Desalination and Water Treatment
www.deswater.com

51 (2013) 458–468
January

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doi: 10.1080/19443994.2012.714527

Comparison of nanofiltration membranes' performance in flat sheet and spiral wound configurations: a scale-up study

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Received 29 February 2012; Accepted 18 July 2012

ABSTRACT

Nanofiltration (NF) membranes have been largely developed and commercialised over the past decade and are currently one of the most promising technologies for the separation of neutral and charged solutes in aqueous solutions. Sometimes NF is defined as a process between ultrafiltration and reverse osmosis; however, the separation mechanisms of this kind of membranes are not clear enough, and even today there are some questions remaining about how NF membranes work. Nowadays, there are many different types of NF membranes commercially available, so the first step before developing a new NF treatment plant is to know which one is going to be the most suitable membrane. There are two main configurations in which NF can be used: flat sheet and spiral wound module. The cross-flow module using flat sheet membranes is the simplest option to test an NF membrane but at the industrial scale, NF is basically used in the spiral wound configuration. Currently, there are no studies available regarding the difference of using both configurations. The objective of this work is to do an experimental study regarding the performance of two different NF membranes, NF270 (Dow Chemical) and ESNA 1-LF2 (Hydranautics), in two different scales, laboratory and pilot plant, using the most typical configurations in each case: flat sheet and spiral wound respectively. Using the same feed water, the operating conditions and the rejections of the membranes in both configurations will be studied in order to check if both operating scales can be comparable.

Keywords: Nanofiltration; Cross-flow module; Spiral wound module; Laboratory scale; Pilot plant; Scale up

1. Introduction

1.1. Use of nanofiltration membranes for the drinking water production

Nanofiltration (NF) membranes are typically asymmetric polymeric membranes which consist of a low resistance support layer with a functionally active porous layer. Sometimes NF is defined as a process between ultrafiltration (UF) and reverse osmosis (RO); however, the separation mechanisms of these membranes are not clear enough, and even today there are some unanswered questions about how NF membranes work.

The history of NF begins in the 1970s, when RO membranes with higher flux and lower working pressures were developed. The higher pressure used

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Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, 23–26 April 2012, Barcelona, Spain

traditionally in RO involved remarkable energy costs, so the development of membranes with lower rejection of dissolved solids, but also with lower working pressures and higher permeabilities, turned out to be a good improvement in separation technology. These lower pressure RO membranes were called NF membranes [1]. Even though the development of NF membranes began in the 1970s, they were not commercialised until the 1980s, and nowadays several NF membranes are commercially available.

At present, NF technologies find the ever greater use in water industry, particularly in drinking water supply. Numerous theoretical and experimental researches of NF show that purification of the water of surface and underground sources by means of NF makes it possible to obtain higher quality drinking water [2–7]. In addition, when removing some polluting impurities this method is considered to be a good alternative to traditional methods of treatment. High degree of water purification for drinking purposes of nitrates is shown in [8,9], that of fluorine in [10,11], phenol and ursolic acid [12] and also heavy metals from seawater [13] and surface waters [4].

The production of high-quality drinking water requires the enhanced removal of natural organic matter (NOM), a precursor of disinfection by-products formation. NF leads to very efficient NOM removal, and in recent years has become an alternative to conventional water treatment. Boussahel et al. [14], Vrijenhoek and Waypa [15] and Yahya et al. [16] demonstrated that NF also allows the control of micropollutants such as pesticides, inorganics like arsenic, microbial contaminants and multivalent ions. Pilot studies and full-scale plants show that NF produces constant water quality and can remove a wide range of components from groundwater and surface water [17,18].

As it is noted in the study of Schäfer et al. [19], over the past years the use of membrane units in drinking water supply in the world, NF included, has dramatically increased. Some of the advantages of water treatment by NF to obtain high quality drinking water are the following:

- Universality of the method, compared with traditional methods of treatment;
- Increasing requirements to the drinking water quality;
- The absence of highly effective and cheap treatment technologies;
- An increase of the degree of purification as a result of using a new generation of membranes with unique properties.

1.2. Membrane configurations and modules

The module is effectively the membrane housing and it has two important roles: supporting the membrane and providing efficient fluid management. Membranes are produced in flat sheet or cylindrical form and this determines the type of module geometry [20]. There are basically four different membrane configurations: plate and frame, spiral-wound, hollow fibre and tubular.

The most popular module for NF in industrial applications is the spiral wound thanks to its packing density that allows greater filtration areas than tubular membranes and presents higher fluxes than hollow fibre membranes.

The simplest way to test an NF membrane is to use a flat sheet membrane with a plate and frame module in a laboratory-scale plant. This type of module appeared in the earliest stage of industrial membrane applications, presenting a simple structure and enabling an easy replacement of the membrane.

With plate and frame modules, the feed mixture is forced across the surface of the membrane, and then a portion passes through the membrane obtaining the permeate and the concentrate streams. The presence of the feed spacer is to guarantee a good mass transfer at membrane surfaces and to minimise the concentration polarisation.

Plate and frame units have been developed for small-scale applications because these units are expensive compared to its alternatives. Presently, this kind of modules are basically used at laboratory scale, as well as in electrodialysis and prevaporation systems [21].

Nowadays, there are several types of NF membranes commercially available, each one with its specific characteristics of permeability and rejection. Therefore, the first step before developing a new NF treatment plant is to know which will be the most suitable membrane for each specific process. As it has been previously told, NF at an industrial scale is basically used in the spiral wound configuration. However, the spiral wound modules cannot be tested in a laboratory-scale plant, and acquiring a spiral wound module is very expensive compared to a piece of a flat sheet sample; so the best way to test different NF membranes is using a cross-flow module in a laboratory-scale plant.

The hydraulics of spiral wound modules is quite more complex than in the flat sheet modules [22], so it is not obvious that the performance of the membranes using both configurations is going to be the same. Currently, there are no studies available regarding the difference of using both configurations. The objective of this work is to do an experimental study regarding the performance of two different NF membranes in two different configurations: flat sheet and spiral wound. Using the same feed water, the operating conditions and the rejections of the membranes in both configurations will be compared with the final aim of knowing if the results obtained in a cross-flow module using flat sheet membranes can be a good option to predict the spiral wound modules performance.

2. Materials and methods

2.1. Rejection experiments at pilot plant scale

The pilot plant used in this study was located in the drinking water treatment plant of Manresa (Northeast of the Iberian Peninsula). It was a two-staged pilot plant with three pressure vessels (PV) containing six NF elements (4-inch spiral wound modules), two in each PV. Fig. 1 shows the arrangement of the membrane modules in the pilot plant used.

The permeate and the concentrate fluxes were measured using two flow-meters, and the sum of both currents corresponds to the feed flow. About the pressure, it was measured using two pressure sensors, one situated in the feed, and the other one in the concentrate. Finally, the conductivity was also monitored online using two sensors, one situated in the feed and one in the permeate.

Flux and recovery of the modules are major parameters that govern concentration polarisation and thus also the risk of fouling of the membranes. Therefore, it is important to design the process using fluxes and recoveries values as low as possible [20].

The total recovery of the pilot plant to do the measurements of this study was fixed at 50%, and the working pressure was adjusted in order to have the desired permeate flux, which was around 27 LMH. This value of the permeate flux is the one recommended when working with a Municipal Surface water with an SDI < 3 (Dow Technical Manual). About the feed flow rate, it was fixed at $2.4\,m^3\,h^{-1}$.

2.2. Rejection experiments at laboratory scale

The laboratory-scale experiments were performed using a cross-flow module (SEPA CFII, GE Osmonics). The flow sheet of the experimental set-up is shown in Fig. 2. The cross-flow velocity and the transmembrane pressure were measured by two pressure sensors and a flow meter, connected directly to a data acquisition card. Conductivity and pH of the permeate stream were measured online, using a conductivity cell (Crison 53 92) and a pH electrode (Crison 53 03).

When performing NF experiments at laboratory scale, the concentrate and the permeate streams are usually recycled. However, in this case, in order to simulate the pilot plant process, the permeate was collected in another tank until the recovery used in the pilot plant was achieved. The pilot plant, as told in point 2.1, worked at a 50% recovery, so in the laboratory-scale set-up a half of the feed solution was recovered as permeate. For that purpose, the feed solution was weighted before starting the experiment, and the permeate weight was monitored until reaching the desired value.

The permeate flux was chosen as the design parameter for setting the experimental conditions in the laboratory set-up, so the pressure was adjusted in order to obtain the same permeate flux than in the pilot plant.

Regarding the cross-flow velocity, it was adjusted to be as similar as possible in the laboratory than in the pilot plant. It is important to state that the feed spacers used in the laboratory-scale cross-flow cell were the same as in the pilot plant.

2.3. Feed solution and membranes studied

The feed solution used for running the experiments in both membrane configurations was collected in the drinking water treatment plant of Manresa. The raw water comes from an artificial lake in Manresa containing water from the Llobregat River. Before the NF step, the water is pre-treated using pre-chlorination and pollyaluminium chloride sedimentation, followed by a sand filtration and, finally, an UF step. The average composition of the water used in the experiments is shown in Table 1. To perform the present study, the rejection of the major ions and also the rejection of total organic carbon (TOC) were considered to compare both configurations.

Two membranes have been chosen to perform the comparative study in both membrane configurations:

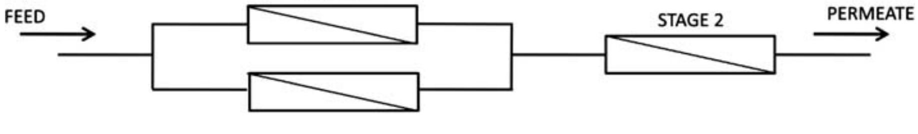

Fig. 1. Arrangement of nanofiltration spiral wound modules in the pilot plant.

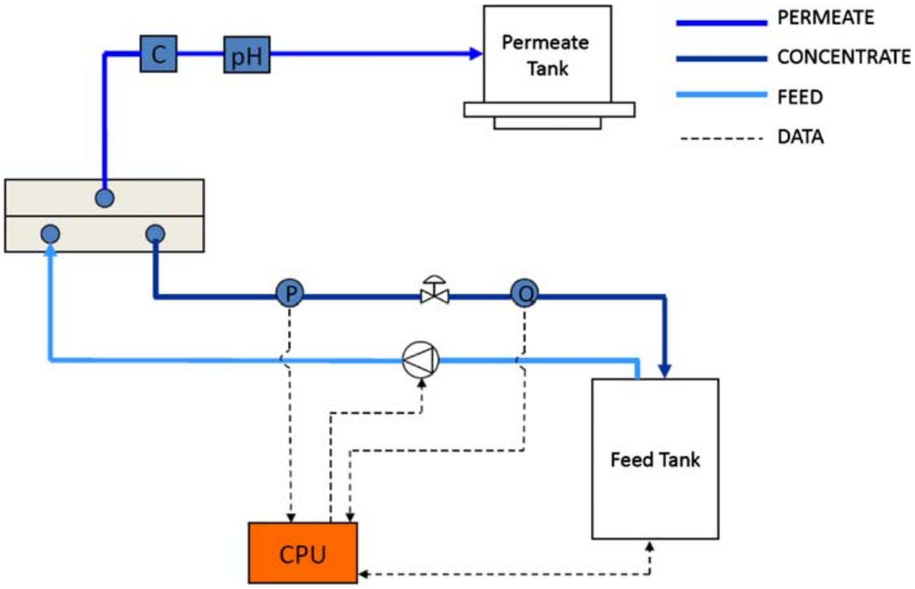

Fig. 2. Experimental system flow sheet.

NF270, from Dow Chemical and ESNA 1-LF2, from Hydranautics. These membranes have been previously characterised [23], and the membrane pore size as well as the membrane roughness for both membranes are shown in Table 2.

One of the rejection mechanisms of NF membranes is the steric exclusion, which is directly related with the membrane pore size. That is why this is one of the main parameters in membrane characterisation.

On the other hand, the membrane surface roughness is one of the most important surface properties as it has a strong influence on membrane fouling [24]. Vrijenhoek et al. [25] demonstrated through use of Atomic Force Microscopy analysis that the deposit of particles is higher for rough membranes than for smooth membranes when all test conditions are held constant.

2.4. Analytical methods

In order to determine the rejection of all the ions present in the feed water, several analytical methods have been used for the analysis of feed water and permeate samples.

Ion Chromatography (Dionex ICS-2000) was used to analyse anions (Cl^-, SO_4^{2-}) and cations (Na^+, Ca^{2+}, Mg^{2+}), and a total carbon analyser (AnalytikJena Multi NC 3,100) was used to analyse total inorganic carbon (TIC) and TOC in the form of non-purgable organic carbon.

Table 1
Average composition of the feed water used

Parameter	Average value	Standard deviation	Parameter	Average value	Standard deviation
Conductivity ($\mu S\,cm^{-1}$)	570	30	Ca^{2+} ($mg\,L^{-1}$)	82	9
pH	7.8	0.2	Mg^{2+} ($mg\,L^{-1}$)	12	2
SDI	1.2	0.9	Na^+ ($mg\,L^{-1}$)	20	6
UVA (254 nm)	0.039	0.015	K^+ ($mg\,L^{-1}$)	2.0	0.5
THMPF ($\mu g\,L^{-1}$)	120	40	Sr ($mg\,L^{-1}$)	1.05	0.05
TOC ($\mu g\,L^{-1}$)	2,560	540	Si ($mg\,L^{-1}$)	0.91	0.93
Al ($\mu g\,L^{-1}$)	51	13	TIC ($mg\,L^{-1}$)	175	8
Ba ($\mu g\,L^{-1}$)	43	10	SO_4^{2-} ($mg\,L^{-1}$)	100	23
Fe_{total} ($\mu g\,L^{-1}$)	7.5		Cl^- ($mg\,L^{-1}$)	35	7
B ($\mu g\,L^{-1}$)	27	2	NO_3^- ($mg\,L^{-1}$)	2.7	1.6
Mn ($\mu g\,L^{-1}$)	0.14	0.17	F^- ($mg\,L^{-1}$)	0.16	0.04

Table 2
Membrane pore size and membrane roughness for the studied membranes [23]

Membrane	rp (nm)	Rms (nm)
NF270	0.50	5.35
ESNA 1-LF2	0.49	49.07

Reference materials and spiked samples were analysed together with samples in each analysis batch, and the recoveries were always between 90 and 110%.

3. Results and discussion

Two sets of experiments have been carried out for each membrane, one in the pilot plant and the other in the laboratory set-up. The operation conditions used in each case are shown in Table 3.

3.1. Rejection results obtained with the NF270 membrane

Fig. 3 shows the rejection of cations for each set of experiments using the NF270 membrane.

Three different cations have been studied: sodium, which is a monovalent ion, and two divalent ions, calcium and magnesium. As it can be observed from the obtained results, sodium is less rejected than the divalent ions studied due to the electrostatic and steric effects between the ions and the membrane surface. Sodium presents rejections around 35%, whereas calcium and magnesium are more rejected with values higher than 60%. The obtained rejections have been compared with some other studies in the literature. D la Rubia and co-workers [26] used the NF270 membrane for the NF of surface water, and the rejections obtained were very similar than the ones observed in this study. The rejection of sodium was around 35%, whereas the calcium and magnesium presented rejections nearly 60%.

Comparing the two sets of experiments performed, no noticeable differences can be observed between them. Therefore, with the obtained results corresponding to the cation rejection, it can be concluded that the results obtained in the laboratory set-up and the ones obtained in the pilot plant are completely comparable between them.

The results obtained for the anions are shown in Fig. 4.

The results obtained in the pilot plant and in the laboratory-scale are very similar for the three anions studied. The rejection order in this case is $Cl^- < TIC < SO_4^{2-}$. For the specific case of sulphate, they are practically totally rejected in both sets of experiments performed. Again, the divalent ion is highly rejected than the monovalent ones. In the study of de la Rubia et al. [26] a rejection around 10% for chloride, 40% for TIC and rejection higher than 90% for sulphate was obtained. So again, the results obtained in this study are very similar.

Finally, if the membrane permeability in both configurations is compared (see Table 3), it can be observed that the values obtained using the pilot plant and the cross-flow module are also very similar. So with the different obtained results, it can be concluded that, using the NF270 membrane, the results obtained with the flat sheet membrane in a cross-flow cell are comparable with the ones obtained using a spiral wound module.

3.2. Rejection results obtained with the ESNA 1-LF2 membrane

In order to check the validity of the results obtained with the NF270 membrane, ESNA 1-LF2 from Hydranautics was tested. The rejection results for the cations and anions are shown in Figs. 5 and 6.

In comparison to the results obtained with the NF270 membrane, the rejections obtained when testing ESNA 1-LF2 are lower in the pilot plant than in the cross-flow filtration cell. The behaviour is the same for the anions and the cations, the decrease being very similar in each case, except for the sulphate, which is practically totally rejected in both configurations. Moreover, the pressure needed in the pilot plant was twice the one used in the laboratory-scale unit (see Table 3).

Table 3
Experimental conditions used in each set of experiments

Membrane	Experimental system	Transmembrane flux (LMH)	Pressure (bar)	Cross-flow ($m\,s^{-1}$)	Recovery (%)
NF270	Pilot plant	26.1	2.35	0.05	50
NF270	Laboratory	25.8	2	0.09	50
ESNA 1-LF2	Pilot plant	27.8	4.05	0.1	50
ESNA 1-LF2	Laboratory	30.5	2	0.08	50

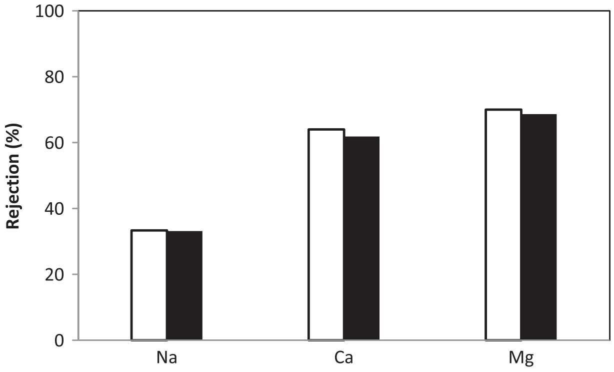

Fig. 3. Cation rejections obtained with the NF270 membrane (white: laboratory scale, black: pilot plant).

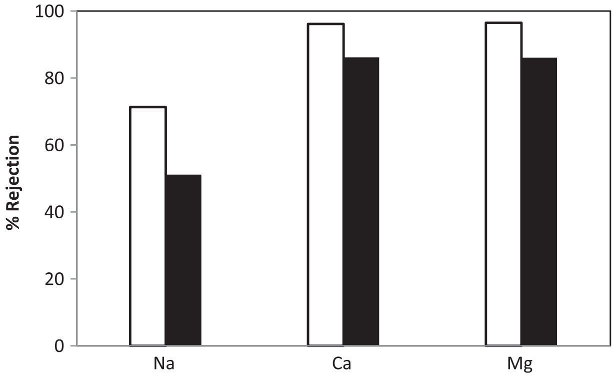

Fig. 5. Cation rejections obtained with the ESNA 1-LF2 membrane (white: laboratory scale, black: pilot plant).

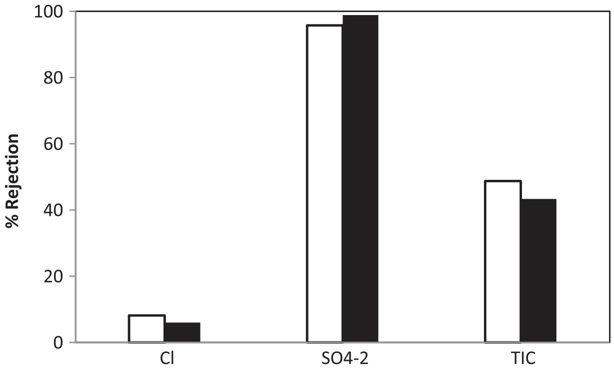

Fig. 4. Anion rejections obtained with the NF270 membrane (white: laboratory scale, black: pilot plant).

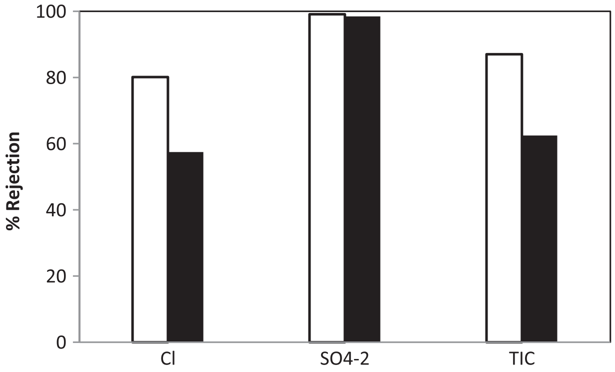

Fig. 6. Anion rejections obtained with the ESNA 1-LF2 membrane (white: laboratory scale, black: pilot plant).

Table 4
Experimental conditions for the fouled ESNA 1-LF2 membrane

Membrane	Experimental system	Transmembrane flux (LMH)	Pressure (bar)	Cross-flow ($m\,s^{-1}$)	Recovery (%)
ESNA 1-LF2	Laboratory	26.1	2	0.18	50

One possible explanation for these obtained results is that the spiral wound membranes were used for more than 6 months, so the membranes could be fouled. In order to check this hypothesis, one of the modules used in the pilot plant was sacrificed, and the rejection measurements in the cross-flow cell were repeated using a sample of the used membrane. Furthermore, the permeability of the membrane obtained in this study was compared with its value at the beginning of the membrane operation and a decrease of 14% was observed.

The new operation conditions used in the laboratory cross-flow cell for this new experiment performed with the fouled membrane are shown in Table 4.

The obtained results with the used membrane are shown in Figs. 7 and 8 together, along with the values obtained in the pilot plant for an easier comparison.

The results obtained using exactly the same membrane in the laboratory set-up than in the pilot plant are more similar than the previous ones (Figs. 5 and 6). In this case, the rejections in both configurations are comparable, like they were for the NF270 membrane. However, looking at Tables 3 and 4, it can be seen that the permeability remains low in the pilot plant, which means that the permeabilities in the pilot plant and in the cross-flow cell for this membrane are

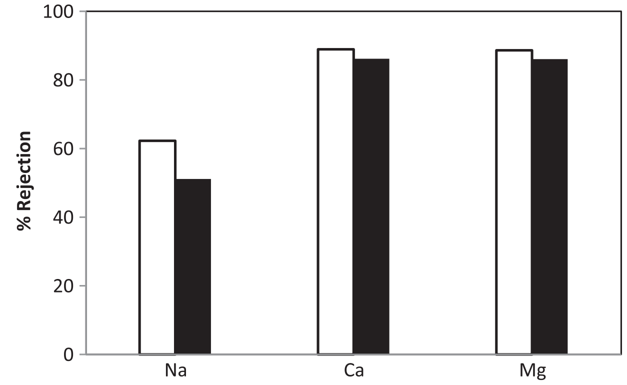

Fig. 7. Cation rejections obtained with the ESNA 1-LF2 membrane (white: laboratory-scale with an used membrane, black: pilot plant).

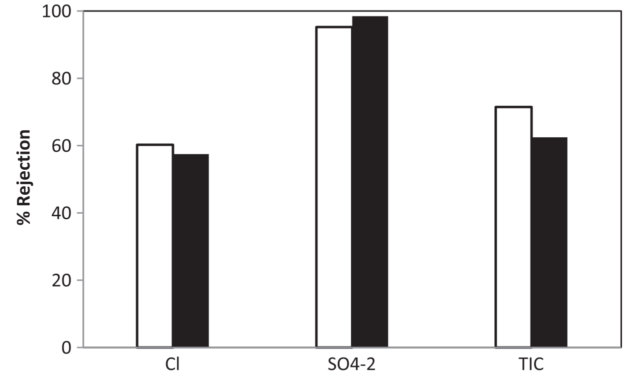

Fig. 8. Anion rejections obtained with the ESNA 1-LF2 membrane (white: laboratory-scale with a used membrane, black: pilot plant).

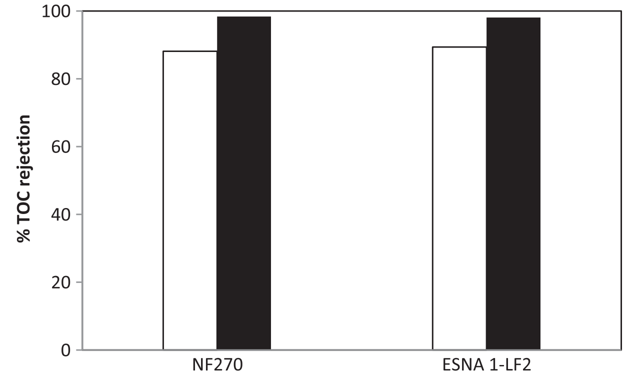

Fig. 9. TOC rejections obtained with the two membranes studied (white: laboratory scale, black: pilot plant).

not comparable. The reason of this difference observed in membrane permeabilities may be because in the laboratory cross-flow cell a different feed spacer than in the pilot plant was used, so the mass transfer in the membrane surface was different. Specifically, the feed spacer used in all the laboratory experiments was the one corresponding to the NF270 membrane.

Two conclusions can be drawn from the results obtained testing the ESNA 1-LF2 membrane. On the one hand, the rejections obtained using a flat sheet membrane in a cross-flow cell, are comparable to the ones using a spiral wound module. On the other hand, it is important to consider that old membranes in large-scale plants can be fouled, so the performance of the membranes will decrease and the rejections obtained will be lower than the ones obtained using a clean membrane.

3.3. TOC rejection

The presence of NOM in water sources affects water quality, such as colour, taste and odour. NOM not only reacts with disinfectants to produce disinfection by-products harmful to human health [27–30], but also leads to the fouling of filters and membranes, reducing the efficacy of some advanced water treatment process [31–35]). In addition, NOM could enhance the transport of some persistent organic pollutants such as polycyclic aromatic hydrocarbons to aquatic organisms [36]. Adding to this concern, a recent study found that NOM concentrations have increased over the past decade in many streams, including some sources for drinking water [37]. Therefore, one of the most important steps in drinking water production is the removal of NOM.

Due to the high importance of NOM removal in drinking water production, the rejection of TOC was also studied. Fig. 9 shows the rejection of TOC with both membranes in the two different configurations used in this work. In the case of ESNA 1-LF2 membrane, the results showed in Fig. 9 correspond to the measurements using the fouled membrane.

The results obtained for both membranes are very similar. In the pilot plant configuration, the TOC is practically totally rejected, whereas in the laboratory set-up, the rejections are around 90%. These high rejection rates observed are greatly important for the removal of NOM, demonstrating that NF is a promising technology for that purpose.

On the other hand, regarding the resemblance between the results obtained in both configurations, there is a difference around 10% between the rejection observed in the pilot plant and the values obtained in the laboratory cross-flow cell. This slight difference observed between both configurations may be attributed to analytical uncertainties due to the low TOC values observed in the permeate. However, the results

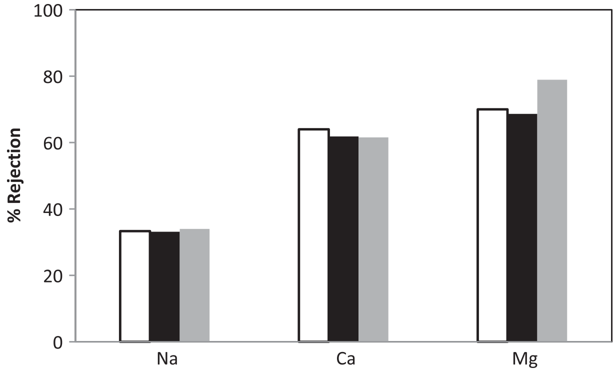

Fig. 10. Cation rejections obtained with the NF270 membrane (white: laboratory scale, black: pilot plant, grey: ROSA software prediction using 4-inch modules).

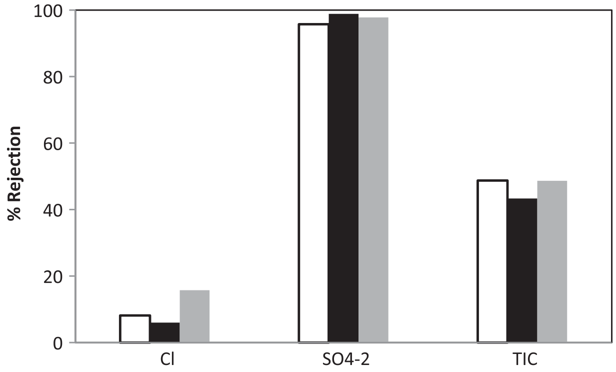

Fig. 11. Anion rejections obtained with the NF270 membrane (white: laboratory scale, black: pilot plant, grey: ROSA software prediction using 4-inch modules).

are good enough to conclude that the performance in both configurations are comparable.

4. Simulation using reverse osmosis system analysis and integrated membrane solutions design softwares

Most of membrane suppliers offer membrane users a design software in order to help them in the design of new membrane processes. With this software, the productivity and the rejection of different membranes can be predicted, so the user can know if a specific membrane could satisfy his needs. In this study, the softwares offered for Dow Chemical and Hydranautics have been used.

Table 5
Input data to ROSA software

Feed flow ($m^3 h^{-1}$)	2.4
Recovery (%)	50
Flow factor	0.9
Feed water temperature (℃)	22
Membrane module	NF270-4040
Feed water composition	See Table 1

Reverse osmosis system analysis (ROSA) is a design software programme from Dow Chemical that offers the most precise design recommendations to optimise system performance. Using this tool, the user can predict the process performance using one specific membrane from Dow.

ROSA software has been used to predict the NF270 membrane performance, in order to compare the software results with the ones obtained in the laboratory set-up and in the pilot plant. The input data to the software were the following:

With these input data shown in Table 5, the software predicted a permeate flux of 26.25 LMH using a pressure of 2.44 bar, which are very similar to the values obtained in the pilot plant operation and the ones used in the laboratory set-up (see Table 3).

Figs. 10 and 11 show the comparison between the cation's and anion's rejection using both configurations and the ROSA software.

With the obtained results, it can be stated that ROSA software is a reliable designing software when working with Dow Chemical membranes. The only rejections that deviate slightly from the behaviour observed experimentally are the magnesium and chloride rejections, which are highly estimated by the software.

The main problem when using ROSA is that the user can only choose between some Dow Filmtec membranes, so the range is very small compared with the high number of commercially available membranes. Another problem is that the user can just predict the inorganic ions' rejection, so if the membrane process has to be applied to separate organic compounds the user will not be able to predict the membrane's performance.

In this study 4-inch spiral wound membranes were tested. However, in the industrial-scale processes, 8-inch modules are used. For this reason, the simulation using ROSA software was also done considering 8-inch modules. The input data to the software are shown in Table 6.

The feed flow was fixed in order to have the desired permeate flux (around 25 LMH). Using 11 $m^3 h^{-1}$ as the value of the feed flow, a permeate flux of 24.67 LMH was obtained. In this case, the software predicted a pressure of 2.25 bar, which is very similar to the value used in the pilot plant experiments (2.35 bar).

Figs. 12 and 13 show the predicted rejections for cations and anions respectively, together with the

Table 6
Input data to ROSA software considering 8-inch spiral wound modules

Feed flow ($m^3 h^{-1}$)	11
Recovery (%)	50
Flow factor	0.9
Feed water temperature (℃)	22
Membrane module	NF270-400
Feed water composition	See Table 1

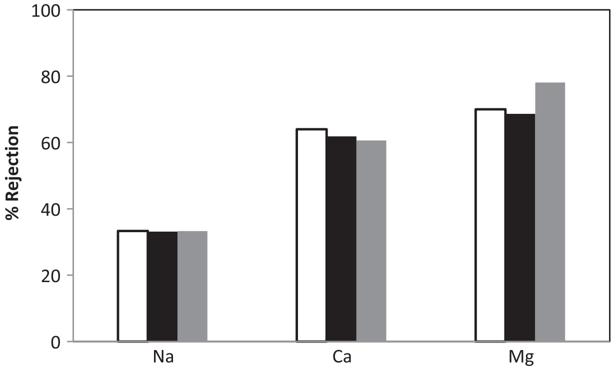

Fig. 12. Cation rejections obtained with the NF270 membrane (white: laboratory scale, black: pilot plant, grey: ROSA software prediction using 8-inch modules).

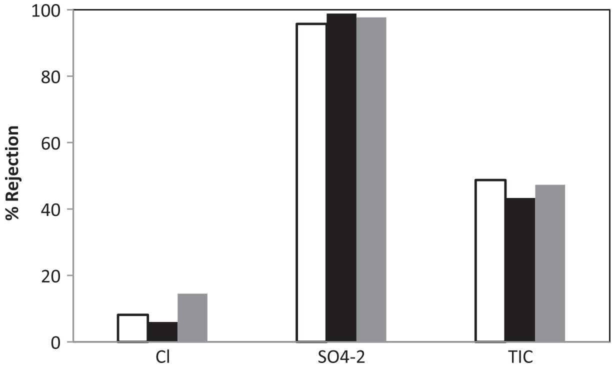

Fig. 13. Anion rejections obtained with the NF270 membrane (white: laboratory scale, black: pilot plant, grey: ROSA software prediction using 8-inch modules).

experimental values obtained in the laboratory and in the pilot plant.

The predicted rejections when working with an 8-inch modules are very similar to the ones obtained when 4-inch modules were used. The ROSA software, once again, has predicted in a good way the experimental results obtained, just chloride and magnesium rejections presented a little deviation.

Finally, the software provided by Hydranautics, integrated membrane solutions (IMS) Design, was also used to predict the ESNA 1-LF2 performance. In this case, only the prediction using the 8-inch module was done because the 4-inch module is not available in the software. Table 7 shows the input data used in the IMS Design.

Again, the feed flow was adjusted in order to have a permeate flux similar than the one obtained in the pilot plant experimentally, which was 27.8 LMH. Using a feed flow of $13\,m^3 h^{-1}$, a value of 29.2 LMH

Table 7
Input data to IMS Design software considering 8-inch spiral wound modules

Feed flow ($m^3 h^{-1}$)	13
Recovery (%)	50
Membrane age (years)	0.6
Feed water temperature (℃)	22
Membrane module	ESNA 1-LF2
Feed water composition	See Table 1

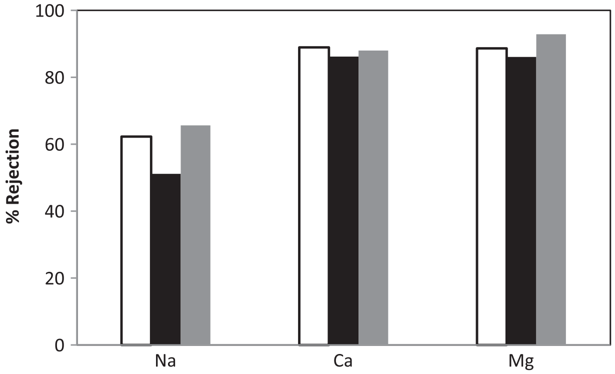

Fig. 14. Cation rejections obtained with the ESNA 1-LF2 membrane (white: laboratory-scale using the fouled membrane, black: pilot plant, grey: IMS-Design software prediction using 8-inch modules).

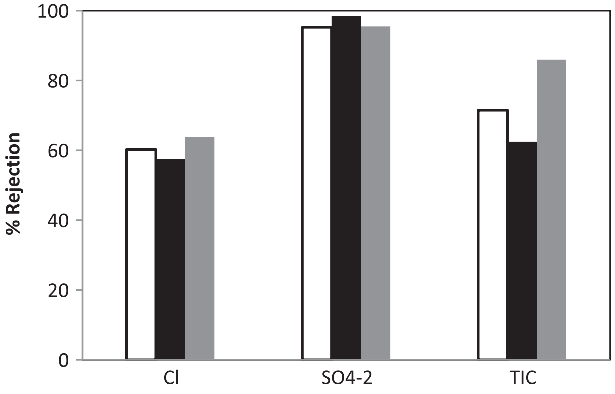

Fig. 15. Anion rejections obtained with the ESNA 1-LF2 membrane (white: laboratory-scale using the fouled membrane, black: pilot plant, grey: IMS-Design software prediction using 8-inch modules).

was obtained. The required pressure predicted by the IMS-Design software was 3.6 bar, which is very similar than the experimental value (4 bar).

As it can be observed in Figs. 14 and 15, the rejections predicted by the software from Hydranautics are similar than the ones observed in the laboratory-scale plant, and a little higher compared with the results obtained in the pilot plant experiments. So it can be concluded that the IMS-Design software can give to the user an approximation of the membrane performance to the membrane users, but it is less accurate than the software from Dow Chemical.

5. Conclusions

Two different NF membranes have been tested in two configurations, flat sheet and spiral wound, in order to compare the membrane performance in both. A cross-flow module was used to test the flat sheet samples, whereas a pilot plant was used to test 4-inch spiral wound modules of the two studied membranes.

With the obtained results, it can be concluded that the experimentation at the laboratory-scale plant can be useful to design a full-scale plant. However, it is important to perform the laboratory experiments working at the same recovery and the same permeate flux than the ones in the full-scale plant.

Simulations of the membrane performance have been done using the softwares provided for the membrane suppliers. The ROSA software, from Dow Chemical, could predict in an accurate way the experimentally obtained results, being the 4-inch or the 8-inch modules the one used for doing the simulation. About the IMS-Design software, from Hydranautics, provided less accurate results compared with ROSA, predicting slightly higher rejections than the ones observed in the pilot plant. However, it can be considered that the softwares provided for the membrane suppliers can also be a good designing tool.

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