 | 300 | slightly hydrophilic negative |
| 2 | PES/PVP | 250 | 0,8/1,3 | 600 | slightly hydrophilic negative |
| 3 | PES/PVP | 150 | 0,8/1,3 | 200 | hydrophobic less PVP |
| 4 | PES/PVP | 150 | 0,8/1,3 | 400 | hydrophilic more PVP |
| 5 | PAN | 13 | 0,8/1,4 | 200 | hydrophilic negative (- 1mV) |
| 6 | PAN | 13 | 0,8/1,4 | 200 | hydrophilic positive (+4 mV) |

Table 1 Membrane characteristics

Streaming potential measurements

According to our hypothesis the charge of the membrane will influence the fouling. Conceptually, two types of charges on or near interfaces such as a membrane or a filter medium are distinguished:

- The surface charge
- The charge which manifests itself in potentials generated when the particle is moving with respect to the liquid surrounding it. One of the experimental methods to establish this phenomenon is the streaming potential measurement. This charge may manifest itself also by movement of a particle when externally a potential difference is applied over the dispersion, in phenomena such as electrophoresis and electroosmosis

These two types of charge differ because the first layers of solvent molecules are thought to adhere to the solid; only at some distance from the phase boundary, at the **slipping plane**, does the solvent behave as a real liquid (Stein, 1995). The streaming potential includes all charges which are behind this slipping plane; not only the charges on the solid itself, but also the ions very near the surface. Therefore the charge manifests itself in movement of the particle when an electric potential difference is applied. It can be quite different (even with regards to its sign) from the surface charge because in the space between the phase boundary and the slipping plane usually ionic charges are present. It is a non-destructive measurement and generates relative differences in charge under strictly defined conditions. Therefore tests will be carried out with conditioned ultra clear water (demi water produced with a reverse osmoses installation with the addition of 10⁻³ Molair NaCl) before, during and after the experiments. Since no absolute data are available the data will be used relatively as a comparison between the membranes and between a clean and a fouled membrane.

The streaming potential measurement itself consists out of two platinum electrodes placed on the feed and permeate side of the membrane and a mV amplifier. The analog signal will be converted to a digital signal by a/d-converter and logged by a computer.

RESULTS

Initial membrane charge characterized by streaming potential

To verify the charges and the charge differences streaming potential (SP) measurements were carried out. The used streaming potential measurement is not a standardized measurement so protocol and equipment had to be developed. The technique is applied in colloidal chemistry to measure porous media like glass beads in tubes (see material and methods).

The streaming potential measurements were carried out on NOM and suspended matter free water at a specific conductivity, pH and pressure.

In table 2 the measured initial charges are summarized.

| Mem. | Material | Comments/expected or measured charge by manufacture | Measured SP at standard conditions |
|------|----------|---|------------------------------------|
| 1 | PES/PVP | slightly hydrophilic negative | -40 till -60 mV |
| 2 | PES/PVP | slightly hydrophilic negative open | -60 till -100 mV |
| 3 | PES/PVP | tends to hydrophobic less PVP | -20 till -25 mV |
| 4 | PES/PVP | more hydrophilic more PVP | -20 till -25 mV |
| 5 | PAN | hydrophilic negative (-1 mV*) | -50 till -100 mV |
| 6 | PAN | hydrophilic positive (+4 mV*) | +200 till +400 mV |

* Zeta potential measured with the flow potential method by Anton-Paar ElectroKiniticAnalyzer

Table 2 Results streaming potential measurements initial membrane charge

The SP measurement was used to verify relative differences in charges. The measured SP's of the PES/PVP membranes seems to be in agreement with the manufacturers information; the membranes with less PVP seem to have a lower negative charge. The only exception is membrane 4, where the highest negative value was expected but the lowest was found. The charge of the PAN membranes follows the manufacturers information. The values measured by the manufacturer and the measured SP values differ but are in the same order of magnitude. The use of the SP-measurement is helpful to verify the charges.

NOM analysis of the raw water and UF feed water types

The ILC feed stream was optimized to a maximum UVT (82%) and an as low as possible zeta potential value to reduce possible adsorption by the membranes. For this very difficult to coagulate raw water a ferric dose of 15 mg Fe³⁺/L at a pH-value of 7,0 with a contact time of 5 minutes was needed. The ion exchange process (MIEX) was optimised to produce a UVT of approximately 92%. For both pre-treatments the total DOC content was reduced from around 5-6 to 3 mg/L. To determine the removal of the different NOM fractions analysis was performed of the raw water, the ILC water and the MIEX treated water. In table 3 and 4 part of the fractionation is given. Table 3 gives the fractionation in hydrophilic and hydrophobic. Table 4 gives hydrophilic chromatographic fractionation.

| | Total DOC [µg/L] | Hydrofobic [µg/L] | Hydrophilic [µg/L] |
|------------|---------------------|----------------------|-----------------------|
| Raw | 5027 | 356 | 4671 |
| After ILC | 3288 | 375 | 2913 |
| After MIEX | 3369 | 303 | 3066 |

Table 3 NOM analysis: total hydrophobic and hydrophilic fraction of raw water and the two UF feed waters

| | Polysaccharides [µg/L] | Humics [µg/L] | Building blocks [µg/L] | neutrals + amphiphilics [µg/L] | Acids [µg/L] |
|------------|---------------------------|------------------|------------------------------|--------------------------------------|-----------------|
| Raw | 839 | 1988 | 1152 | 630 | 62 |
| After ILC | 385 | 789 | 1143 | 530 | 66 |
| After MIEX | 848 | 509 | 1197 | 511 | 0 |

Table 4 Chromatographic fractionation from HMW (PS) to LMW (acids)

The results are very interesting, after pre-treatment more or less the same total amount of DOC is present but the fractionation is completely different. After ILC most of the larger compounds like the polysaccharides and a big part of the humics are removed. After ion-exchange only the negatively charged smaller DOC compounds like the acids and most of the humics are removed. The goal to produce water with a lower content of HMW compounds like polysaccharides and a water with polysaccharides but without LMW charged matter seemed to be successful.

Experiments with PES/PVP membranes

First experiments were carried out with the standard PES/PVP membranes and the PES/PVP membranes with a lower negative charge. The flux was increased from 50 – 100 L/(h.m²) if a stable operation occurred. In figure 3 the TMP over time is displayed of the first experiment at a flux of 50 L/(h.m²) for ILC only.

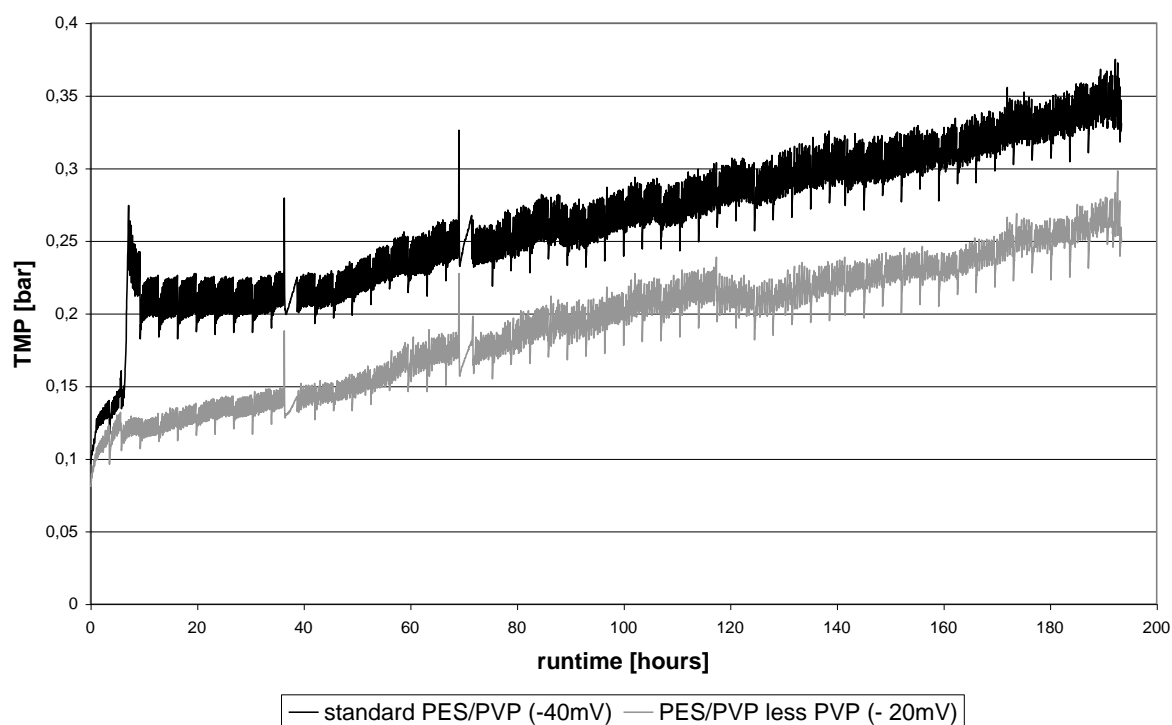


Figure 3 TMP over time at flux 50 l/m².h, feed in-line coagulated water

Both membranes foul quickly. The backwashes and the enhanced backwashes are not capable to restore the TMP sufficiently during the experiment. The overall fouling rate is more or less the same for both membranes. At the beginning of the experiment pressure increased rapidly with the standard PES/PVP module which did not happen with the lower charged one. The fouling rate within a filtration cycle was lower for the lower charged PES/PVP membrane. Hypothesis for the cause of the rapid increase and poor restoration after the washes, the attachment of colloidal polymers was confirmed. Visually long chains of material were released from the fibre which seemed to be very difficult to flush out or to dissolve with the used chemicals (see also figure 4 and 5). Although the fouling rate seems to be higher for the more negatively charged membrane rapid fouling of both membranes took place.

In figure 4 the same experiment is displayed. In this figure the TMP in time of both PES/PVP membranes with the lower negative charge are plotted but now to compare the influence of the two feed water types. There is a significant difference in fouling behaviour between the two feed water types. TMP restoration after a backwash for the MIEX treated water is better than for the coagulated water. Both membranes foul but the fouling rate of the MIEX treated water is lower. Visually there was also a remarkable difference. No long chains of suspended matter were released from the fibres of the membrane on the MIEX stream. The fibres were as clean as at the start (see also figure 5 en 6). The MIEX treated matrix does not seem to form a thin film as in the coagulated stream. The NOM analysis of the permeate of the membranes (table 5) shows that both membranes rejected a big part of the polysaccharides. The smaller polar compounds (building blocks and acids) also seem to be rejected while their size is too small to be size excluded by the membrane. The amount and the difference between the two streams is too small to conclude anything significant about the impact of small polar organics on the formation of this thin film but there is a clear difference in membrane performance and visual formation of long chains in the fibres.

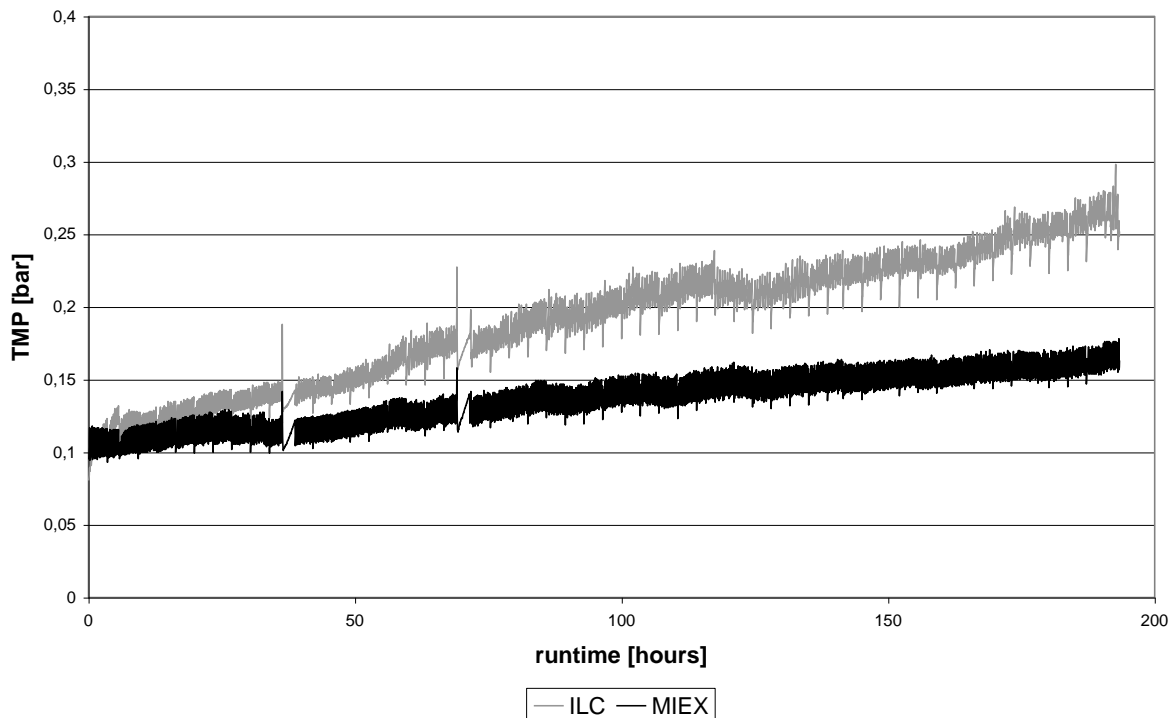


Figure 4 TMP over time at flux $50 \text{ L/m}^2 \cdot \text{h}$, PES/PVP membranes with less PVP (-20mV) feed ILC and MIEX water



Figure 5 Feed stream ILC, backwash

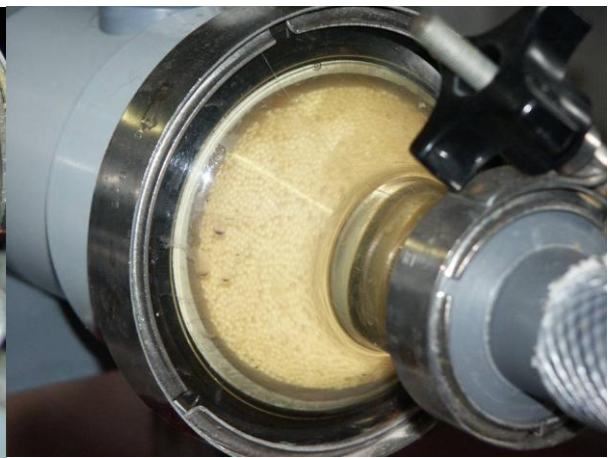


Figure 6 Feed stream MIEX, backwash

| | Polysaccharides [$\mu\text{g/L}$] | Humics [$\mu\text{g/L}$] | Building blocks [$\mu\text{g/L}$] | neutrals + amphiphilics [$\mu\text{g/L}$] | Acids [$\mu\text{g/L}$] |
|--------------|--|-------------------------------|---|---|------------------------------|
| PermeateILC | 85 | 765 | 1037 | 480 | 60 |
| PermeateMIEX | 181 | 401 | 1118 | 441 | 0 |

Table 5 Chromatographic fractionation from HMW (PS) to LMW (acids) for membrane permeate

In figure 7 normalized clean water fluxes (CWF) are displayed of this experiment with the PES/PVP membranes (-40 and -20 mV) on both pre-treatment streams at the beginning of the experiments and after the experiments when they have been cleaned intensively.

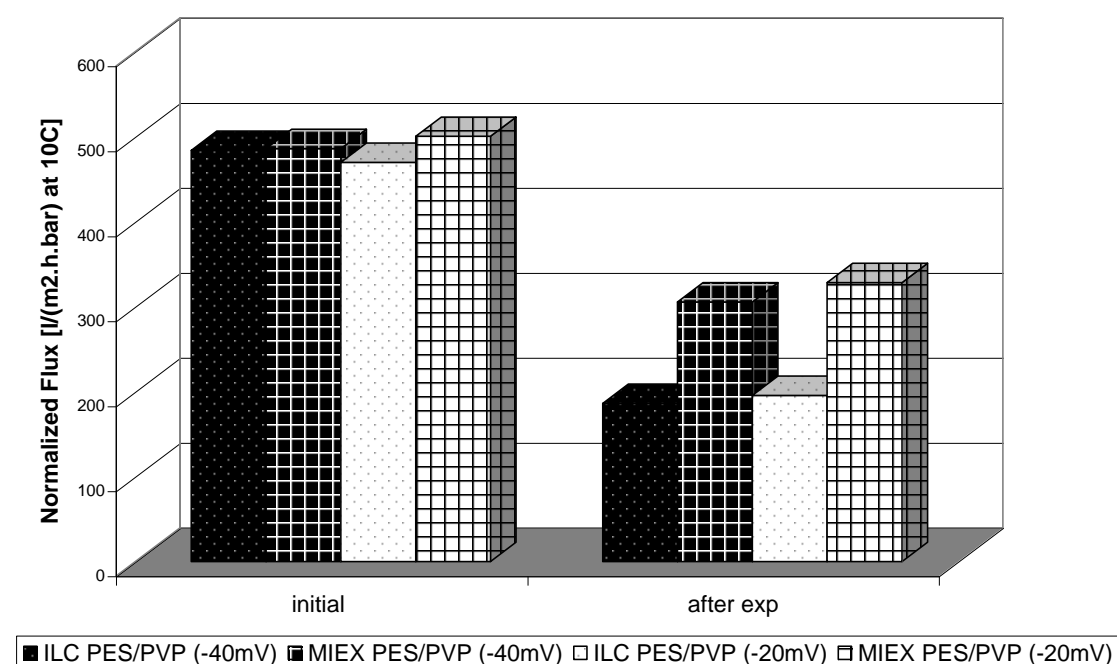


Figure 7 CWF initially and after experiments

The irreversible fouling after cleaning for both membranes and both pre-treatments is significant. In all cases initial CWF could not be restored. The irreversible fouling for the coagulated water is higher than for the ion exchanged water. The significance in charge differences is less till none however both standard membranes with the higher negative charge seem to be a bit lower in flux restoration. After the experiments the SP-values were also determined but since the SP is so much influenced by the permeability of the membranes it was hard to determine if the differences were caused by changes in charge or changes in permeability of the membrane.

Experiments with PAN membranes

Polyacrylonitrile is much more hydrophilic than polyethersulphon. The PAN membranes used in these experiments are also much smoother in membrane surface caused by a tighter and lower MWCO value, this results also in a much lower permeability and therefore higher TMP. Normally a PAN membrane has a negative surface charge. In this case the supplier delivered the same material but positively charged.

The results of the PAN modules were more or less the same as the PES/PVP modules on the two different pre-treatments. Also with the PAN modules the fouling rate of the coagulated water was much higher than the MIEX treated water. There was one remarkable difference, on MIEX treated water the positively charged module did not foul. In figure 8 the TMP in time is given of two different PAN modules on the MIEX treated water. The gross flux during this experiment was $100 \text{ L}/(\text{h.m}^2)$, so already much more increased.

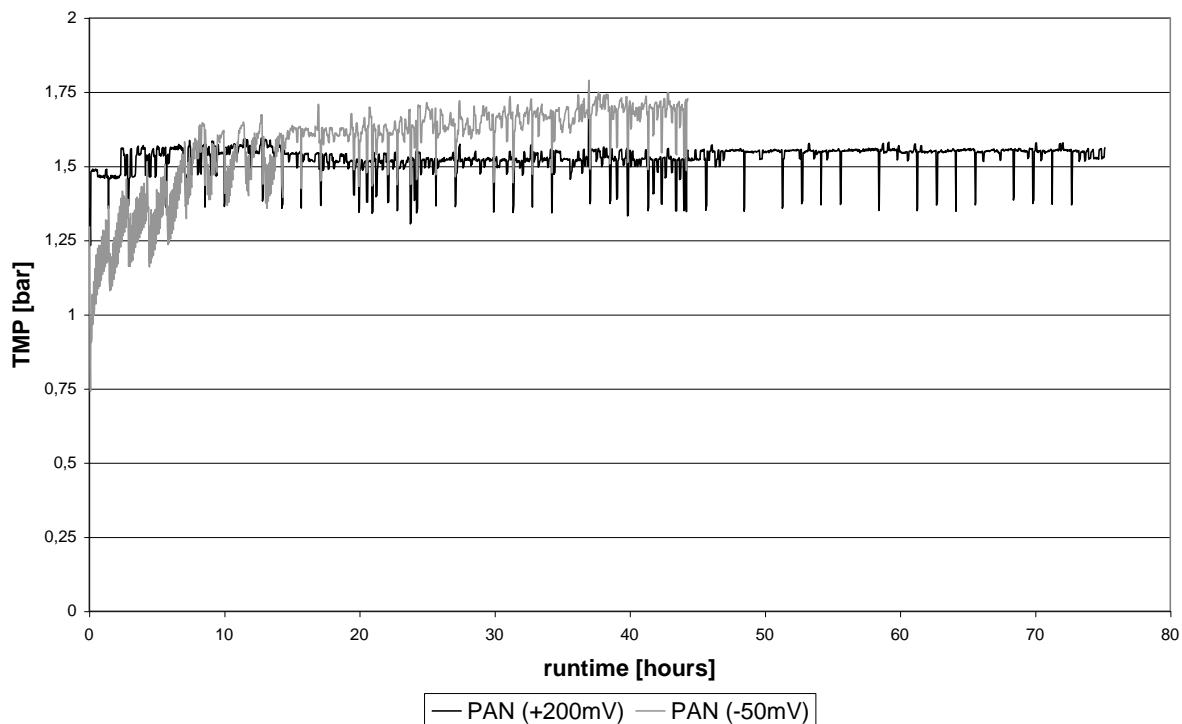


Figure 8 TMP in time of PAN modules on MIEX pre-treated water

After two days the negatively charged membrane unit was switched off while at constant flux the maximum system pressure was reached. The positively charged membrane did not seem to be bothered by anything. An integrity check was performed but the module was found to be in good shape. This makes the result very remarkable. The TMP is not even increasing during a filtration cycle. An explanation could be the positive charge of the membrane since the MIEX exchanged a lot of negatively charged dissolved and suspended matter for negatively charged ions, the charge of the remaining dissolved matter is neutral. An additional explanation could be the carry over out of the MIEX installation positively charged, creating a coating layer. Either way the result is interesting enough for further investigation.

CONCLUSIONS

From this orientating study on the influence of the membrane charge and NOM fractions on the membrane fouling behaviour in treating Lake IJssel water the following can be concluded:

- streaming potential measurements are non-destructive measurements to differentiate between initial membrane charges but can not yet be used to measure changes in charges after membrane fouling;
- enhanced coagulation is a good pre-treatment method to remove the larger part of the high molecular weight (HMW) fraction of the NOM, like polysaccharides (PS);
- ion-exchange with an anion resin like the MIEX removes all negatively charged low molecular weight (LMW) fraction of the NOM, like humics and acids;
- removal of HMW (PS) organic matter does not lead to a lower fouling potential compared to the removal of LMW negatively charged fractions;
- the membrane fouling can be avoided by not forming any film on the membrane surface;
- **the combination of a relatively high positively charged hydrophilic membrane and the removal of LMW fractions with MIEX lead to a high gross flux rate and almost no fouling. Resulting in a product free of suspended matter and a relatively high UV-transmission compared to any other pre-treatment technique.**

LITERATURE

- Amy G, Cho J: *Interactions between Natural Organic Matter (NOM) and Membranes: Rejection and Fouling*; 1999. J. Water Science and Technology, Vol. 40, No. 9: 131-139
- Amy G. [et al] (2001). *Natural Organic Matter (NOM) rejection by, and fouling of, NF and UF membranes*; ISBN 1-58321-106-3
- Cho J., Amy G., Pellegrino J. (2000). *Membrane Filtration of Natural Organic Matter: Comparison of Flux Decline, NOM Rejection, and Foulants during Filtration with Three UF Membranes*. J. Desalination, Vol. 127: 283-298
- Cho J., Amy G., Pellegrino J. (2000). *Membrane Filtration of Natural Organic Matter: Factors and Mechanisms Affecting Rejection and Flux Decline with Charged Ultra filtration (UF)*. J. Membrane Science, Vol. 164: 89-110
- Cho J., Amy G., Pellegrino J., Yoon Y. (1998). *Characterization of Clean and Natural Organic Matter (NOM) Fouled NF and UF Membranes, and Foulants Characterization*. J. Desalination, Vol. 118: 101-108
- Galjaard G., Kruithof J.C. (2002). *Enhanced Pre-Coat Engineering (EPCE) for MF and UF: Steps to Full-Scale Applicatio*. Proceedings IWA, ISSN 0941-0961
- Kaiya Y., Itoh Y., Takizawa S., Fujita K., Tagawa T. (2000). *Analysis of Organic Matter Causing Membrane Fouling in Drinking Water Treatment*. J. Water Science and Technology, Vol. 41, No. 10-11: 59-67
- Laine J.M., Campos C., Baudin .I, Janex M.L. (2002). *Understanding Membrane Fouling: A Review of Over a Decade of Researc*. Proceedings IWA, ISSN 0941-0961
- Lee H., Amy G., Cho J., Yoon Y., Moon S.H., Kim I.S. (2001). *Cleaning Strategies for Flux Recovery of An Ultra filtration Membrane Fouled by Natural Organic Matter*. J. Water Resources, Vol. 35, No. 14: 3301-3308
- Lee S., Shim Y., Kim I.S., Sohn J., Cho J. (2002). *Determination of Mass Transport Characteristics for Natural Organic Matter (NOM) in Ultrafiltration (UF) and Nanofiltration (NF) Membranes*. J. Water Science and Technology, Vol. 2, No. 2: 151-160
- Mulder M. (1991). *Basis Principles of Membrane Technology*. ISBN 0-7923-0978-2
- Shim Y., Lee H.J., Lee S., Moon S.H., Cho J. (2002). *Effects of Natural Organic Matter and Ionic Strength on Membrane Surface Charge*. J. Environmental Science Technology, Vol. 36, No. 17: 3864-3871
- Stein H.N.(1995). *The preparation of dispersions in liquids*. ISBN 0-8247-9674-8