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MFI–UF constant pressure at high ionic strength conditions

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ABSTRACT

It has been clearly proven that particles much smaller than 0.45 μm are responsible for colloidal fouling of the surface of RO and NF membranes. As a consequence the predictive value of SDI and MFI (0.45 μm) in particulate fouling is doubtful. To overcome this deficiency the MFI–UF has been developed, making use of ultrafiltration membrane with different pore sizes and measured at constant pressure or constant flux. The MFI–UF has not yet been tested and evaluated for brackish/estuarine water and seawater. The objective of this work is to investigate the effect of salinity on the MFI–UF constant pressure for higher ionic strength conditions present in brackish/estuarine waters and seawater prior to application to reverse osmosis. For this, specific objectives are to ascertain the effect of pressure and ionic strength on various membrane filters. Membrane filters consisting of three membrane materials were tested – PES, RC, and PVDF – with different MWCOs (100, 30 and 10 kDa and 0.1 μm for PDVF). Ultra pure water was used to prepared standard solutions having different salinities, together with Delft canal water and Delft tap water. One membrane filter showed significant compaction after testing with ultra pure water namely 100 kDa RC membrane at pressures above 1.5 bar. "Salt compaction" measured at 1 bar and by increasing the salt concentration in 5 g/L steps was higher for PES than for RC membranes. PVDF membranes only showed apparent/salt compaction starting at 20 g/L. For PES membranes,the observed flux decline due to sodium chloride was faster and higher than for RC and PVDF membranes. The calculated "blank" or apparent MFI–UF values due to salinity were low compared to MFI values usually observed in surface and seawaters. Pre- conditioning of the membranes by soaking in sodium chloride solutions might eliminate this blank previous testing. Addition of different amounts of sodium chloride to tap water and to canal water resulted in higher values of MFI for MF membranes, while for UF membranes the effect was not significant (7% deviation from 0 to 35 g/L).

Keywords: MFI–UF; Constant pressure; Seawater; Ionic strength

1. Introduction

Particulate fouling of RO elements can seriously harm performance by lowering productivity and sometimes salt rejection. An early sign of colloidal fouling is often an increased pressure differential across the system. The source of particles or colloids in reverse osmosis feed waters is varied and often includes bacteria, clay, colloidal silica, and iron corrosion products [1–3]. Several methods or indices have been proposed to predict particulate

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fouling potential of feed waters, including turbidity, silt density index (SDI) and modified fouling index (MFI). The SDI is the most commonly used fouling index.

Traditionally, an indirect estimate of fouling potential has been done through the silt density index (SDI) and, later on, the modified fouling index (MFI), making use of membrane filters with pores of 0.45 μm and 0.05 μm. The MFI (0.45) has many advantages above SDI e.g. it shows a linear relation with concentration of colloidal particles and is based of the cake filtration mechanism. However, it has been clearly proven that particles much smaller than 0.45 μm are responsible for colloidal fouling of the membrane surface. Therefore, in 2003, Boerlage developed the MFI–UF, where the MFI–UF was measured with membranes with different pore sizes and used at constant pressure and constant flux [4].

The MFI–UF — using ultrafiltration membranes — has not yet been tested and evaluated for brackish/estuarine water and seawater. Nevertheless, it is possible to find studies that made use of the MFI — using a 0.45 μm filter — as fouling indicator in these kind of waters. Khirani et al. [5] made an attempt to improve the MFI test by using nanofiltration membranes (MFI–NF); in this case, the salt retention of NF membranes limited the study to natural organic matter solutions and wastewater effluents.

The objective of this work was to investigate the effect of salinity on the measurement of MFI–UF with membranes with different materials and pore sizes. In particular the effect of the permeability of the membrane filters used and the effect on the MFI–UF itself due to changes in specific permeabilty of the formed cake.

2. Background

Salinity affects mainly the membrane permeability and specific cake resistance formed by particles on the membrane surface.

2.1. *Effect of salinity on the permeability/pore size*

Tansakul et al. [6] observed that the pure water membrane permeability of PES 30 kDa was reduced after submersion of the membrane in 10 mg/L humic acid solution for 24 h at pH 7 with and without salts (36 g/L NaCl + 400 mg/L $CaCl_2$). The highest reduction of permeability was obtained in the presence of salts of around 35%. Tansakul attributed the water permeability loss due to an adsorption phenomenon (charge neutralization).

The adsorption of solutes has a negative influence on the flux because the adsorbed layer presents an extra resistance towards mass transfer and consequently contributes to a decline in flux [7].

Cho et al. [8] studied the influence of ionic strength on PEG rejection and found higher PEG rejection with higher ionic strength, thus indicating that the pore radii of the membranes are decreased by higher ionic strength. In the same study when natural organic matter (NOM) was used, it was observer that pH and ionic strength play an important role in the charge repulsion between NOM and the membrane surface and NOM adsorption.

Braghetta et al. [9] studied the permeability of a negatively charged sulfonated polysulfone NF membrane with 1 kDa MWCO and found that the permeability decreased when using ultra-pure water with different amounts of NaCl (93–4380 mg/L) at pH 7. The reduction of permeability was attributed to a compaction of the membrane matrix resulting from charge neutralization at the membrane surface and electric double layer compression.

2.2. *Effect of salinity on characteristics of the particles*

Guéguen et al. [10] cited that increasing ionic strength is known to decrease the effective molecular size of organic molecules in solution, potentially increasing their absorption properties on membrane sites. High ionic strength may also favor cake formation on a tangential flow filtration (TFF) membrane (fouling process).

Typically, surface water particles are negatively charged and stable due their high zeta potential which is a measurement of the electro-kinetic potential of the surface. Also, the membrane surface and pores have a negative charge and when it contact with water cause a polar medium which develop a double layer. Therefore, an increase of ionic strength may cause compression of the double layer around the particles and membrane surface which lead to an increase of specific cake resistance [4].

Ribau Teixeira and Rosa [11] in 2002 reported that at high ionic strength humic substances have a small hydrodynamic radius in solution and a large adsorbed layer thickness when adsorbed on the surface. On the other hand, at low ionic strength, humic substances have a large hydrodynamic radius and a small adsorbed layer thickness.

3. Material and methods

Different types of water and three membrane materials of various MWCOs were used to assess the effect of ionic strength (mainly due to sodium chloride) on membrane permeability.

3.1. *Feed solutions*

Ultra pure water (milli-Q), Delft tap water (DTW), Delft canal water (DCW), prepared Delft tap water (PDTW) and seawater from the North Sea (NSW) were used in this study.

Milli-Q water is produced by RO permeate that is fed to a Millipore unit (model A10 with TOC monitor device). This unit includes three purification steps namely: i) "plug-in Q-Guard" purification pack, ii) ion exchange cartridge and iii) 0.22 μm membrane filter. Milli-Q water is deionised water with a resistance equal to 18.2 mΩ (0.055 µS/cm) and TOC ~4 ppb. This water was used to pre-condition membranes by soaking them before filtration in any test for around one day, to calculate the clean water flux, and to prepare feed solution. Delft tap water (DTW) was collected directly from a tap at IHE's laboratory facilities. Evides Drinking Water Company produces the DTW and the quality composition is shown in Table 1. The SUVA is 1.4 L/mg-m and DTW can be classified as a non-humic water. Delft canal water (DCW) was collected from the canal in front of IHE. Samples were pre-filtered through a 0.45 µm filter (Cellulose Acetate) and stored at 4°C. Prepared Delft tap water (PDTW) is a mixture of DCW and DTW with a ratio of 1:16 respectively. Table 1 shows the water quality parameters for both DCW and PDTW used as feed water in filtration test. Both DCW and PDTW could be classified as transition waters between humic and non humic (NOM) waters.

North seawater (NSW) was collected from the North Sea about 30 m from the shore at Scheveningen (The Netherlands) and stored at cold temperature in the dark. Table 1 shows the characteristics of NSW. This seawater could be classified as non-humic where the SUVA is less than 2 L/mg-m and has low salinity compared with other seawater such as Mediterranean, Red Sea and Oman Gulf seawater (> 35 g/L).

Table 1
Water quality characteristics

Parameter	DTW	DCW	PDCW	NSW
pH	8.16	7.8	7.7	8.2
EC, µS/cm	486	1100	510	52,500
TDS, mg/L	116*	700	330	35,000
DOC, mg/L	1.9	18.5	1.85	2.85
UV_{254}, abs/cm	0.027	0.584	0.042	0.048
SUVA, L/mg.m	1.4	3.2	2.3	1.7

* Value for alkalinity, mg HCO_3/L

3.2. Membranes

Three membrane materials — polyethersulfone (PES), regenerated cellulose (RC) and polyvinildifluoride (PVDF) — and a range of molecular weight cut offs (MWCO) — 100, 30, 10, 5 kDa and 0.1 µm for PVDF — were used in this study and tested at constant pressure filtration mode under different conditions of ionic strength. Table 2 summarizes the membranes for this study.

Fig. 1 shows the chemical structure of common MF/UF membrane materials. Despite the excellent chemical and thermal conditions of hydrophobic polymers, stable hydrophilic polymers are more interesting as membrane materials because of their reduced adsorption tendencies [7]. The cellulose acetate (CA) chemical structure shown is representative of regenerated cellulose (RC).

3.3. Filtration set-up

In this study the filtration tests were performed at constant pressure mode. The set-up is illustrated in Fig. 2. Batch experiments were conducted using un-stirred Amicon cells (Millipore series 8000, models 8050 and 8010) with a maximum process volume of 50 ml and 10 ml where the effective membrane area used for these models are 13.4×10^{-4} m^2 and 4.1×10^{-4} m^2, respectively. The stirring assembly was entirely removed from the cell in order to permit a cake to form where the filtration was achieved under dead-end, constant pressure mode.

The feed water was transferred to the pressure vessel which has a maximum volume of approximately 4 liters. The required pressure was achieved by applying pressurized nitrogen gas adjusted by a pressure sustaining valve (FESTO, model LRP: ¼–4) with a maximum operating pressure of 4 bar. Then, feed water was passed through a membrane filter where permeate was collected in a beaker set on an electronic balance (Mettler Toledo, Model PB 602-S). The scale has an RS 232 interface with a computer in order to acquire permeate weight from the balance.

Data sets of collected filtrate weight and filtration time are recorded and imported into a MS Excel spread sheet with data acquisition software "WinWedge". The

Table 2
Membranes used in the study

Material	Acronym	MWCO, (kDa)	Wettability	Manufacturer
Polyvinylidene fluoride	PVDF	0.1 µm	Hydrophilic	Millipore
Regenerated cellulose	RC	100	Hydrophilic	Millipore
	RC	30	Hydrophilic	Millipore
	RC	10	Hydrophilic	Millipore
Polyether–sulfone	PES	100	Hydrophilic	Millipore
	PES	50	Hydrophilic	Millipore
	PES	30	Hydrophilic	Millipore
	PES	10	Hydrophilic	Millipore

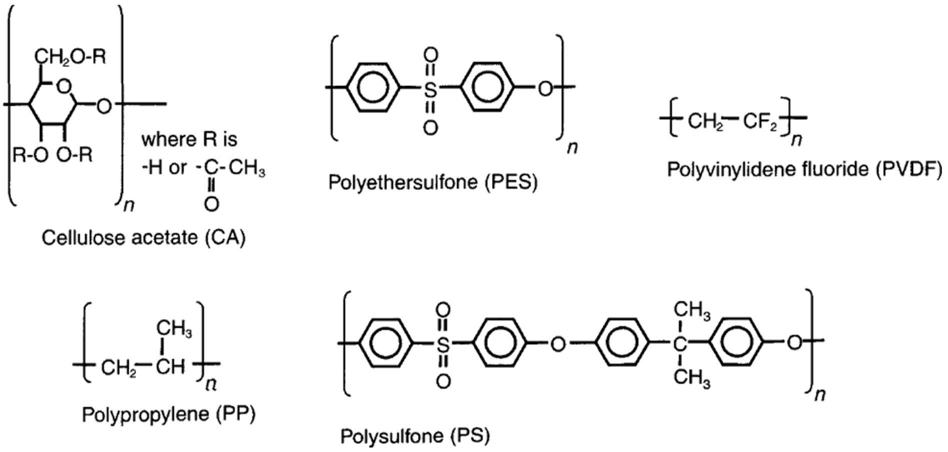

Fig. 1. Chemical structure of common MF/UF membrane materials [12].

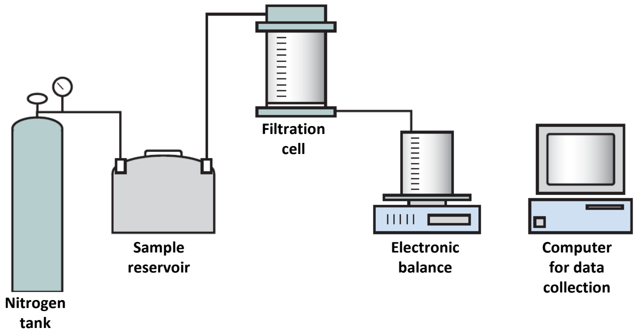

Fig. 2. Scheme of filtration setup [13].

recording interval in the spreadsheet could be adjusted (minimum interval of 1 s) prior to the filtration run, and was constant throughout the run. The spreadsheet was adapted to include a graph of the calculated value of MFI versus time in order to set the criteria of filtration time discussed later in this paper.

4. Results and discussion

4.1. Membrane characterization: R_m

All the tested membranes were first characterized by measuring the membrane resistance. This test was performed by filtrating ultra pure water at a constant pressure.

Membrane permeability is a function of membrane properties such as thickness, surface porosity, pore radius and tortuosity and it can be measured using the equation $R_m = \Delta P/(\eta \cdot J)$ when ultrapure water is filtered through the membrane at a fixed pressure. Normally, the membrane flux depends on the applied pressure, pore size, pore size distribution and surface porosity. It was assumed that it is constant for the same membrane material of same MWCO, porosity, tortuosity, etc., made by the same manufacturer and from the same batch.

Fig. 3 shows the membrane resistance (R_m) values obtained for new-clean membranes used during the study.

The regenerate cellulose (RC) membrane showed a higher membrane resistance than polyethersulfone (PES) for the same MWCO. This suggested that RC membranes required higher pressure than PES membrane to produce the same flux or gave a much lower flux at the same pressure. This may be attributed to a lower surface porosity, tortuosity, and to pore size of the RC compared with PES, which reduced the effective filtration area; hence, leading to lower flux through the membrane at same pressure. Mulder reported that a uniform molecular weight of membrane polymer does not exist but rather a molecular weight average [7]. Hence, even though the MWCO's

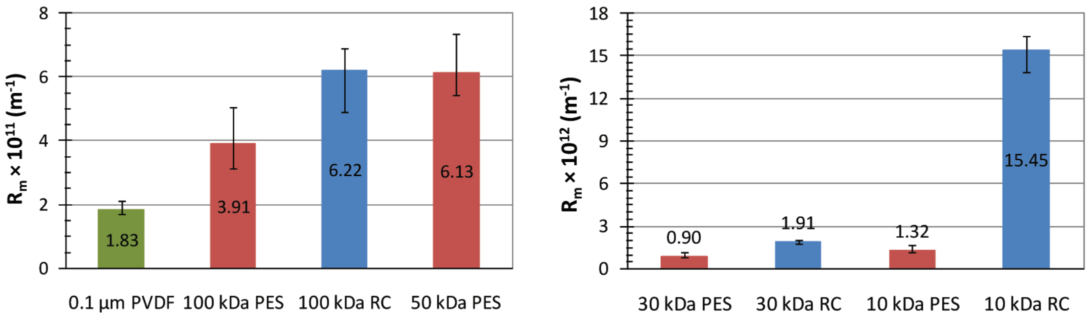

Fig. 3. Membrane resistance (R_m) for the membranes tested in the study.

are the same this does not mean that the pore size is the same as most manufacturers measure the MWCO in different ways.

4.2. Effect of pressure on membrane material

Compaction of membranes may influence the MFI–UF value as membrane resistance in compacted membranes increases. Membrane compaction is defined as mechanical deformation of a polymeric membrane under pressure causing the porous structure to densify and consequently the flux to decline [7]. In order to evaluate the effect of pressure on membrane compressibility (increase in R_m), milli-Q water was filtered through PES and RC membranes with various MWCO. The TMP was varied between 0.5 to 3.5/4.0 bar in 0.5 bar intervals. The temperature of the feed water was maintained constant throughout the experiments ranging from 20.5 to 22.2°C. The pressure effect on UF membrane compressibility was assessed for 100, 30, 10 kDa RC and PES membranes.

By re-arranging the equation $R_m = \Delta P/(\eta \cdot J)$, a linear relationship between applied pressure (ΔP) and flux (J) through membrane was obtained. This equation is applicable if the feed water temperature is kept constant throughout the tests with consideration that the R_m is constant at different applied pressures.

$$J = \frac{\Delta P}{\eta \cdot R_m} \tag{1}$$

Fig. 4 (left) shows the results of flux depending on pressure for the studied membranes. The results indicate that 100, 30, 10 kDa PES membranes are stable over the pressure range 0.5–3.5 bar, and a linear relationship was obtained between flux and ΔP ($R^2 = 0.99$).

In the case of RC membranes, for 30 and 10 kDa no significant effect of pressure on membrane compressibility was observed ($R^2 = 0.99$ linear). In contrast, the 100 kDa RC membrane showed some signs of compaction as the pressure increased from 0.5 to 3.5 bar; the flux did not increase linearly, but started to level-off above a pressure of 1 bar. Moreover, the initial R_m was increased by 38% from 4.9 to 7.9×10^{11} m^{-1} as shown in Fig. 4 (right).

The membrane compaction coefficient was calculated using Eq. (2):

$$R_m = R_{mo} \Delta P^h \tag{2}$$

where R_m is the membrane resistance (m^{-1}), R_{mo} is the membrane resistance at zero compressive pressure, ΔP is the transmembrane pressure (bar) and h is the membrane compaction coefficient.

For the 100 kDa RC membrane, a power law relationship between membrane resistant and pressure with a compaction coefficient of 0.25 was observed for the range of applied pressure (0.5 and 3.5 bar). Boerlage [14] also found a power law relationship between membrane resistance and pressure for the PAN 13 kDa. A compaction coefficient of 0.058 and 0.052 was estimated for new and used membranes, respectively. In her study, the initial membrane resistance increased by 8% and 7% for new and used membranes, respectively, while the applied pressure increased from 0.5 to 2 bar using RO permeate water. Boerlage concluded that this increase was not expected to have a significant effect on membrane surface properties such as pore size.

4.3. Ionic strength effects

This section deals with the influence of ionic strength on membrane permeability. Ionic strength was controlled by NaCl which represents ~73% of the ionic strength of seawater [15]. Results showed a flux decline over time during filtration tests.

4.3.1. Effect of ionic strength on membrane resistance

Three different membranes were used namely: 0.1 µm PVDF, 100 kDa PES and 100 kDa RC. The filtration tests were performed at constant pressure (1 bar) with an effective membrane diameter of 22.85 mm (4.1×10^{-4} m^2). Feed solutions were prepared with milli-Q water and different

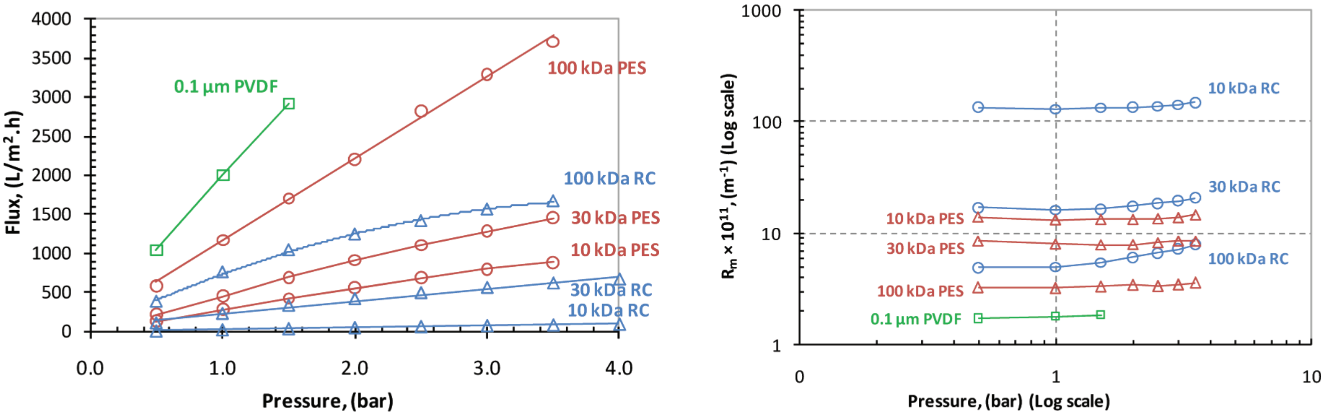

Fig. 4. Flux vs. pressure (left) and log plot of R_m vs. pressure (right) — RC and PES membranes.

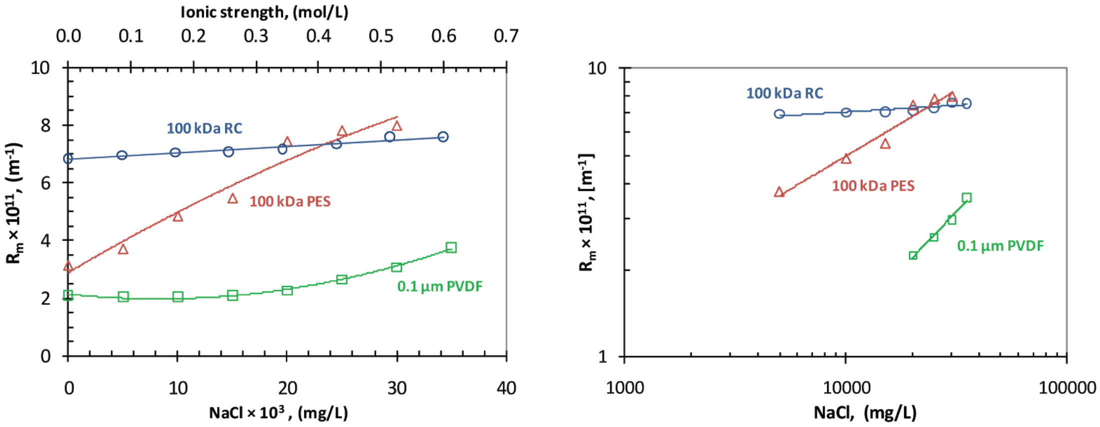

Fig. 5. $\boldsymbol{R_m}$ vs. ionic strength ($\boldsymbol{P}$ = 1 bar) (left) and log plot $\boldsymbol{R_m}$ vs. log NaCl concentration (right).

NaCl concentrations from 0 up to 35 g/L. For each test, the same membrane filter was used for all tests.

Fig. 5 (left) shows the R_m for various ionic strength conditions. For the 100 kDa PES membrane, the initial R_m (3.15×10^{11} m^{-1}) increased by 150% as the sodium chloride concentration increased from 0 to 30 g/L. For 100 kDa RC, the R_m slightly increased (10%) for the same sodium chloride range. On the other hand, for the 0.1 µm PVDF membrane, the R_m showed no significant change for NaCl between 0–20 g/L, and a gradual increase was observed between NaCl concentrations of 20–35 g/L (80% increase). In average, each test lasted around 45 min.

A possible explanation of the observed results can be explained using the zeta potential of membranes. The zeta potential is not constant and mainly dependent on two parameters, the surface charge of the membrane and the ionic strength of the feed solution. The surface charge may be strongly dependent on pH (constant in these tests), while the ionic strength depends on the concentration and on the valence of the ions involved [7]. This suggests that an increase of the ionic strength results in a decrease of the double layer thickness and of the zeta potential. Braghetta et al. [9] reported that increasing ionic strength decreased organic matter rejection despite a reduction in membrane permeability.

According to the aforementioned, ionic strength most likely caused a pore size reduction by adsorption of Na^+, or Cl^- ions which could be the cause of decrease in zeta potential of the membrane. Consequently, this leads to a reduction in permeability and flux decline. Also, the membrane surface is negatively charged; therefore, the increasing of ionic strength by NaCl most likely will cause compression in double layer of membrane surface where zeta potential increase up to positive charge, which lead to a reduction in pore size and hence, a reduction in membrane permeability.

Fig. 5 (right) shows the results of log plot of R_m for different NaCl concentrations, and Table 3 shows the results of "apparent compaction" due to high ionic strength.

The calculated "salt compaction" factors were obtained from Eq. (2) (power law fit) and the obtained values were 0.05 for the 100 kDa RC, 0.46 for the 100 kDa PES, and 0.81 for the 0.1 µm PVDF. A high value of apparent compaction may indicate that the membrane is highly influenced by ionic strength as PES results suggest.

Bragettha et al. [9] reported that the surface of a regenerated cellulose acetate UF flat disc (amicon YM series) is considered non-ionic and hydrophilic in nature and has been shown to be relatively unaffected by change in solution pH and ionic strength.

Summarizing this section, the 0.1 µm PVDF and 100 kDa PES membranes were affected by ionic strength of the feed solution. Less effect of high ionic strength on the 100 kDa RC membrane was observed.

4.3.2. *Effect of filtration time*

From the previous section it was observed that salin-

Table 3
Membrane "salt compaction" due to ionic strength at P = 1 bar

Membrane	NaCl (g/L)	Equation	Compaction factor	R^2
0.1 µm PVDF	20–35	$R_m = 0.0007\ \mathrm{NaCl}^{0.81}$	0.81	0.98
100 kDa PES	5–35	$R_m = 0.07\ \mathrm{NaCl}^{0.46}$	0.46	0.96
100 kDa RC	5–35	$R_m = 4.63\ \mathrm{NaCl}^{0.05}$	0.05	0.77

ity may have caused the pores to shrink. The reduction of membrane permeability when in contact with saline water influences the measurement of MFI–UF/MF values.

Three membrane materials (PVDF, RC and PES) with different MWCO values were assessed. The membrane area was constant in all cases and the feed solutions were prepared from ultra pure water "milli-Q water" with addition of 35 g/L of NaCl and allowed to equilibrate at room temperature (~21.5°C) before the filtration test was started. The experiments were performed at constant pressure (1–1.5 bar).

The flux decline vs. filtration time is presented in Fig. 6.

From Fig. 6 it is observed that the flux decline with the PES membranes was faster than in the case of PVDF and RC membranes in the presence of 35 g/L NaCl. For RC membranes, the lower the MWCO the lower the flux decline; while for PES membranes, the 100 kDa showed higher flux decline compared to the 30 kDa. The PVDF membrane showed a trend intermediate PES and RC.

The membrane resistance was monitored versus time as shown in Fig. 7. In all cases, R_m increased with the time. Both the 30 and the 10 kDa PES had similar membrane resistance. At time zero, the R_m corresponded to the clean water resistance and it can be observed that in the presence of salt, the membrane resistance increased; this may be attributed to the decrease in pore size resulting from the ionic strength effect [9]. Another alternative is that particles were present in the ultra pure water. However, in all cases PES showed a higher flux decline than in the case of RC membrane.

In Fig. 8, a comparison of flux decline among three membrane materials after the same filtered volume (1.8 L) and same exposure time (3.4 h) is shown. Considering the flux decline after same filtered volume, for PES it was observed that the salt effect increased as the membrane pore size decreased. In the case of RC the flux decline was less significant than for PES and PVDF. Considering the same salt loading (same exposure time to 35 g/L salt), it was observed that the higher the MWCO the higher the flux decline for PES and RC.

These results suggest that RC membranes are less affected by salt than PES membranes. An implication of these results may indicate that it is necessary to precondition the membranes by soaking them in high ionic strength solution (milli-Q + 35 g/L) for one day before MFI–UF test to avoid any contribution of flux decline due to high ionic strength.

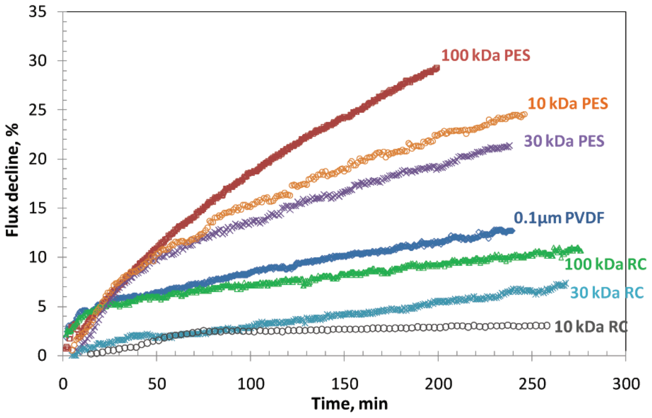

Fig. 6. Flux decline vs. filtration time (milli-Q + NaCl 35 g/L)..

4.4. *Effect of ionic strength on MFI–UF value*

4.4.1. *Effect of ionic strength on the MFI–UF value: apparent MFI–UF*

The results from the previous section were used to calculate an "apparent MFI–UF" with ultra pure water and no particles and therefore the results show "only" the effect of salt on the MFI–UF values (apparent MFI due to salt).

Fig. 9 shows the calculated apparent MFI–UF values for PES, RC and PVDF membranes. In all cases a MFI–UF value was registered; for PES higher values than for RC and higher when lowers the membrane MWCO. As the MFI–UF value is a measure of particulate/colloidal fouling, the colloids present in the tested water may come

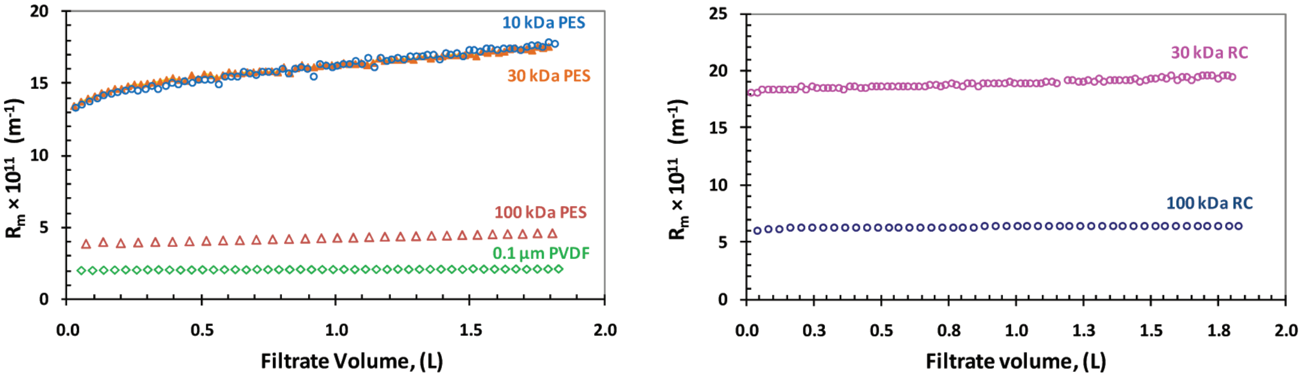

Fig. 7. R_m vs. filtrate volume for PES, RC and PVDF membranes (milli-Q + NaCl 35 g/L).

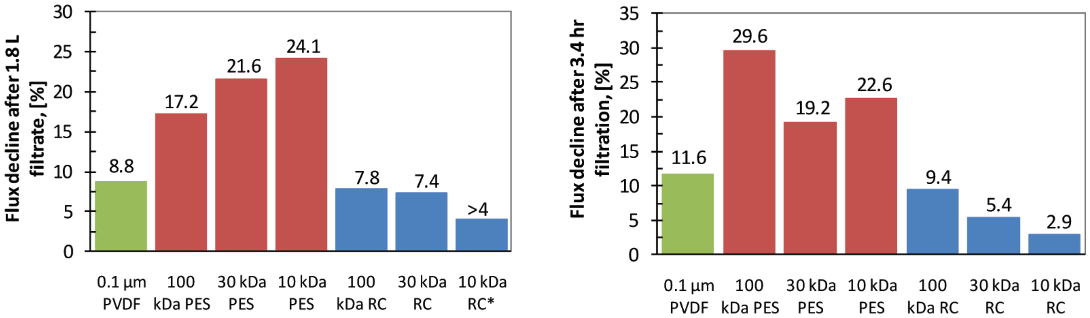

Fig. 8. Flux decline in % at same filtered volume (left) and at same exposure time (right) vs. membrane type.

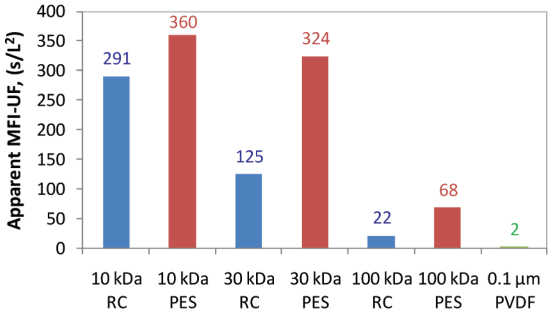

Fig. 9. Apparent MFI–UF after filtration with milli-Q + NaCl (35 g/L).

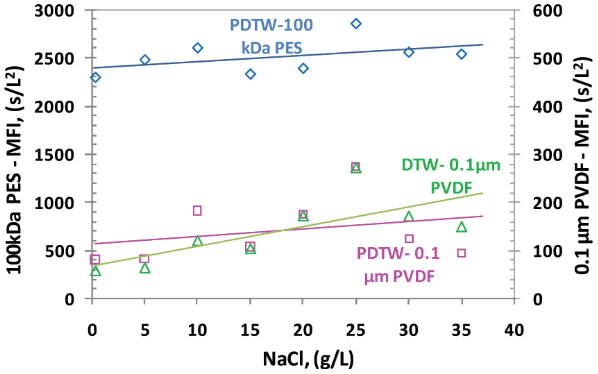

Fig. 10. MFI–UF at different addition of ionic strength of NaCl for 0.1 µm PVDF and 100 kDa PES at $P = 1$ bar.

from impurities in the NaCl reagent that did not dissolve completely and created resistance while filtration occurred, or from particles/colloids present in the ultra pure water smaller than 0.22 µm (see section 3.1).

4.4.2. Effect of ionic strength on MFI–UF value

Two different water samples were used, DTW and PDTW. A 0.1 µm PVDF and 100 kDa PES were used at a constant pressure (1 bar). The feed-water samples were prepared at various NaCl concentrations (0, 5, 10, 15, 20, 25, 30, 35 g/L) and allowed to equilibrate at room temperature before each filtration test. In all experiments, a new flat membrane filter was used and pH of feed solution ranged from 7.7 to 7.8.

The results are illustrated in Fig. 10. For the three tests, the MFI trend is similar depending on the NaCl concentration. As expected, for the 100 kDa PES, the MFI values are higher than using the 0.1 µm PVDF membrane, as smaller particles are caught by the smaller MWCO membrane.

The DOC content for DTW and PDTW (DCW + DTW) was 1.9 and 2.3 mg/L, respectively. The UV_{254} for DTW was 0.027 abs/cm and SUVA was 1.4 which would classify it as a non-humic water. On the other hand, the UV_{254} for PDTW was 0.042 abs/cm and the SUVA was 2.3, which would classify it as a transition water between humic and non humic.

The MFI–UF results presented in Fig. 10 show a slight increase in value as the salt concentration increases. The standard deviation in the case of 100 kDa PES was 7% while in the case of 0.1 µm PVDF the standard deviation was about 50%. In the 100 kDa membrane, the increase could be considered as not significant while in the case of 0.1 µm PVDf the increase was significant. Nevertheless, more research is needed to understand all the factors influencing the results.

Boerlage et al. [4] cited that the ionic strength causes an initial increase in specific cake resistance due to a reduction in cake porosity which is caused by a decrease in the inter-particles distance between particles in cake filtration. On the other hand, the decrease in specific cake resistance is probably due to an increase in ionic strength where zeta potential is reduced to zero which leads to a larger particles aggregation that cause increasing in cake filtration permeability.

Summarizing, the results of increasing, in steps, the ionic strength suggest that from 0 to 0.171 M NaCl the increase in MFI value was due to reduction in cake porosity (increase of specific cake resistance). In the case of higher ionic strength (>0.43 M NaCl), the decrease of MFI value is attributed to an increase in ionic strength above the critical concentration of coagulation which leads to larger particles aggregation, causing a reduction in specific cake resistance.

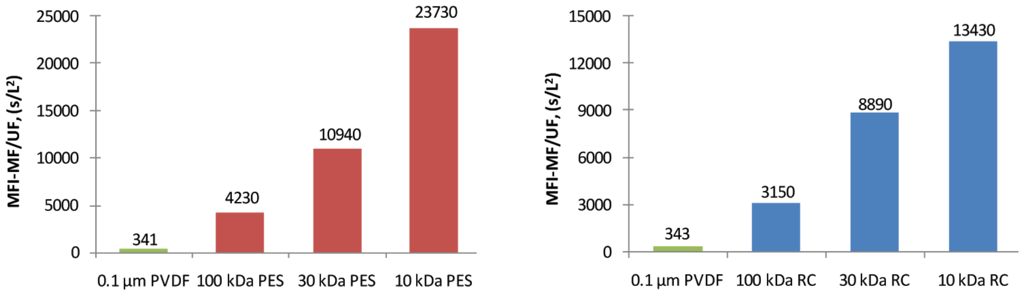

Fig. 11. MFI–UF values for pre-filtered (0.45 μm) North Sea water as function of MWCO and membrane material.

North Sea water was pre-filtered in a 0.45 μm cellulose acetate filter. Later on, this water was tested using PES, RC and PVDF membranes and different MWCOs. The results are presented in Fig. 11.

As can be observed, MFI–UF increases as the membrane MWCO decreases for both materials (PES and RC). MFI–UF using PES is higher than for RC comparing the same MWCO. This could be attributed to a lower surface porosity of RC (discussed in section 4.1) which cause a lower flux resulting in low cake formation on the membrane surface hence a low MFI–UF value.

The measured MFI values (Figs. 10 and 11) were substantially higher (~50 times) than the blanks obtained in the previous section (Fig. 9).

5. Conclusions

Based on the experimental results, analysis and literature review, the following conclusions were drawn from this study:

- Significant compaction was observed for the 100 kDa RC membrane at pressures above 1.5 bar. For 30 and 10 kDa RC no compaction was observed. PES membranes did not compact under the effect of pressure.
- The permeability of membranes filters decreased due to the NaCl concentration. This was expressed as "salt" compaction factor ranged from 0.46 for PES and 0.05 for RC. PVDF membranes only showed "salt compaction" starting at 20 g/L.
- The MFI of ultra pure water with salt was defined as "blank" MFI. "Blank" MFI values ranged from 20 to 360 depending on the pore size and material of the membrane filters. These values were much lower than the measured values of different water types.
- The flux decline with the PES membranes was faster than in the case of PVDF and RC membranes in the presence of 35 g/L NaCl. Pre-conditioning of the membranes by soaking in NaCl solution 24 h before MFI-UF test is suggested to reduce the effect of salinity on the membrane filter (blank).
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