BRACKISH WATER TREATMENT REASEARCH IN PILOT SCALE USING DUAL-STAGE NANOFILTRATION FOR DOMESTIC/ DRINKING WATER SUPPLY IN THU BON RIVER BASIN

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Abstract: *Due to the impact of climate change, the process of salinity intrusion occurs frequently in coastal areas of Vietnam. Therefore, the main objective of this study is to evaluate the brackish water treatment capacity of different nanofiltration (NF) processes for domestic and drinking water supply for residential areas in Thu Bon river basin, where the salinity varies significantly within seasons. Results have shown that during season change when the river's salinity increases up to 17.5‰, application of dual-stage NF is most appropriate. The energy costs were 8.28 and 33.4 $/m^3 with salt concentrations of 1-6‰ and 6-12.5‰, respectively. This dual-stage NF process not only guarantees the effluent quality to meet National Technical Regulation on potable water (QCVN 01:2009/BYT), but also offers reasonable energy cost and finally can heip to prolong the membrane lifespan.*

Keywords: *Drinking water treatment, dual-stage nanofiltration, Brackish water, variation of salinity with seasons.*

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1. Introduction

Desalination is a process of removing dissolved ions in the seawater, brackish water or underground water. According to the International Desalination Association, there were 18,426 desalination plants operated worldwide as of June 2015, producing 86.8 million m^3/d, providing water for 300 million people [1]. Desalination can be conducted via ion exchange, solar energy, distillation or membrane processes. The last two methods, which are distillation and membrane processes, have been applied the most due to the high efficiency and more reliability [2,3]. Distillation often requires large spaces for equipment and mostly relies on the weather. Membrane technologies such as Reverse Osmosis-RO, Nanofiltration-NF, Ultrafiltration-UF, Microfiltration-MF, etc., therefore, have been used tremendously in the past two decades because of many advantages. Among the above membrane processes, RO and NF are considered most favorable for desalination. RO can remove up to 99% dissolved ions, however, the capital cost and operation cost are substantial due to material, pump energy, electricity and fouling [4]. With those constraints, the application of RO in desalination for drinking water purpose seems to be a big challenge [4,5].

NF membrane has been proved to be quite effectiveness in controlling divalent ions, turbidity, residual bacteria, hardness ions, and seawater TDS (Fig. 1). The main advantage of NF membranes is lower energy consumption and low capital cost compared to RO membrane [6-8].

The application of NF for desalination worldwide was in the early years of 2000 [9,10]. A single stage NF was proved not so high removal efficiency. To maximize this outcome, using integrated membrane pro-

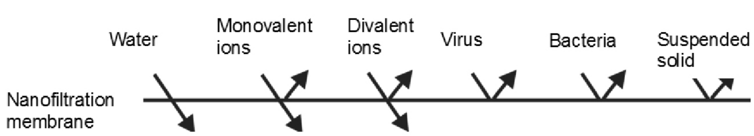

Figure 1. *Rejection mechanism of Nanofiltration [5-14].*

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cess (NF-NF or NF-RO) has been getting more of interest [11].. Al Taee and Sharif [7] concluded that the energy consumption of NF-NF was 0.38 kWh/m^3 lower than that of NF-RO, however TDS in the permeate of NF-NF was 1030 mg/l while TDS in the permeate of NF-RO was only 125 mg/L. Nevertheless, NF has high potential for application in desalination in some circumstances. According to [2], NF is comparable with RO in treatment of low salt concentration seawater. At high salt concentration or wide concentration variable water, NF can not meet the requirement.

In Vietnam, there have been some studies on desalination but mostly on low and stable salinity and small-scale system [12]. In fact, the salinity varies quite substantialy within seasons. Thus, the main objective of this study is therefore to evaluate the brackish water treatment capacity of different nanofiltration (NF) processes for domestic and drinking water supply for residential areas in Thu Bon river basin. The results of this research would probably apply for other areas with similar conditions.

2. Materials and Methods

2.1 Feed water

Brackish water from Thu Bon River estuary has been used as feed water. This water is strongly influenced by natural conditions and human life activities, so the tidal regime and water quality changes seasonally. The water transportation and fishing activities occur frequently in the region, which generate huge amount of organic matter content, suspended solids, solids, trash, etc., in the water. In particular, the salinity of this river varies considerably within seasons. The range of salinity at Cua Dai ward (Hoi An city, Quang Nam province) where the pilot was installed (from August 1, 2012 - October 30, 2013) was 2.3-27.5‰, while it was always mainly 20‰ higher than from June to August. With this condition, it is believed that it would be impossible to apply a single process (whether it is conventional or advanced one) for treating this river for drinking water purpose.

2.2 Experimental procedure

In this study, we treated the brackish water using dual-stage NF filtration in two phases. Phase 1 involved testing with single-stage NF from 1/8/2012 to 13/11/2012. The feed water had a wide range of salinity, ranging from 2.3‰ to 27.5‰. The purpose of this step was to find the favorable salinity level that a single-stage NF could handle, as well as find the appropriate salinity range for the next step. Sand filters followed by UF pre-treatment units were employed in order to remove residuals, viruses and bacteria. This pretreatment step also helped to reduce membrane fouling during the subsequent desalination stage. After that, the water would undergo NF1. The implementation and equipment installed for this step are shown in Fig. 2.

In Phase 2, the dual - stage NF was tried from 4/2/2013 to 12/6/2013. Based on the results of Phase 1, the appropriate input salinity concentration was found to proceed to Phase 2, where the minimum salinity of the input water NF2 feed would be equal to the maximum salinity of the permeate (NF-1permeate) at which it still obtains the NF2 permeate < 0.495‰ [13]. The implementation plan and equipment installed for this step are shown in Fig. 3.

Both phase 1 and phase 2 experiments were set up at site (see Fig. 4 for details).

The pilot was designed with capacity of 5 m^3/d, operating 16h/d, including a composite filter

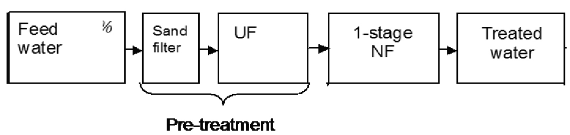

Figure 2. *Diagram of a single NF process*

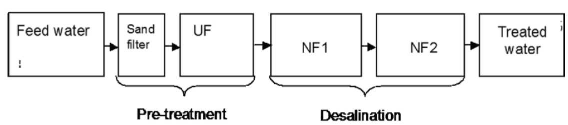

Figure 3. *Diagram of dual-stage NF process*

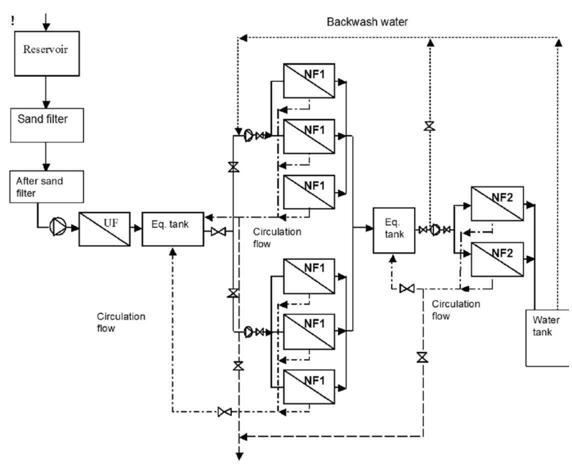

Figure 4. *Process flow chart of the pilot unit at site (Q=5 m^3/d)*

with sand (D 600mm, 2000mm height); UF membranes NTU3360-K4R provided by Nitto Denko company, Q = 7m^3/h, N= 2 modules and Polyvinylidene Fluoride (PVDF) NF membranes (ESPA1- LF- 4040) were provided by Nitto Denko company. This kind of membrane was reported to have high corrosion resistance. The ceramic housing was stable and durable.

The operating pressure of NF system was set at 11±0.2 bar for both phases. The pressure and flowrate were recorded everyday so as to be able to determine the recovery rate and salt rejection at different cases.

Recovery rate was estimated based on the following formula:

$$\% \text{ Recovery rate} = (Q_P/Q_f)*100 \quad (1)$$

$$Q_f = Q_P + Q_C \quad (2)$$

where: Q_f, Q_P, Q_C are the flowrates of the feed, permeate and concentrate.

Salt rejection was determined by:

$$\% \text{ Salt Rejection} = (TDS_f - TDS_P)/(TDS_f) \times 100 \quad (3)$$

In addition, the energy cost was also determined for treatment of 1m^3 brackish water at different salinity concentrations (for Q = 5 m^3/d, operating time = 16h/d):

$$E = N \times n_h \times U \ (\$/m^3) \quad (4)$$

$$N = \frac{QxHx\psi}{102x\eta_{đc}x\eta_b} \times K \quad (kW) \quad (5)$$

in which N is Pump power (kW);); n_h is operating time (h); ψ is Density of fluid, 1000 kg/m^3; Q is Pump flowrate (m^3/s); H is Pump head (m); $\eta_{đc}$ is Engine efficiency; η_b is Total pump efficiency ($\eta_{đc} \times \eta_b$ = 0,85); K is Power reserve coefficient.

The current unit electricity cost U ($/kWh) was based on national electricity norm which was about 0.91 $/kWh. The energy cost for treatment of 1 m^3 brackish water was evaluated for dual-stage NF and NF-RO processes. Data for NF-RO was referred elsewhere [14].

2.3 Sampling and Analytical method

Samples were collected twice per day from the feed, after sand filter, after NF1 and NF2. Each sample was analyzed in terms of salt concentration, TDS, conductivity, COD, SO_4^{2-}, Cl^- and Coliform. The sampling technique (including sampling points, sampling container decontamination, sample preservation) was strictly followed Vietnam Standard TCVN 5992:1995 Water Quality - Sampling - Part 2: Guidance on Sampling Technique. Besides, other parameters were analyzed in accordance with other Vietnamese Analytical Method Standards, including TCVN 6492:2011 for pH, TCVN 6184:2008 for Turbidity, TCVN 6186:1996 for COD_{KMnO4}, TCVN 6200 - 1996 for SO_4^{2-}, TCVN 6194:1996 for Cl^- and TCVN 6187-2:1996 for Coliform. Salinity was measured by SA287 Digital 1-Click Simple Salinity Meter Tester (Hangzou Sinomeasure, China). TDS was measured by TDS Tester (Hanna HI98302, Bedfordshire UK).

3. Results and Discussion

3.1 Characteristics of feed water

As the composition of brackish water from Thu Bon river varied quite significantly seasonally, the test was conducted from autumn (phase 1), and continued in spring and summer (phase 2) to experience the wide change of salinity of the river. The average value of feed water used in this study is described in Table 1.

It can be seen from Table 1 that the season change had great impacts on salinity, TDS, Cl^- concentration, but not the turbidity or pH.

Table 1. *Analytical result of feed water*

No	Parameters	Rainy season	Dry season
1	pH	7.1-7.8	7.2-7.8
2	Turbidity, NTU	20-45	14-31
3	Salinity, ‰	1-8.5	7.5-27.5
4	TDS, mg/L	1,150-9,600	8000-29,000
5	COD_{KMnO4}, mg/L	2.5-8.3	2.6-5.6
6	SO_4^{2-}, mg/L	110-1850	750-2450
7	Cl^-, mg/L	600-5900	4500-16800
8	Coliform, MPN/100mL	103-105	103 - 106

3.2 Recovery rate and salt rejection of one-stage NF (Phase 1)

The results of Phase 1 showed that with salt concentration in the range of 2.3-6‰, the permeate salt concentration after NF process ranged from 0.2-0.5‰ which met QCVN 01: 2009/BYT requirements (National Technical Regulation on drinking water quality issued by Ministry of Health, i.e. less than 0.5‰). Salt rejection efficiency was in range of 88-94% and recovery rate was between 25% and 37.5%, depending on salt concentration (Fig. 5). Fig. 6 demonstrates that the permeate salt concentration was a function of the square root of the feed salt concentration. High R^2 value (R^2=0.998) proves high reliability of this correlation. The trans-membrane pressure of this phase was relatively stable (10.5±0.5 bar).

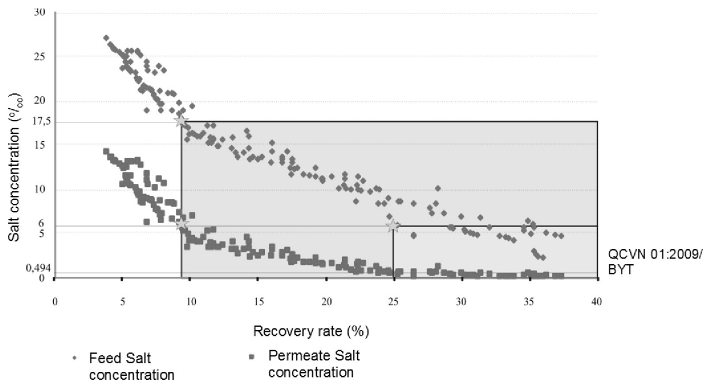

Figure 5. *Recovery rate of the single NF process with wide range of salt concentration*

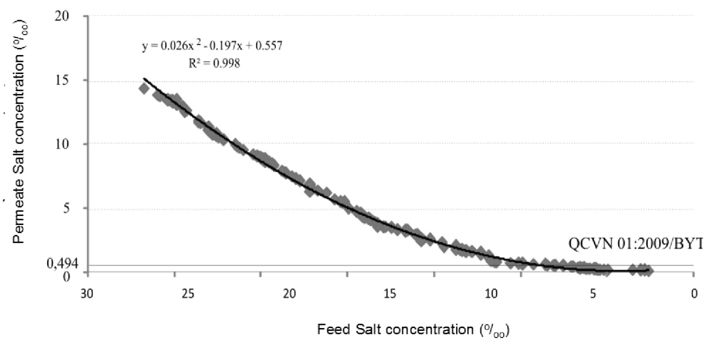

Figure 6. *Correlation between Feed and Permeate salt concentrations of the single NF process*

It should be noted that for this study, constant pressure was maintained to compare the membrane performance as a function of salt concentration. Normally, under the same salt concentration, increasing operating pressure increases the ion rejection efficiency because the water flux increases linearly with increase of operating pressure while ion permeation is only a function of feed concentration and is independent of the operating pressure [15].

With the feed salinity of 6-27.5‰, the permeate salinity ranged from 0.52 to 14.3‰ (Fig. 5), which did not meet drinking water quality standards under QCVN 01: 2009/BYT (<0.5‰). The salt rejection reached 47.4-91.5% and the recovery rate was low, ranging from 4-35%, depending on the salinity of the input.

From Phase 1's results, it was found that when the input water had a maximum salinity of 17.5‰, the output was approximately 6 ‰ - equals the highest possible input salinity value to obtain accepted water (meeting QCVN 01:2009/BYT). This means that for a two-stage NF process, the input salt concentration could not exceed 17.5 ‰. Besides, the minimum limit would be 6‰ because if salt concentration is lower than 6‰, one-stage NF is recommended to apply.

3.3 Recovery rate and salt rejection of two-stage NF (Phase 2)

Fig. 7 shows clearly the recovery rate of 1st-stage NF process was from 10-35% for a range of salinity of 6-17.5‰. The permeate concentration of NF1 was 0.5-5.5‰. The trans-membrane pressure was kept constant at 10.5±0.5 bar. Membrane flowrate was from 13.2-20.6 L/min. After 2nd-stage NF, the permeate salt concentration was 0.1-0.3‰. The

Table 2. *Effluent quality*

No	Parameters	Average Value	QCVN 01:2009/BYT*
1	pH	6.5-7.5	6.5-8.5
2	Turbidity, NTU	< 1	2
3	Salinity, %o	<0.2	< 0.5
4	COD_{KMnO4}, mg/L	1,3	-
5	SO_4^{2-}, mg/L	≤20	250
6	Cl^-, mg/L	≤150	250 - 300
7	Coliform, MPN/100mL	0	0

** National Technical Regulations for drinking water purposes.*

overall salt rejection of the dual stage NF system was from 66.5 to 89.7% and the recovery rate was 32-47% (Fig. 8). It is obvious that with additional NF stage, the salt removal increases to some extent and so does the recovery rate. The permeate after dual-stage NF process all met the requirement of Vietnam standard for drinking water purpose (Table 2). Azhar et al. [16] observed the recovery rate of their dual-stage NF was 18.9% at input salt concentration of 35‰ and decreased with the increasing salinity. As in this study, the input salinity was max 17.5‰ for dual-stage NF testing, the recovery rate was more than 30% which was quite reasonable. AlTaee and Sharif [7] also observed high permeate TDS of 1.3‰ after dual-stage NF process at the feed salinity of 43‰. Normally, the diffusion mechanism is limited at high concentration, leading to lower recovery rate. In other speaking, at high salinity (i.e. > 20‰), dual-stage NF system will not be suitable for desalination to meet drinking water quality.

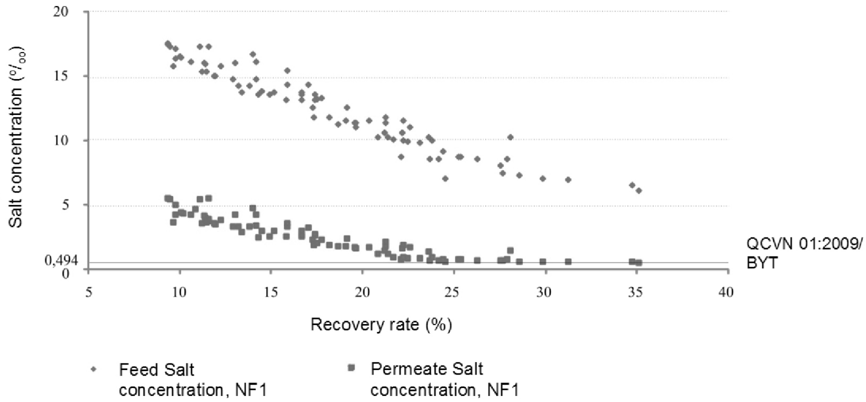

Figure 7. *Recovery rate of NF1 with input salt concentration of 6-17.5‰*

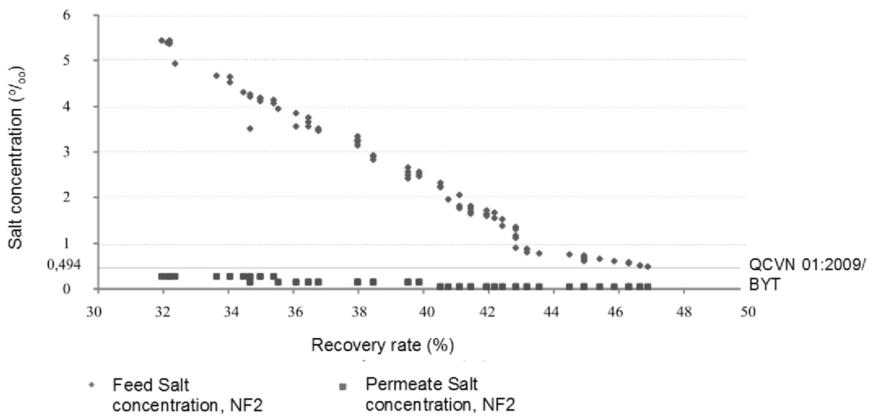

Figure 8. *Overall recovery rate of two-stage NF with input salt concentration of 6-17.5‰*

Through the test, the trans-membrane pressure was relatively stable, the desiccation efficiency (salt rejection) of dual-stage NF process was inversely proportional to input salt concentration. Increasing salt concentration would decrease the salt rejection efficiency (Fig. 7). Similarly, the water recovery rates after dual-stage NF process were also inversely proportional to the input salt concentrations (Fig. 8). At maximum salt concentration (27.5‰), the desalination efficiency was only 47.5% and the recovery rate was very low, only 4% (Fig. 6). The possible explanation may lie in that when a large number of salt ions exists in feed water, and then in membrane pores, the layer of adsorbed water on pore walls will be thinner due to “salting-out” effect, thus, the salt concentration in the permeate as well as permeate water will be limited [17].

Compared to the artificial seawater desalination test conducted at lab-scale in our previous research [12], the desalination efficiency at pilot scale was higher, and so was the recovery rate. The main reason for this difference was that these experiments performed at 10.5±0.5 bar trans-membrane pressure, which was 8-10 bar higher than those in the previous experiment [12]. Basically, if the difference in membrane pressure was eliminated, the results of this experiment would probably be similar to those of previous tests. This confirms the consistency of the results at both lab scale and pilot scale.

Table 3. *Energy cost for treatment of brackish water with salinity of 12.5 - 17.5‰*

Treatment unit	Q_P (m^3/h)	P (bar)	Rec. rate (%)	Q_f (m^3/h)	Q_{pump} (m^3/h)	Pump head H (m)	Power re-serve coef.	Den-sity of fluid (T/m^3)	Total Pump efficien-cy η_b	Engine effi-ciency η_{dc}	Pump power (kWh)
NF2	0.45	11	35.78	0.87	0.87	110	1.5	1	0.85	1	0.460
NF1	0.11	11	11.65	7.50	7.50	110	1.25	1	0.85	1	3.304
Sand filter + UF	7.50	3.3	100	7.50	7.50	33	1.25	1	0.85	1	0.991
Feed	7.50	1.5		7.50	7.50	15	1.25	1	0.85	1	0.451
	Energy use per day (16 hrs), kW/day										83.291
	Unit price of electricity, $/kW										0.91
	Energy cost for 1m^3 treated water, $										75.70

3.4 Energy consumption

In addition to membrane performance, energy consumption and cost is also discussed in this section. The estimated energy cost for treatment of 1 m^3 brackish water treated using dual-stage NF process was present in Table 3, when influent salinity was from 12.5-17.5‰.

Similar estimation for energy consumption and cost was implemented at lower salt concentration. It was found that energy costs were 8.28 and 33.4 $/$m^3$ at (1-6‰) and (6-12.5‰) salt concentrations, respectively. When replacing two-stage NF process by NF-RO process, which had been described in details about the experimental system and testing procedure in previous study [14], the energy cost of NF-RO was a bit lower at salt concentration of about 22.5‰, however, it was much higher (about 110 $/$m^3$) when the salinity was higher than 22.5‰ (Fig. 9).

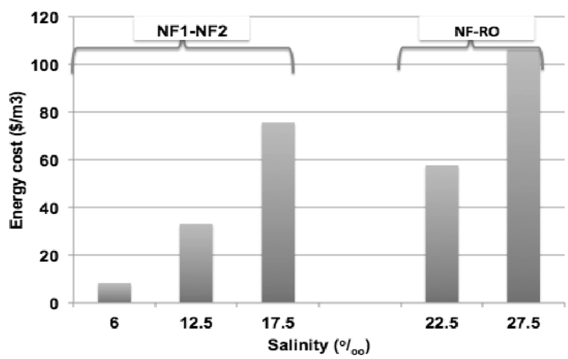

Figure 9. *Comparison of energy cost for different processes (dual-stage NF and with NF-RO)*

4. Conclusions

Thus, the main objective of this study is to seek for a proper solution for a wide range of salinity water via piloting at Thu Bon river site. The fluctuation range of salinity at Cua Dai ward (Hoi An city, Quang Nam province) where the pilot was installed (from August 1, 2012 - October 30, 2013) was 2.3-27.5‰, while it was always higher than 20‰ from June to August. With this condition, it is believed that it would be impossible to apply a single process (whether it is conventional or advanced one) for treating water for drinking purpose. A seven-month test with NF processes for brackish water treatment has revealed that the nanofiltration process is a promising solution, providing drinking water for the lower Thu Bon River, where salinity fluctuates significantly within seasons. In rainy season, when the input salinity is less than 6‰, one-stage NF can completely meet the water quality's standard. When the input water has a salinity in the range of 6‰ - 17.5‰, two-stage NF filtration is the appropriate choice. However, during the dry season peaks, when the salinity was greater than 17.5 ‰, the two-stage NF filtration method was not effective.

The experiment showed that the desalination efficiency (salt rejection) and recovery rate of the NF filter were inversely proportional to the salt concentration of feed water. At the same time, the operation cost of two-stage NF process is more reasonable at lower concentrations. In order to be able to treat water during high salt concentration period, further research will be required.

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