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Water defluoridation using nanofiltration vs. reverse osmosis: the first world unit, Thiadiaye (Senegal)

Maxime Pontie[a,*], Hanane Dach[a,b], Abdekhaadi Lhassani[b], Courfia Kéba Diawara[c]

[a]*Angers University, GEPEA, CNRS 6144, 2 Bd. Lavoisier, 49045 Angers, France*
Email: maxime.pontie@univ-angers.fr
[b]*FEZ Faculty of Sciences, Morocco*
[c]*Ziguinchor Faculty of Sciences, Senegal*

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ABSTRACT

The possibility of producing drinking water from brackish groundwater polluted with F^- using nanofiltration (NF) process was previously studied at a pilot scale. Brackish groundwaters were taken from the south of Morocco (Tan Tan city) and from the center west of Senegal (Thiadiaye City). The performances of few commercialized NF spiral wound elements, low-pressure reverse osmosis (LPRO), and reverse osmosis (RO) were compared to a large-scale pilot experiments (membrane area, 7.6 m^2). The following parameters were determined: hydraulic permeability, total salinity; and Cl^-, F^-, and SO_4^{2-} removals were compared under the influence of various experimental parameters such as flow yield ratio, transmembrane pressure, energy consumption and water compositions before and after treatment. This study shows that NF provides specific advantages for fluoride removal as compared to LPRO and RO. Indeed, NF permits to reduce partially the total salinity and to reject selectively fluorides with a high flow yield ratio, at low pressure (lower than 20 bars) and therefore with a low energy consumption as compared to actual RO membranes. Furthermore, this paper presents *the first NF plant in the world dedicated to water defluoridation by nanofiltration* and built recently in Thiadiaye (Senegal) (fresh water production 33,000 L/h).

Keywords: Water treatment; Desalination; Defluoridation; Nanofiltration; Reverse osmosis

1. Introduction

The nanofiltration (NF) membrane is a type of pressure-driven membrane having properties situated between reverse osmosis (RO) and ultrafiltration (UF). NF offers several advantages such as low operational pressure, high flux, high rejection for multivalent anions salts, and biodegradable organic compounds with molecular weight above 300 Da, relatively low investment and low operation and maintenance costs. Because of these advantages, application of NF worldwide has increased since 15 years [1–5].

This study contributes to the development of NF technology to produce affordable drinking water from brackish groundwaters containing high fluoride concentrations. The aim of this study is to compare the performances in terms of hydraulic permeability, total salinity rejection, and fluoride removal of two membranes (NF90 and BW30) (see Fig. 1).

*Corresponding author.

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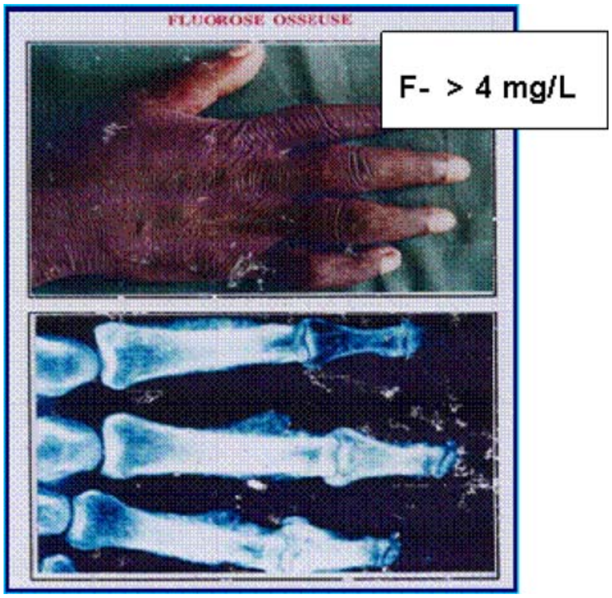

Fig. 1. Illustration of a hand attained by osseous fluorosis in Senegal after regular ingestion of drinking water with F^- concentration higher than 4 mg/L during 30 years exposition in the endemic region of Fatick, Senegal [6].

1.1. *Excess fluorides in drinking water and human health diseases*

Fluorosis, caused by high fluoride intake predominantly through drinking water containing F^- concentrations > 2 mg L^{-1}, is a chronic disease manifested by mottling of teeth (dental fluorosis) in mild cases and changes in bone structure, ossification of tendons and ligaments and neurological damage in severe cases [6–9].

To prevent these adverse effects, the World Health Organization (WHO) fixed the maximum acceptable concentration of fluoride ions in drinking water to 1.5 mg L^{-1}.

2. Pilot-scale study in Tan Tan, Morocco

The pilot-scale experiments were performed on an NF/RO pilot plant supplied by Veolia Environnement. The pilot unit (Fig. 2) is composed of three main systems: (i) a feed tank (volume: 3 m^3), (ii) a chilling unit for temperature control of the feed water (experiments conducted at a constant temperature of 21 ℃), and (iii) a pilot skid that is equipped with one pressure vessel housing one spiral wound module (4´´).

The membranes used for this study were NF90 and BW30 (DOW Filmtec), and have a membrane surface of 7.6 m^2. Those membranes are thin film composite (TFC) materials with a skin layer in polyamide. The applied feed pressure could be varied between 0 and 20 bars.

The study was carried out at a full-scale brackish water RO plant located in Tan Tan (southwest of Morocco). This full-scale facility operates since 2003 and it is equipped with BW30 spiral wound modules to deliver 150 m^3/h of potable water from a brackish groundwater which composition is detailed in Table 1. The brackish groundwater samples were collected after sand filtration and antiscalant injection (polyphosphate 3 mg L^{-1}). Water analysis (Table 1) shows that the water contains high concentrations of Cl^-, NO_3^-, SO_4^{2-}, and Na^+ in comparison with Moroccan and WHO standards.

The total salinity of the permeate and the raw water were measured with a TDS meter (ECOSCAN TDS6). For F^-, ionic selective electrode was used to determine the concentration of fluoride ions concentrations present in the solutions.

Fig. 2. Photograph of the NF/RO pilot plant (Tan Tan, Morocco, 2008).

Table 1
Characteristics of Tan Tan brackish water with Moroccan and WHO guidelines

	Tan Tan feed water	*Moroccan standards*	**WHO guidelines**
T (°C)	27	–	–
pH	7.9	*6.0–9.2*	**6.5–8.5**
TDS (ppm)	4,010	*1,000–2,000*	**<1,000 (recommended for taste)**
Cl^- (ppm)	1,349	*350–750*	–
NO_3^- (ppm)	80	*<50*	**<50**
F^- (ppm)	1.1	*0.7–1.5*	**<1.5**
SO_4^{2-} (ppm)	500	*<200*	–
Hardness (ppm)	384	*<500*	–
Na^+ (ppm)	595	*<200*	–

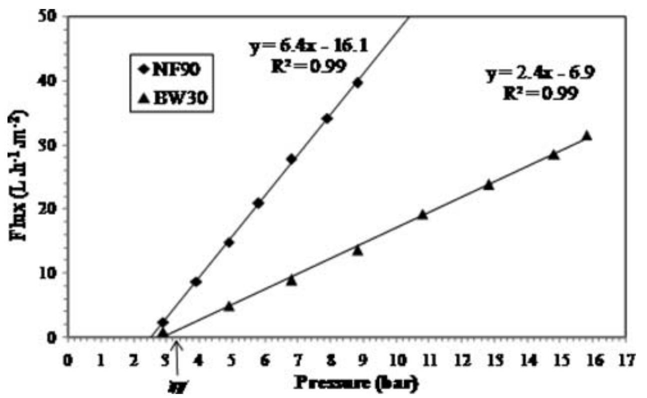

Fig. 3. Effect of the applied pressure on Tan Tan water flux for the NF90 and BW30 membranes (pH = 7.9; T = 20°C).

3. Results and discussion

3.1. Hydraulic permeability

The interest in measuring the hydraulic permeability of the studied membranes with Tan Tan water is usable to estimate fluxes for feed water and sizing big plants. In Fig. 3, we have reported flow rate as a function of transmembrane pressure for Tan Tan water.

As illustrated in Fig. 3, the NF90 membrane shows a higher hydraulic permeability. Then, the permeate flux obtained for the NF membrane is three times higher than the BW30 membrane, as usually observed. This is mainly due to the larger pores size of the NF90 membrane vs. BW30.

Furthermore, the critical driving pressure (P_c), which is defined as the pressure at which the permeate flux is measurable, is observed in NF at 2.5 ± 0.1 bars and 3 ± 0.1 bars for the BW30 in comparison with the theoretical osmotic pressure calculated, which is 3.3 bars. Then, NF offers the advantage of larger hydraulic permeability correlated with a low effect of the osmotic pressure on P_C vs. low-pressure reverse osmosis (LPRO) membranes.

3.2. Salt retention with time and flow yield

The rejections of the total salinity (TDS) were analyzed as a function of flow yield, see Fig. 4. As expected, an increase in the flow yield at constant permeate flux caused an increase in the total salinity in the permeate and water permeate decrease.

The rejection remains practically constant for the LPRO membrane with the flow yield. If we compare F^- retentions obtained for the NF90 and the BW30 membranes, we can observe that the NF membrane produces water with a total salinity lower than the standards and allows a partial demineralization of Tan Tan water. The rejection rate of the LPRO membrane is extremely low because the membrane is nonporous. As usual in RO, a more drastic remineralization step is necessary as a post-treatment.

The feed pressure required for the BW30 membrane is two times higher than the NF90 membrane (19.1 bars vs. 9.2 bars for a flow yield of 70%).

Furthermore, a steady state flow was obtained after 9 h of filtration with a tendency of F^- stabilization in the permeate for both membranes tested, as observed in the Fig. 5.

As well illustrated, the evolution of the fluoride contents in permeate solutions increases as the following order: NF90 > BW30. Furthermore, with the NF90 membrane, F^- level concentration in the permeate after filtration is sufficient to attain the recommended fluoride concentration in drinking water, as reported in Senegal to a value of 0.8 mg/L [9]. On the contrary, the BW30 membrane shows lower F^- concentration in the permeate with a very low TDS.

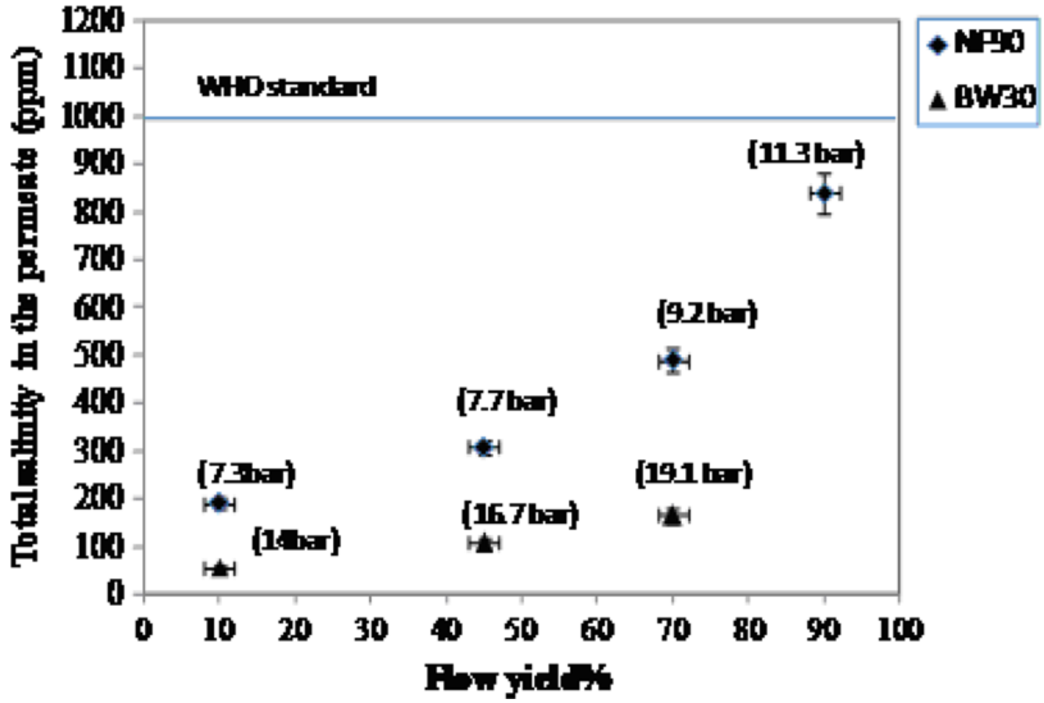

Fig. 4. Variations of the total salinity in the permeate as a function of flow yield (feed pressures are detailed into brackets) for the NF90 and BW30 membranes (Permeate flow = 0.2 $m^3 h^{-1}$; pH = 7.9).

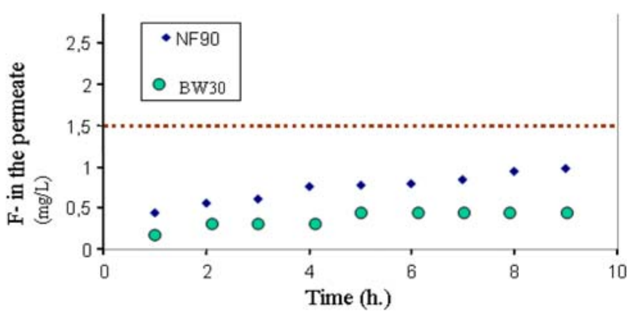

Fig. 5. F^- concentrations in the permeate vs. time during the filtration of the Fatick water on the NF90, NF270, and BW30 membranes (Feed composition: see Table 1; operation conditions: Transmembrane pressure 7.5 bars; conversion ratio 0.87).

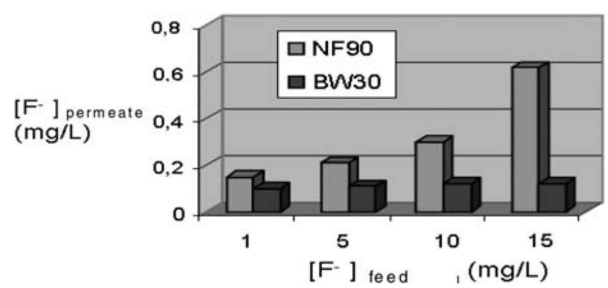

Fig. 6. Variations of fluoride concentration in the permeate for the studied membranes with F^- concentrations added in the Tan Tan brackish water (Y = 70%, permeate flow = 0.2 $m^3 h^{-1}$).

3.3. Defluoridation of brackish water spiked with F^-

The fluoride content in many regions of Morocco (as also in 44 others countries in the world) is exceeding the acceptable standards. For its high and specific membrane selectivity, NF appears to be the best membrane process to remove fluoride from brackish Senegalese underground waters, as reported for the first time in 1996 [10,11].

A comparison of the performances of RO and NF membranes was carried out using various initial fluoride contents in the Tan Tan brackish water (spiked with NaF at 5, 10 and 15 mg/L). The flow yield was set at 70%. Fig. 6 shows the variations of the permeate fluoride concentration as a function of the initial fluoride content.

Practically, no influence of the initial fluoride in feed water on fluoride rejection was observed for the BW30 membrane. The fluoride concentration in the permeate is very low, and the beneficial effect of fluoride for drinking water is not attained due to the fact that fluorides are highly rejected by the BW30 membrane.

For the NF membrane, the fluoride concentration in the permeate was increased with increasing

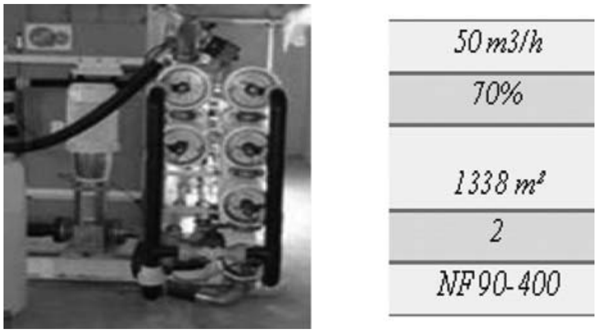

Fig. 7. SKID photograph and operating conditions.

Table 2
Water analysis for feed and nanofiltered waters vs. standards (Thiadiaye, September 2009)

Water parameters	Thiadiaye feed water	NF water
Fluorides (ppm)	4.67	0.56
Sodium (ppm)	235	25
Chlorides (ppm)	280	28
TH (ppm)	11	<1

fluoride concentration in the feed water, but fluoride was reduced to a satisfactory value for all concentrations (up to 15 mg/L F).

3.4. *Full-scale defluoridation plant in Thiadiaye (Senegal)*

The following part is dedicated to the description of the first membrane plant in the world equipped with the NF90 membrane for the removal of fluorides in drinking water (Fig. 7).

The SKID is a typical two passes design plant with a water tank of 1 m^3 and a membrane area of 1,338 m^2 ($4 \times 6 + 2 \times 6 = 36$ modules NF90-400). Cartridge filters (5 μm) are located upstream of the RO units in order to limit particulates fouling.

F^- concentration in the feed water was 4.67 mg/L, see Table 2. With the use of NF90 membrane the value obtained was drastically decreased to a value of 0.56 mg/L. Nanofiltered water is then remineralized through percolation on a soil of neutralite™, and then chlorinated.

4. Conclusion

The possibilities of producing drinking water from F^-polluted brackish water collected from the south of Morocco and from Senegal, using NF membranes, were studied. NF process appeared the more efficient process vs. RO. Drinkable water was obtained in one pass. The TDS of the permeate obtained with this process was inferior to the standard value authorized in Morocco, and higher product water fluxes was obtained with a flow yield of 90% for a half time lower pressure in NF90 vs. BW30.

This study confirms the good performances of the NF90 membrane for defluoridation of a brackish drinking water. NF permits to reduce partially the total salinity and to reject the fluoride ions excesses in brackish waters with higher flow yield ratio, lower pressure, and lower energy consumption.

We present *the first NF plant in the world dedicated to water defluoridation by nanofiltration* and built recently in Thiadiaye (Senegal) (size: 33,000 L/h and 1,338 m^2 of membrane area and equipped with NF90–400 membranes).

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