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UF pretreatment at elevated temperature within the scheme of hybrid desalination: Performance and environmental impact

Sergey Agashichev* and Jayesh Kumar

NEWRC (ADWEA), PO Box 54111, Abu Dhabi, UAE

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Abstract. This study was aimed at ultrafiltration (UF) as a pretreatment before reverse osmosis (RO) within the scheme of hybrid reverse osmosis-multistage flush (RO-MSF) desalination. Seawater at elevated temperature (after MSF heat-exchangers) was used as a feed in this process. The pretreatment system was represented as a set of functionally-linked technological segments such as: UF filtration, backwashing, chemical- enhanced backwashing, cleaning, waste disposal, etc. The process represents the sequences of operating cycles. The cycle, in turn, consists of the following unit operations: filtration, backwashing and chemical-enhanced backwashing (CEB). Quantitative assessment was based on the following indicators: normalized permeability, transmembrane pressure, specific energy and water consumption, specific waste generation. UF pre-treatment is accompanied by the following waste streams: *W*1=1.19×10 power of -2 m^3 (disposed NaOCl with 0.0044% wt.)/m^3(filtrate); *W*2=5.95×10 power of -3 m^3 (disposed H_2SO_4 with 0.052% wt.)/m^3 (filtrate); *W*3=7.26×10 power of -2 m^3(disposed sea water)/m^3(filtrate). Specific energy consumption is 1.11×10 power of -1 kWh/m^3 (filtrate). The indicators evaluated over the cycles with conventional (non-chemical) backwashing were compared with the cycles accompanied by CEB. A positive impact of CEB on performance indicators was demonstrated namely: normalized UF resistance remains unchanged within the regime accompanied by CEB, whereas the lack of CEB results in 30% of its growth. Those quantitative indicators can be incorporated into the target function for solving different optimization problems. They can be used in the software for optimisation of operating regimes or in the synthesis of optimal flow- diagram. The cycle characteristics, process parameters and water quality data are attached.

Keywords: hybrid desalination; elevated temperature; UF pre-treatment; UF cycle; chemical-enhanced backwashing; performance indicators; waste intensity indicators

1. Introduction

Desalination industry is expected to demonstrate unprecedented growth in the nearest future. Recent trends and the aspects of technological sustainability were considered by Gude (2016). It was accentuated that the selection of optimal configuration of desalination system and evaluation of technological sustainability are essential issues in strategic planning and development (Gude 2016). Conventional technologies, referred to as co-generative technologies are based on the coupling of power production with thermal desalination such as multistage flush (MSF) or multi

*Corresponding author, Ph.D., E-mail: agashichev@gmail.com, spagashichev@adwea.ae

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effect distillation (MED). These technologies are characterized by some disadvantages such as high energy consumption, elevated greenhouse gas emissions and inflexible limits of the power-to-water production and as a consequence they cannot meet the required pattern of demand. In this regard the concept of hybridization of conventional technologies with membrane processes is becoming attractive. Analysis of published data revealed the fact that the particular attention was given to hybridization of thermally and electrically driven desalination (Fritzman *et al.* 2007, Ludwig 2003, May 2000, Suk and Matsuura 2006). It was shown that integrated (or hybrid) processes can enhance technological flexibility and overcome limitations and disadvantages inherent to conventional technology such as vulnerability to fouling factors, elevated osmotic pressure, high energy consumption, etc. There are different technological combinations from using common intake for MSF and RO to developing coherent technological regimes for power and water production (Ludwig 2003, Agashichev 2004, 2010). The most promising option of hybrid desalination represents the scheme where seawater at elevated temperature 35-37 C (downstream after MSF heat-exchanger) is used as feed for RO desalination. Current status of seawater desalination technology highlighting the system integration and decrease of energy consumption was scrutinized by Amy *et al.* (2016).

Since RO is characterized by high vulnerability to the quality of feed water this process requires the proper development of individual site- specific pre-treatment. There is a wide spectrum of site- specific technological combinations having the function of pre-treatment (Al-Katheri and Agashichev 2008, Burashi and Hussain 2004, Sandin *et al.* 2013, Knops *et al.* 2013, Nappa *et al*. 2013, Pearce *et al.* 2004, Pearce 2017, Wilf and Schierach 2001). Conventional pre-treatment represents the combination of traditional unit operations such as coagulation, flocculation, multi-media filtration, dissolved air flotation, sedimentation, etc. Recently one can see the growth of new generation of pretreatment based on membrane operations such as NF, UF and MF and their multiple combinations. Advantages of UF over conventional technologies are well known: smaller footprints; operational reliability and better quality of treated water, but at the same time UF pretreatment is characterized by some operational disadvantages such as membrane maintenance, chemical consumption for cleaning; high power consumptions and elevated replacement cost (Guilbert and Laverty 2013). Lau *et al*. (2014) highlighted the integration of sea-water RO desalination with UF as a pretreatment where the potential advantages of this technological combination were considered. Different technological scenarios based on low-pressure membrane processes were outlined by Maddah and Ghogle (2015).

Integrated/hybrid membrane- based pretreatment was considered by Ang *et al*. (2015). Their study outlines different technological combinations such as MF/UF/NF, dual- media filtration/ MF, etc. as a pretreatment for a SWRO. It was shown that incorporation of the membrane- based pretreatment into the system of hybrid desalination can eliminate many technological limitations. It can improve techno- economic indicators as well. However it was stated that there is a shortage of information required for comprehensive analysis of integrated and hybrid systems. In particular many essential aspect such as energy consumption, waste generation and discharge analysis require further studies (Ang *et al.* 2015). The study done by Bundy *et al*. (2016) focuses on the optimization of MSF-RO hybrid system. In that study different optimization algorithms providing the lowest cost of water production were compared. Different innovative technological combinations used for pre-treatment were considered by Vedavyasan (2007). Those options were compared in terms of capital cost, energy requirement, footprints, chemical cost along with the potential impact on indirect improvement of RO characteristics. Their study (Vedavyasan 2007) deals with the methods of analysis of performance in terms of process variables, water quality parameters, cleaning frequency, chemical and energy consumptions as well.

Membrane-based pretreatment before RO desalination was considered by Tabatabai *et al.* (2013). It was focused on the feasibility of low molecular weight cut-off ultrafiltration as a pretreatment for seawater reverse osmosis in periods of algal bloom with high algal organic matter content in feed water. Conventional pretreatment (e.g., coagulation/dual media filtration) and the current generation of UF membranes are not capable of completely removing TEP's and biopolymers. Recent results showed that while 150 kDa membranes removed approximately 60% of biopolymers during bloom conditions, 7 kDa UF removed approximately 96% of biopolymers. In terms of TEP removal, the 150 kDa UF membrane removed 100% of TEP's larger than 0.4 μm and >90% of the TEP's>0.1 μm (the current lower limit of the analytical method for TEP) during a simulated algal bloom. However, TEP's smaller than 0.1μm also exist in seawater, and their removal can be enhanced by the use of low MWCO UF membranes with a narrow pore size distribution. The main aspects of development of desalination pretreatment were considered by Henthorne and Boysen (2015).

Recent tendencies in theory of macroeconomic analysis are characterized by incorporating characteristics, being exogenous to economics, into economic methodology. In particular, Ayres (1998) considered exergy as a factor of production along with the labor and capital. Nowadays the carbon risk management is getting inextricably linked with engineering and technological consulting. Accounting the carbon risk and environmental damage in cost-benefit analysis is becoming essential, that was accentuated on by different authors in particular by Ayres (1998), Costanza (1991), Duic *et al.* (2005), O'Riordan (1997). The study done by Macedonio and Drioly (2010) contains some indicators specifying mass intensity, waste intensity, energy efficiency, etc. It implies a comprehensive evaluation of all the technological segments of the process at different regimes. In accordance with the contemporary standards and guidelines the comparison and selection of technological alternatives should be based on the following groups of multi-parameter variables: (1) indicators for estimation of water quality; (2) estimation of resource consumption; (3) estimation of environment, and group of indicators for estimation of (4) social aspects and (5) efficiency indicators (Afgan and Karvalho 2002, Afgan *et al.* 2002). UF pre-treatment can be characterized by the following groups of indicators and variables: (1) variables specifying technological performance such as specific permeability, driving force, differential pressure, etc.; (2) water quality parameters such as turbidity, SDI index, etc.; (3) recourse consumption such as specific energy consumption and "water footprints"; (4) indicators specifying environmental impact and allocated environmental damage (such as "carbon footprints" and chemical consumption allocated per cubic meter of filtrate, etc.) along with economic indicators.

In this regards the current study focuses on characterization of UF pre-treatment built into the scheme of hybrid RO-MSF desalination (where the seawater after MSF heat-exchangers at elevated temperature was used as a feed for this process). Some similar approaches to the process analysis were considered by Agashichev and El-Nashar (2004) and by Agashichev (2012). The current study is aimed at the quantitative comparison of conventional cycles without chemical-enhanced backwashing (CEB) with the cycles accompanied by CEB. The comparison has to be based on of the following groups of variables: (1) variables specifying technological performance such as specific permeability, driving force and apparent resistance; (2) variables characterising the recourse consumption in particular specific energy consumption and (3) indicators specifying environmental impact and allocated environmental damage (such as chemical consumption allocated per cubic meter of filtrate, etc.)

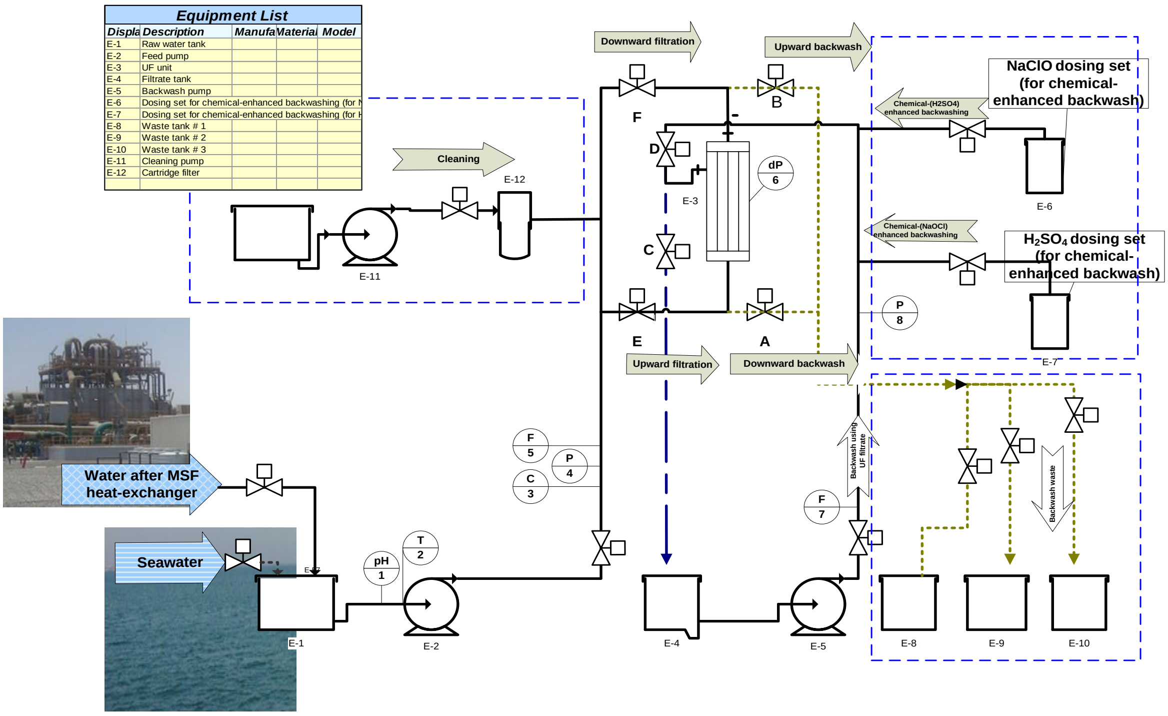

Fig. 1 Simplified flow diagram of UF pre-treatment

2. UF pretreatment incorporated into the pilot system of hybrid (RO-MSF) desalination

This study is aimed at UF pretreatment before RO within in the scheme of hybrid desalination, where seawater at elevated temperature 35- 37 C (downstream after MSF heat-exchangers) is used as a feed for RO desalination. The simplified flow- diagram is shown in Fig. 1. Water after MSF heat- exchanger having passed through the tank (E-1) was pumped to UF unit (E-3). The filtrate was accumulated in the tank (E-4). The pilot system was equipped by UF module *Dizzer* ® *5000 plus* (*Inge Co*), where poly-ether-sulfonic polymer membranes (PSEM) were used. Total membrane area: 150 m^2, where three elements with effective membrane area 50m^2 per element were assembled within the pressure vessel (see INGE Catalogue). Specific permeability ranges from 0.06 to 0.14 m^3/ [m^2-h-bar] during filtration and from 0.20 to 0.25 m^3/[m^2-h-bar] during back washing. The driving force varies from 0.1 to 0.8 bar during filtration and from 0.3 to 2.5 bar during back washing. UF filtrate enters the first pass RO with prior to pH adjustment.

The pre-treatment system, in turn, can be represented as a set of functionally- integrated technological subsystems of the different hierarchy levels such as UF-filtration, backwashing, chemical-enhanced backwashing and waste treatment (see Fig. 1). UF filtration cycle, in turn, represents the sequence of the following unit processes: downward filtration, downward water backwashing, upward filtration, upward water backwashing, downward backwashing using NaOCl, upward backwashing using NaOCl, upward backwashing using sulphuric acid solution, downward backwashing using acid, soaking and flushing. (Itemized list of elementary operations of cycle and the main process parameters and water quality characteristics are given in Append. A)

The downstream after MSF heat-exchanger was used as a raw water for RO desalination. Over the test period it water was characterized by the following values: temperature was ranging from t= 29 C to 38 C (with average value was 34.8 C); conductivity ranged from 67.45 ms/cm; to 71.86 ms/cm (average value was 69.32 ms/cm); pH varied from pH=6.4 to pH=7.4 (average value was pH= 7.04); The silt density index (SDI_5) of raw water ranged from 15.1 to 17.1 (with average value 16.1) and raw water turbidity ranges from 0.605 NTU to 5.833 NTU (with average value equal 1.869 NTU). An average degree of rejection of UF pre-treatment expressed in terms of SDI_5 was equal to 84%.

3. Performance, resource consumption and waste generation

3.1 Technological performance

Evaluation of the cycles in different regimes (in the regime accompanied by CEB and regimes without CEB) was based on the comparison of experimental values of permeability, driving force and membrane resistance. Experimental data on the flow rate at operating temperature were used for estimation of normalized flow rate.

$$V_{t=25} = \left[\mu(t)/\mu_{t=25}\right]\ Q(t)/A\,\Delta P \tag{1}$$

Where $V_{t=25}$-hydraulic permeability (specific) normalized at reference temperature, t=25; $m^3/[m^2$-h-bar]; $Q(t)$-flow rate at operating temperature m^2/h; A-membrane area, m^2; ΔP-driving force; $\mu(t)/\mu_{t=25}$-viscosity correction factor. Transmembrane pressure difference (driving force) and

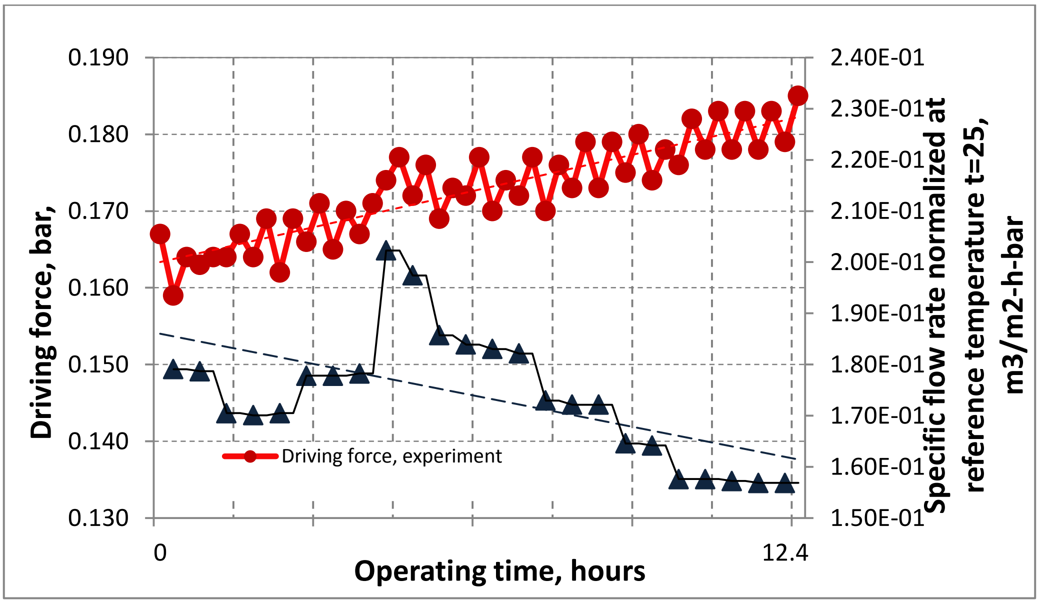

Fig. 2 Specific permeability normalized at reference temperature, t=25 C and driving force for the regime without chemical–enhanced backwashing (Experimental data and linear trends)

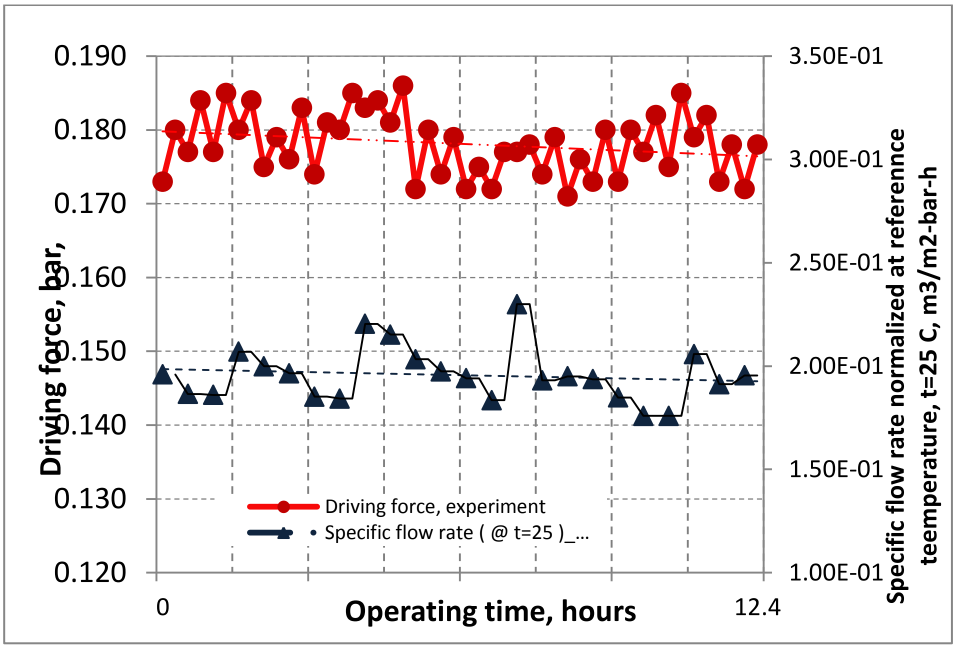

Fig. 3 Specific permeability normalized at reference temperature, t=25 C and driving force for the regime accompanied by chemical–enhanced backwashing (Experimental data and linear trends)

specific flow rate normalized at reference temperature, t=25 C for the regime accompanied by chemical-enhanced backwashing and for the case without it are shown in Figs. 2 and 3.

Relying upon the experimental data on driving force and specific permeability (see Figs. 2-3) one can see the deterioration of performance during UF operation in the regime without chemical enhanced backwashing, in particular the transmembrane pressure goes up while the normalised permeability goes down. In the case if the process is accompanied by CEB, no deterioration was observed. One can see the stable behaviour of driving force and permeability (see Figs. 2 and 3). For quantitative comparison of technological performance we can use specific resistance as an apparent indicator. The ratio of apparent driving force to the permeability normalized at reference temperature (t=25) can be used as a measure of overall resistance. (This indicators includes all the constituents of resistance such as membrane itself, gel and CP layers).

$$r_{t=25} = A\Delta P \,/\left[\left(\mu(t)/\mu_{t=25}\right)\, Q(t)\right] \tag{2}$$

Since the time-dependent fouling rate is assumed to be proportional to resistance, the fouling rate of the regime accompanied by chemical enhanced backwashing can be compared with the regime without it. Non-dimensional ratio of current resistance to the value in the beginning of filtration cycle) can be used.

$$R(\theta) = r_{t=25}(\theta)/r_{t=25}(\theta = 0) \tag{3}$$

It was demonstrated that normalized UF resistance remains unchanged within the regime accompanied by CEB, whereas the lack of CEB results in 30% growth of resistance during UF filtration, (see Fig. 4).

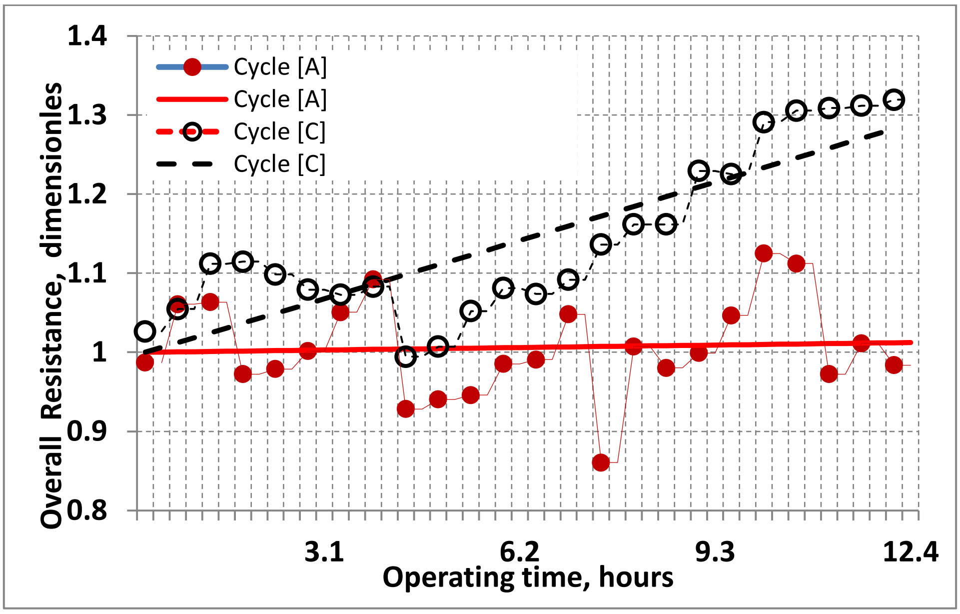

Fig. 4 Overall resistance for the regimes accompanied by chemical enhanced backwashing and without it. (Experimental data and linear trends)

3.2 Recourse consumption

The study published by Macedonio and Drioly (2010) contains some indicators specifying mass intensity, waste intensity, energy efficiency, etc. It implies that any technological scheme must be decomposed into the set of technological segment and unit processes. In particular, UF cycle represents the sequence of elementary unit processes such as: downward filtration, downward water backwashing, upward filtration, upward water backwashing, downward backwashing using NaOCl, upward backwashing using NaOCl, upward backwashing using acid solution, downward backwashing using acid solution, soaking and flushing. (Itemized list of elementary operations within the structure of cycle; main process parameter and water quality characteristics are given in Appendix A). In this study the following indicators were used: specific energy consumption, specific water consumption, specific waste generation. Specific energy consumption of the pre-treatment was estimated as the ratio of consumed energy to the filtrate produced. According to data published by Pearce (2008), energy requirements for conventional pre-treatment is reported to be between 0.2 and 1 kWh/m^3 whereas, the energy consumption for UF pre-treatment ranges from 0.08 to 0.1 kWh/m^3 (see Fan and Wang 2013, Sarkal and Arafat 2013). The target level of energy consumption of pre-treatment was formulated by Fane and Wang (2013). According to their estimates it can be reduced up to < 0.02 kWh/m^3. There are some energy- consuming pieces of equipment on this stage, they are UF feed pump; UF backwash pump; UF cleaning pump. They are characterised by the values 7-9×10 power of -2; 3-4×10 power of -3 and 3-4×10 power of -3 kWh/m^3 (filtrate). In our case the total value of specific energy consumption ranges from 0.1 to 0.13 kWh/m^3 (filtrate). The UF feed pump represents the most energy consuming piece of equipment. Specific water consumption or “water footprints” was estimated as water consumed for auxiliary operations such as backwash or chemical-enhanced backwash during an operating cycle.

Table 1 Water consumption and waste generation during an operation cycle of UF pre-treatment

	Volumes generated and to be disposed during operation cycle	Value (m^3)
1	Total volume of filtrate produced during the operation cycle at operating temperature	1.07E+02 m^3
2	Total volume of filtrate produced during the operation cycle (calculated at normalized temperature, *t*=25 C)*	[8.56E+01] m^3
3	Total volume of backwash water to be disposed during the operation cycle (waste #1)	7.79E+00 m^3
4	Total volume of chemical–enhanced backwash (NaOCl) to be disposed during the operation cycle (waste #2)	1.28E+00 m^3
5	Total volume of chemical–enhanced backwash (H_2SO_4) to be disposed during the operation cycle (waste #3)	6.38E-01 m^3
	Specific water consumption	Value (dimensionless)
6	Specific volume of sea water backwash per cubic meter of filtrate (for waste #1)	7.26E-02
7	Specific volume of chemical- enhanced backwash (NaOCl) per cubic meter of filtrate (for waste #2)	1.19E-02
8	Specific volume of chemical- enhanced backwash (H_2SO_4) per cubic meter of filtrate (for waste #3)	5.95E-03

*- for reference

3.3 Waste generation

Any membrane operation is accompanied by chemical reagent consumption required by auxiliary operations such as chemical cleaning, chemical- enhanced backwashing etc. (Kha *et al.* 2015). Specific water consumption for auxiliary operations was assumed to be proportional to waste generation. The waste streams to be disposed can be subdivided into three main sub-categories depending upon the difference in hazardous or polluting potential. In particular the waste #1 contains V=7.79 m^3 of seawater used for backwashing; the waste #2 contains V=1.28 m^3 of NaOCl solution with C=0.0044 % (wt), and waste #3 comprises V=0.638 m^3 of H_2SO_4 solution with C=0.052 % (wt). These volumes have to be allocated per one operating cycle. UF operating cycle produces 107 m^3 of filtrate to be passed for RO desalination. Any waste stream is characterised by certain index equal to the ration of waste volume to filtrate volume. The index values are equal to 7.26×10 power of -2, 1.19×10 power of -2 and 5.95×10 power of -3 for the waste streams #1; #2 and #3 respectively (see Table 1). These indicators are essential for the comparison of technological alternatives; for the synthesis of optimal schemes and in evaluation of technological sustainability. Structure of the cycle along with the sequence and duration of elementary unit operations are essential in optimal selection of pre-treatment as well.

4. Conclusions

It was confirmed that UF process can be recommended as a pretreatment before RO within the scheme of hybrid RO-MSF desalination. The case where the seawater at elevated temperature (after MSF heat-exchangers) was used as a feed for this process. For the evaluation to be done the pretreatment system can be decomposed into set of functionally-linked technological segments such as: UF filtration, backwashing, chemical- enhanced backwashing, cleaning, waste disposal, etc. Those segments, in turn, represent the sequences of operating cycles including the following unit operations: filtration, backwashing and chemical-enhanced backwashing. Those operations occur in the following sequence: downward filtration, downward water backwashing, upward filtration, upward water backwashing, downward backwashing using NaOCl, upward backwashing using NaOCl, upward backwashing using sulphuric acid solution, downward backwashing using acid solution, soaking and flushing.

Assessment of UF pre-treatment was based on the following indicators: (1) normalized permeability, (2) transmembrane pressure, (3) normalized resistance; (4) specific resource consumption and (5) specific waste generation.

Specific permeability ranges from 0.06 to 0.14 m^3/m^2-h-bar during filtration and 0.20 to 0.25 m^3/m^2-h-bar during back washing; operating pressure varies from 0.1 to 0.8 bar during filtration and 0.3 to 2.5 bar- during back washing. UF filtrate enters the first pass RO with prior pH adjustment. A positive impact of CEB on performance indicators was demonstrated. It was demonstrated that the normalized UF resistance remains unchanged within the cycle accompanied by CEB, whereas the lack of CEB can result in the growth of resistance during an operating cycle up to 30%. Specific energy consumption ranges from 0.07 to 0.1 kWh/m^3 (filtrate) that is close to the values in available published sources. UF pre-treatment is characterized by the following waste streams: *W*1; *W*2 and *W*3, where: *W*1=1.19×10 power of -2 10^{-2} m^3 (disposed NaOCl, 0.0044% wt.) /m^3(filtrate); *W*2=5.95×10 power of -3 10^{-3} m^3(disposed H_2SO_4, 0.052% wt.) /m^3(filtrate); *W*3=7.26×10 power of -2 10^{-2} m^3(disposed sea water) /m^3(filtrate). The indicators evaluated over the cycles with conventional backwashing (without chemical enhancement) were compared with the cycles accompanied by chemical-enhanced backwashing. It was demonstrated that normalized UF resistance remains unchanged within the regime accompanied by CEB, whereas the lack of CEB results in 30% growth of resistance during UF filtration. The values of generated indicators can be used as an input data for comprehensive evaluation of technological sustainability. Those quantitative indicators can be incorporated into the target function for solving different optimization tasks. They can be built in the software for optimisation of operating regimes, for the synthesis of the optimal cycle structure and optimal flow- diagram. The cycle characteristics, process parameters and water quality data are attached.

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Symbols and abbreviations

A	Membrane area, m^2;
r	Hydraulic resistance, [h-bar]/ m^3;
R	Normalized resistance, $R = r(\theta)/r(\theta = 0)$, dimensionless
$V_{t=25}$	Specific flow rate normalized at reference temperature, m^3/[m^2-h-bar];
$Q(t)$	Flow rate at operating temperature, m^3/h;
ΔP	Trans-membrane pressure difference (driving force), Pa;
μ	Dynamic viscosity, Pa s^{-1};
$\mu(t)/\mu_{t=25}$	Viscosity correction factor, dimensionless;
CEB	chemical-enhanced backwashing

Appendix A.

Structure of UF cycle (The cycle includes the following unit processes: downward filtration; upward filtration; backwashing; downward backwashing chemically enhanced by NaOCl; upward backwashing chemically enhanced by NaOCl; downward backwashing chemically enhanced by H_2SO_4; upward backwashing chemical enhanced by H_2SO_4).

Number of elementary operation	Duration of operation	Operating temperature	pH	Raw water turbidity.	Turbidity rejection at beginning of filtration	Turbidity rejection at end of filtration	Transmembrane pressure at the beginning of filtration	Transmembrane pressure at the end of filtration	Specific flow rate at operating temperature	Specific flow rate at normalized temperature, t=25	estimated at operating temperature; normalized driving force= 0.3 bar &	estimated at normalized t= 25 C, normalized driving force= 0.3 bar, operating time= 31	Volume consumed for backwash	Volume used for chemical enhanced backwash (NaOCl)
Dimension	Min, sec	^0C		NTU	%	%	bar	bar	m^3/ m^2-h-bar	m^3/m^2-h-bar	m^3	m^3	m^3	m^3
Downward filtration_0	31’ 15"	35.2	7.1	0.51	9.47E+01	9.61E+01	1.92E-01	1.99E-01	2.18E-01	1.69E-01	5.07E+00	3.92E+00		
Downward backwashing _0	56"												3.25E-01	
Upward filtration_0	31’ 15"	35.1	7.1	0.77	9.65E+01	9.75E+01	1.98E-01	2.05E-01	2.10E-01	1.63E-01	4.88E+00	3.78E+00		
Upward backwashing _0	56"												3.25E-01	
Downward filtration_1	31’ 15"	34.9	7.1	1.40	9.84E+01	9.86E+01	1.97E-01	2.07E-01	2.10E-01	1.63E-01	4.88E+00	3.80E+00		
Downward backwashing _1	56"												3.25E-01	
Upward filtration_1	31’ 15"	34.7	7.1	1.81	9.88E+01	9.90E+01	2.06E-01	2.17E-01	1.95E-01	1.53E-01	4.54E+00	3.56E+00		
Upward backwashing _1	56"												3.25E-01	
Downward filtration_2	31’ 15"	34.9	7.3	1.45	9.85E+01	9.87E+01	2.04E-01	2.16E-01	1.89E-01	1.47E-01	4.39E+00	3.42E+00		
Downward backwashing _2	56"												3.25E-01	
Upward filtration_2	31’ 15"	34.7	7.1	1.35	9.84E+01	9.86E+01	2.16E-01	2.24E-01	1.89E-01	1.48E-01	4.39E+00	3.44E+00		
Upward backwashing _2	56"												3.25E-01	
Downward filtration_3	31’ 15"	34.1	7.1	0.57	9.52E+01	9.66E+01	2.08E-01	2.18E-01	1.95E-01	1.55E-01	4.54E+00	3.61E+00		
Downward backwashing _3	56"												3.25E-01	
Upward filtration_3	31’ 15"	34.1	7.1	0.71	9.68E+01	9.73E+01	2.17E-01	2.32E-01	1.95E-01	1.55E-01	4.54E+00	3.61E+00		
Upward backwashing _3	56"												3.25E-01	

Downward NaOCl backwashing	56"									3.19E-01
Upward NaOCl backwashing	56"									3.19E-01
Downward filtration_4	31’ 15"	34	7	1.16	9.79E+019.84E+012.12E-012.25E-01	1.95E-01	1.55E-01	4.54E+003.62E+00		
Downward backwashing _4	56"								3.25E-01	
Upward filtration_4	31’ 15"	34	7	0.25	8.43E+019.28E+012.28E-012.36E-01	2.03E-01	1.61E-01	4.71E+003.75E+00		
Upward backwashing _4	56"								3.25E-01	
Downward filtration_0	31’ 15"	33.9	7	0.23	8.59E+019.23E+012.25E-012.40E-01	2.03E-01	1.61E-01	4.71E+003.76E+00		
Downward backwashing _0	56"								3.25E-01	
Upward filtration_0	31’ 15"	33.2	7	0.35	9.28E+019.48E+012.35E-012.50E-01	1.83E-01	1.49E-01	4.25E+003.45E+00		
Upward backwashing _0	56"								3.25E-01	
Downward filtration_6	31’ 15"	33	7	0.48	9.58E+019.62E+012.28E-012.35E-01	1.89E-01	1.54E-01	4.39E+003.59E+00		
Downward backwashing _6	56"								3.25E-01	
Upward filtration_6	31’ 15"	33	7	0.48	9.60E+019.62E+012.17E-012.29E-01	1.95E-01	1.59E-01	4.54E+003.71E+00		
Upward backwashing _6	56"								3.25E-01	
Downward filtration_7	31’ 15"	33.1	6.9	0.43	9.54E+019.58E+012.14E-012.37E-01	2.10E-01	1.71E-01	4.88E+003.97E+00		
Downward backwashing _7	56"								3.25E-01	
Upward filtration_7	31’ 15"	33.1	7	0.44	9.55E+019.57E+012.33E-012.44E-01	1.83E-01	1.49E-01	4.25E+003.46E+00		
Upward backwashing _7	56"								3.25E-01	
Downward NaOCl backwashing	56"									3.19E-01
Upward NaOCl backwashing	56"									3.19E-01
Downward filtration_8	31’ 15"	33.8	7	0.31	8.99E+019.38E+012.25E-012.40E-01	1.83E-01	1.46E-01	4.25E+003.40E+00		
Downward backwashing _8	56"								3.25E-01	
Upward filtration_8	31’ 15"	33.6	7	0.33	9.30E+019.45E+012.22E-012.36E-01	1.89E-01	1.52E-01	4.39E+003.53E+00		
Upward backwashing _8	56"								3.25E-01	
Downward filtration_9	31’ 15"	33.3	7.1	0.41	9.46E+019.56E+012.33E-012.49E-01	1.77E-01	1.43E-01	4.12E+003.34E+00		

Downward backwashing _9	56"							3.25E-01	
Upward filtration_9	31’ 15"33.2	7.1	0.48	9.54E+019.62E+012.38E-012.51E-01	1.77E-01	1.44E-01	4.12E+003.34E+00		
Upward backwashing _9	56"							3.25E-01	
Downward filtration_10	31’ 15"33.3	7.1	0.47	9.55E+019.59E+012.38E-012.53E-01	1.83E-01	1.48E-01	4.25E+003.44E+00		
Downward backwashing _10	56"							3.25E-01	
Upward filtration_10	31’ 15"33.3	7.1	0.47	9.55E+019.59E+012.41E-012.48E-01	1.77E-01	1.43E-01	4.12E+003.34E+00		
Upward backwashing _10	56"							3.25E-01	
Downward filtration_11	31’ 15"33.9	7	0.32	9.27E+019.43E+012.40E-012.53E-01	1.89E-01	1.51E-01	4.39E+003.51E+00		
Downward backwashing _11	56"							3.25E-01	
Upward filtration_11	31’ 15"33.9	7.1	0.32	9.24E+019.43E+012.41E-012.61E-01	1.77E-01	1.41E-01	4.12E+003.29E+00		
Upward backwashing _11	56"							3.25E-01	
Downward H2SO4 backwashing	56"								3.19E-01
Upward H2SO4 backwashing	56"								3.19E-01
Total volume of filtrate produced during the operation cycle at operating temperature								**1.07E+02 m^3**	
Total volume of filtrate to be produced during the operation cycle (calculated at normalized temperature, *t*=25C)								**[8.56E+01] m^3**	
Total volume of backwash water to be disposed during the operation cycle									**7.79E+00 m^3**
Total volume of chemical–enhanced backwash (NaOCl)to be disposed during the operation cycle									**1.28E+00 m^3**
Total volume of chemical–enhanced backwash (H_2SO_4)to be disposed during the operation cycle									**6.38E-01 m^3**