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Pretreatment for desalination of seawater from an open intake by dual-media filtration: Pilot testing and comparison of two different media

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Abstract

The results of pilot testing of dual media filtration on seawater from an open intake in the Thermaikos Gulf, northern Greece, are presented in this study. Two different filter materials, FILTRALITE MC, a processed expanded clay material with particle range 1.5–2.5 mm, and anthracite coal with a similar particle range, were tested in parallel operation under various operating conditions (coagulant type and dose, filtration rate). Attention was focused on filtrate quality parameters relevant to feeding RO membrane desalination systems, that is, turbidity, silt density index (SDI), total organic carbon (TOC). In order to evaluate the effect of temperature variations on pretreatment performance, similar experiments were performed during a winter and a summer campaign of the same year. Despite the poor quality of feedwater, through an open intake, very low turbidities and SDI values lower than 5 could be obtained by means of coagulation and dual media filtration.

Both filtration materials demonstrated almost similar performance in removing particulates from the feed water and produced permeates of acceptable quality for feeding RO systems (SDI_{15} values lower than 5) during the winter and summer campaigns. It was observed that both filters were much more effective during the summer period due to the higher temperatures prevailing, which allowed the formation of larger aggregates and their subsequent effective capture within the filter media. Laboratory and on site pilot tests showed that optimal performance was achieved when polyaluminum chloride (PACl) was added to the feed water as a coagulant medium at a dose 1.8 mg Al/L. In the winter period similar SDI_{15} values were obtained by both filters when operating at a flow velocity of 10 m/h, whereas at 5 m/h the sand/filtralite column produced water with lower SDI_{15} values and better quality compared to the one from the sand/anthracite column. On the other hand, during

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the summer period, and for the same coagulant dose, similar SDI_{15} values (usually close to 3) were obtained by both filters at all the tested flow velocities (5, 10, 15 m/h). Furthermore, due to the effect of temperature on aggregation, in the winter period the duration of filtration cycles was found to be determined by particle breakthrough. In contrast, in the summer no breakthrough was observed and the filtration cycles were determined by the available free space for hydrostatic head buildup above the filter media. Finally, regarding the hydrostatic head development, it was observed that the sand/filtralite column had a slower head buildup than the sand/anthracite column for the same duration of filter operation.

Keywords: Seawater pretreatment; Desalination; Dual media filtration; Pilot tests

1. Introduction

The most critical step for the efficient operation of membrane desalination installations is the prevention of membrane fouling. The latter is caused by dissolved or dispersed materials that deposit on membranes and brine flow channels thus interfering with the membrane operation. The major effects of fouling are increased process downtime, increased consumption of cleaning chemicals, decreased membrane productivity and deterioration of product water quality. All these effects increase the capital and operating costs of the membrane installations.

Membrane fouling is broadly categorized into colloidal, organic, precipitation and biological fouling. All these types of fouling require separate and specialized pretreatment operations. In particular, colloidal species and organic substances present in the feed waters or created within the bounds of the desalination facilities through the action of microorganisms are usually the most troublesome. Organic deposits, together with iron oxide, silica and aluminum oxide, account for more than 70% of the deposits detected in membrane autopsies throughout the world [1].

The extent and complexity of the pretreatment systems for colloidal and organic fouling varies depends on site-specific conditions. A critical factor is the possible presence of an intake well. If such an intake well exists, it is part of the pretreatment process because of the capacity of the sand at the well bottom to perform a first filtration of the suspended solids. Then, a simple form of pretreatment consisting of media filtration without addition of coagulants may be adequate. If on the other hand the feed water is received through an open intake, the pretreatment process is usually more complex [2]. On open seawater intake, reverse osmosis membranes are sensitive to different types of pollution: particles, precipitated metals, organic matters, hydrocarbons etc. An efficient pretreatment must control the flux of each pollutant. The pretreatment must be designed to face the worst water quality, providing a constant and good RO feed water [3]. For example, the use of coagulants and sedimentation or flotation equipment may be necessary in addition to media filtration. Also, in recent years low-pressure membrane operations (microfiltration and ultrafiltration) to remove colloidal species are attracting interest by the membrane community.

Regarding the assessment of the propensity of feed waters for colloidal fouling, several types of measurements, such as turbidity, particle counts, and particle electrophoretic mobility are employed. However, none of these is accepted as a reliable tool for fouling prediction. The most widely accepted quality criterion which is endorsed by the membrane desalination industry and membrane manufacturers for more than 30 years is the silt density index (SDI). In general an acceptable correlation of the SDI with desalination membrane performance exists. Thus, despite the criticism on the drawbacks of SDI

[4], which is well known to the membrane community, and several research efforts that led to modified indices and variants thereof, a better alternative to the SDI does not exist, at present.

Briefly, the SDI is based on measurement of the time required to pass the first 500 mL of feed water through a 0.45 µm filter and the time required for another 500 mL, 15 min later. Membrane manufacturers recommend that the SDI should not exceed 4 or 5 and set limits of membrane productivity depending on the SDI (i.e. 8–14 gfd for SDI 2–4, 14–18 gfd for SDI < 2 and 20–30 gfd for SDI < 1) [5–7]. SDI tests of shorter duration exist as well, such as the 10-min, 5-min and 2-min tests. However, these are used only to get absolute SDI values (greater than the maximum 6.6 of the 15-min test) for high fouling waters not suitable for direct feed to RO membranes.

The general objective of the present study is to assess and compare the efficiency, under the different prevailing temperatures of winter and summer period in Mediterranean sea, of two different filtration media, namely FILTRALITE® MC 1.5–2.5 mm, a crushed expanded clay material, and anthracite coal of the same grain size, in the pretreatment of seawater to achieve a water quality that meets the criteria for feeding reverse osmosis membrane desalination installations. The pretreatment process involves dual media filter beds composed of the above materials on top of a sand layer. The specific objectives are to study the effect of parameters such as feed water temperature, filtration rate through the columns, and coagulant type and dose, and to assess and compare the performance of the two types of filter media in terms of water quality and duration of the filtration cycles. Emphasis is placed on the SDI, being the criterion for the suitability of the product water to be fed to RO desalination membranes. To facilitate comparison of the two different media, the filter columns operate in parallel with the same feed water and under the same conditions.

To meet the above objectives a pilot unit was constructed within the industrial facilities of TATE&LYLE, in Thessaloniki, Greece. Seawater, obtained through an open intake and used in the plant for cooling purposes, was made available for the study. Results from the whole campaign during winter and summer period are presented herein.

2. Materials and methods

2.1. Feed water

The feed to the pilot unit was seawater employed in the industrial plant to cover cooling needs. The seawater is obtained from an open intake in the Thermaikos Gulf in the vicinity of the plant. A slip-stream from the main supply line serving the plant was used to cover the needs of the study. A physicochemical characterization of the raw seawater is presented in Table 1.

Table 1
Raw seawater physicochemical analysis

Parameter		Cations, mg/L	
pH	8.1	Na^+	12.8×10^3
Conductivity, µS/cm	47×10^3	K^+	533
TDS, mg/L	38×10^3	Ca^{2+}	487
Total hardness, °F	615.8	Mg^{2+}	1.2×10^3
Carbonate hardness, °F	15.3		
Non-carbonate hardness, °F	600.5		
Alkalinity, M, mg/L $CaCO_3$	152.5		
$SDI_{2\,min}$	~38		
Trace elements, mg/L		**Anions, mg/L**	
B	9.5	Cl^-	21.2×10^3
Cu	0.4	HCO_3^-	186
Fe	1.3	SO_4^{2-}	10×10^2
Mn	0.5	NO_3^-	2.87
Zn	0.2	NO_2^-	<0.01
		PO_4^{3-}	<0.46

It is important to note that preliminary quality measurements indicated turbidity close to 2 NTU, although seasonal or more frequent fluctuations would naturally exist, as will be also presented in section 3 of this study. Moreover, a very high SDI was measured. Essentially complete plugging of the microfilters of the SDI test was taking place after the first 3 min of testing. Given that the seawater supply is through an open intake, this is not completely surprising as discussed in the introduction. Finally, ultraviolet absorption at 254 nm and dissolved organic carbon (DOC) measurements from feedwater samples showed that specific ultraviolet light absorbance (SUVA), which is defined as the ratio of the UV absorbance to the DOC concentration, was less than 3 L/mg C m^{-1} for all samples during the entire experimental period. Thus, it appears that the feedwater contains a low humic acid fraction (generally indicative of low-DOC water), and hence relatively low removal of DOC could be expected (20–50%) [8].

2.2. Filter materials

The granular bed filtration applied in this project was based on dual media. Either FILTRALITE® MC 1.5–2.5 mm or anthracite coal, on top of sand, were used as filter material in two columns operating in parallel. In both beds the depth of the sand bottom layer was 50 cm, while the top 70 cm layer was FILTRALITE® MC 1.5–2.5 mm in the first column and anthracite coal in the second column. The characteristics of different filter materials are reported in Table 2.

Table 2
Characteristics of filter media

Parameter	Sand	Filtralite	Anthracite
Particle size range, mm	0.8–1.25	1.5–2.5	1.2–2.5
Bulk density, kg/m^3	1550	550	730
Particle density, kg/m^3	2650	1300	1400
Effective size (d_{10}), mm	0.9	1.7 ± 0.3	1.55
Coefficient of uniformity (d_{60}/d_{10})	<1.5	<1.5	<1.5
Particle porosity, %	–	52	–
Voids, %	–	58	–

The filter media used for the seawater pretreatment applied in this project are depicted in Fig. 1.

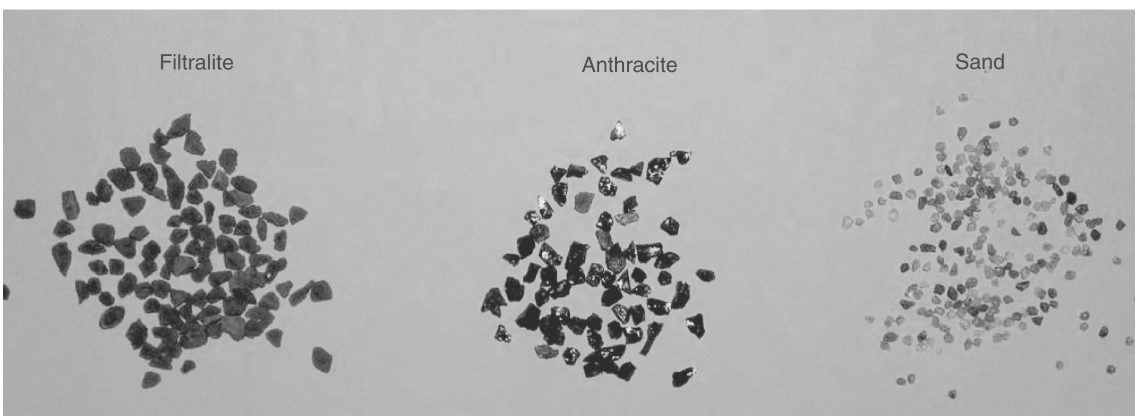

Fig. 1. Picture of filter media used in the two columns.

Table 3
Characteristic properties of coagulants tested

Parameter	$FeCl_3$	$FeClSO_4$	PACl
Concentration in $FeCl_3$, % w/w	41	–	–
Solution density in 20°C, g/cm^3	1.445	1.52	1.31
Fe^{3+} concentration, % w/w	14.0–14.1	12.3	–
Concentration in $FeClSO_4$, % w/w	–	40–41	–
Al_2O_3, % w/w	–	–	14
Basicity, %	–	–	40
pH (50% dilution)	–	–	2.0

2.3. Coagulants

Three different commercial types of coagulants, two ferric salts (ferric chloride solution and ferric chlorosulfate solution) and one pre-hydrolyzed metal salt prepared from aluminum chloride (called polyaluminum chloride or simply PACl), were selected to be investigated in the laboratory (jar testing) regarding their effectiveness in removal of particulates from sample seawater. The main characteristics of the selected coagulants are summarized in Table 3.

2.4. Pilot unit

In Fig. 2a schematic diagram is shown of the pilot unit, designed to meet the objectives of

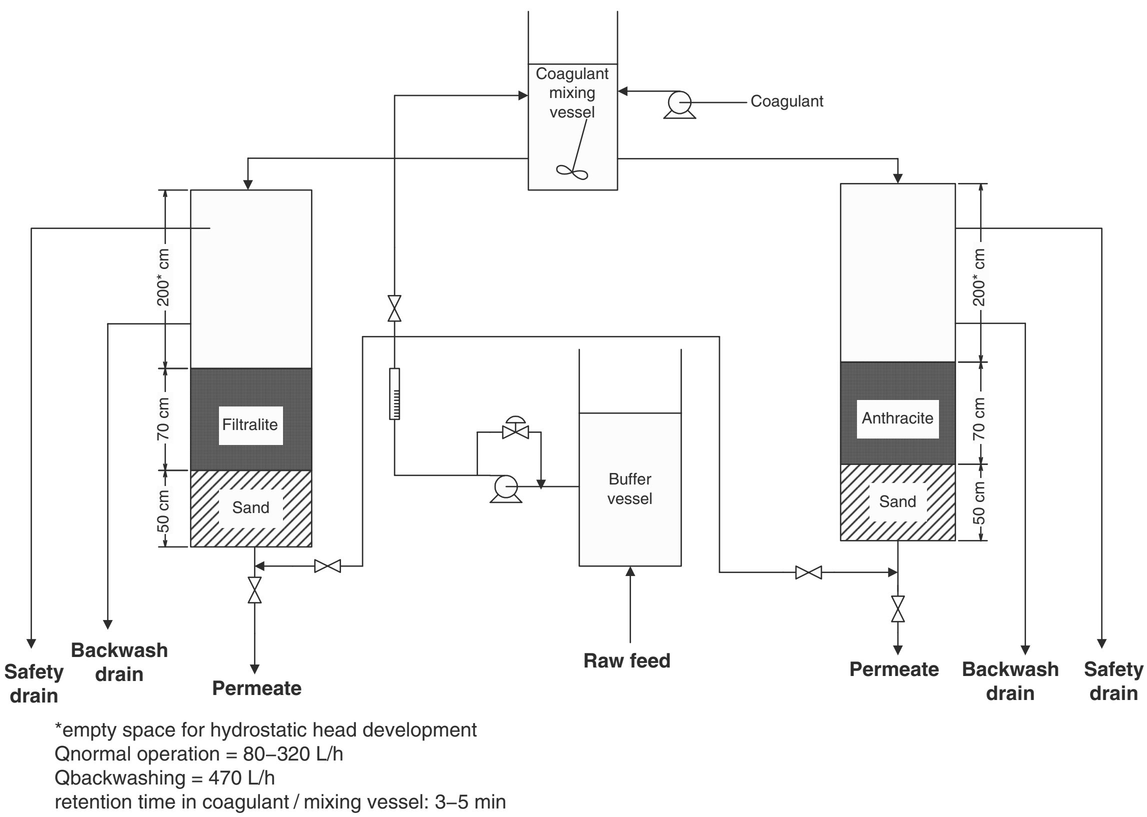

Fig. 2. Schematic diagram of pilot unit.

the study. A slip-stream from the main supply line serving the plant is collected in a buffer vessel of maximum capacity 230 L. A pump (IWAKI MD-15R-230GS, maximum capacity 19 L/min, maximum head 3.4 m) attached to the buffer vessel is used to supply feed water to both filter columns, as well as to provide the water necessary for filter backwashing. The flow rate measurement is performed by a Fischer Porter flowmeter calibrated in the Laboratory.

The feed water is pumped to a 30 L coagulant mixing vessel, sized to obtain a retention time of 3–5 min. The homogenisation of coagulant in the mixing vessel is accomplished through a magnetic stirrer (Thermolyne, Cimarec 3). A dosimetric pump (FMI) is employed to supply the coagulant to the vessel at a rate of 1 mL/min. Then the coagulated seawater flows by gravity to the two filters operating in parallel. Two 3.2-meter long pipes made of PVC with a diameter of 0.1 m are employed as filter columns. The total depth of filter media in the filter is 1.2 m while the available space above the filter beds allows the build-up of the necessary head for constant flow rate, regardless of filter plugging.

Filtration rates of 5 and 10 m/h (in winter period tests), while 5, 10 and 15 m/h (in summer period tests), during normal operation were investigated. After a period of operation referred to as filter cycle, the filters become clogged by the retained particulates and require cleaning. The cleaning is performed by backwashing, using an upward high flow rate of seawater (60 m/h), resulting in a bed expansion of about 10–15%. Data on the performance of the filtralite material during backwashing, provided by maxit Group AB, Norway, are shown in Fig. 3. Similar trends regarding bed expansion as a function of flow rate were found with the anthracite as well as with the dual media beds in tests performed at the CPERI laboratory with small glass columns of 2 in. in diameter.

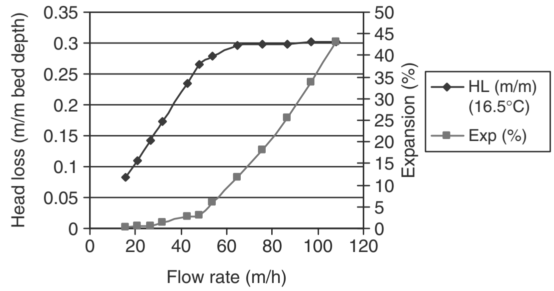

Fig. 3. Backwash head loss and expansion of filtralite beds as a function of flow rate. Filter bed material MC 1.5–2.5. Temperature 16.5°C [9].

2.5. Laboratory and on site measurements

2.5.1. Sampling and procedures

Three samples were collected on a daily basis. One sample was collected from the buffer vessel and the other two from the filtrates of the filtralite and anthracite columns in order to compare the quality of raw untreated water with that of filtered water. Temperature and turbidity of the three samples were measured on site. Measurement of SDI was also performed on site, according to ASTM standard test method D 4189-82 using Millipore membrane filters, 47 mm in diameter, gridded, with a mean pore size 0.45 ± 0.02 micron. The procedure is based on the time required to filter a volume (500 or 100 mL) of feed water through a 0.45 micron filter paper at a feed pressure of 30 psig at start and then after 5, 10 and 15 min of continuous filtration. If the test is limited to only 5 to 10 min reading, due to the plugging of the filter pad, one can expect a high level of plugging of the membrane. To perform the measurements filtrate was collected from each column in 30 L vessels and fed to the SDI filtration apparatus through a pump. The required test pressure of 30 psi was adjusted through a pressure regulator.

Other parameters measured on a daily basis in the laboratory were pH, with a pH-meter

(Metrohm, 744), conductivity with a conductivity meter (Metrohm, 712), UV absorption at 254 nm with Shimadzu UV-visible spectrophotometer UV-1700 (for the determination of aromatic organic compounds, [8,10,11]) and total organic carbon (TOC) with Shimadzu TOC – 5000A analyzer. Additional measurements, including concentration of total suspended solids (TSS) [12], total dissolved solids (TDS) [12] and particle counting on feed and outlet water were done on selected samples. The particle measurements in the range of 2–400 µm were conducted using a CHEMTRAC PC 2400D particle counter, which is based on the principle of laser light extinction.

3. Results and discussion

3.1. Tests during the winter campaign

3.1.1. Laboratory jar tests

Jar tests were conducted with the following coagulants: polyaluminum chloride, ferric chloride salt and ferric chlorosulfate. The influence of each coagulant on the pH value of seawater is presented in Fig. 4.

It is clear that polyaluminum chloride (PACl) has the smallest effect on the pH of seawater (operation pH). This is desirable since coagulants perform better in a narrow pH range where the "optimum sweep coagulation" is achieved [8]. A comparison of the performance of the three different coagulants in terms of their effect on the turbidity of the feed water is shown in Fig. 5. It may be observed that much smaller

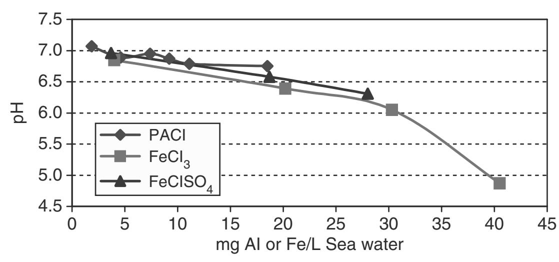

Fig. 4. Effect of coagulant dose on pH value.

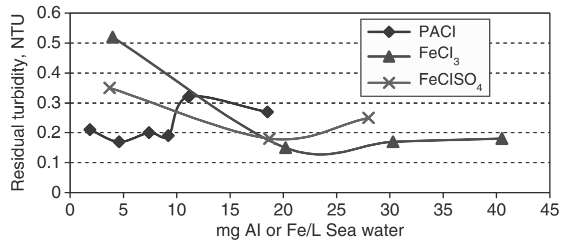

Fig. 5. Effect of various coagulant doses on seawater turbidity removal.

concentrations of PACl result in a similar or better reduction of seawater turbidity. Even at doses 1–5 mg Al/L, PACl reduces the initial seawater turbidity from 1.7 NTU to less than 0.2 NTU.

On the basis of the above laboratory observations, PACl appeared to be the most promising coagulant to assist the performance of the dual media filtration units, and it was decided to proceed with the pilot tests with this coagulant in the range of concentrations of 1–10 mg Al/L.

3.1.2. Pilot testing conditions and data

The operation of pilot unit took place continuously over a time period of six and a half weeks, from 6th of February to 22nd of March 2006. The operation was continuous throughout each week and was interrupted during the weekends.

As may be observed from Fig. 6, the temperature of the feed water during the experimental

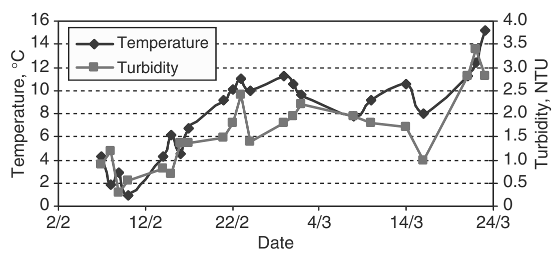

Fig. 6. Feedwater turbidity and temperature variation during experimental period.

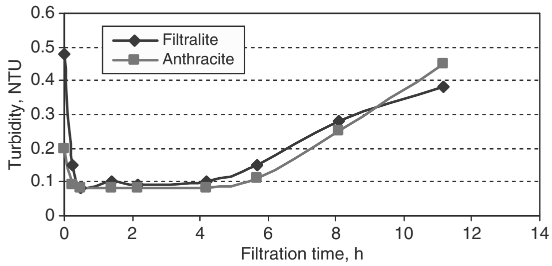

Fig. 7. Effect of filtration time on filtrate turbidity at flow velocity 10 m/h and coagulant dose 1.8 mg Al/L (16/3/2006).

period fluctuated from 0.9°C (on the 10th of February 2006) to 15.2°C (on the 23rd of March). However, apart from the first two weeks of the testing period, the temperatures were fairly uniform and close to 10°C. Shown in the same figure is also the feed water turbidity, which ranged from 0.3 NTU (on the 9th of February) to 3.4 NTU (on the 22nd of March) but was close to 2 NTU during most of the testing period.

The parameters that were investigated, regarding their effect on the quality of filtrate, were filtration velocity and coagulant dose. Reference pilot tests without coagulant addition were performed first. These tests started at a typical filtration velocity of 10 m/h in the two columns. A significant reduction in TSS (~60%) and turbidity (from 0.9 NTU of feed water down to 0.1 NTU) was observed and the SDI's were measurable up to 10 min, as compared to only 2 min for the feedwater. The above suggested that a marked improvement in water quality is obtained after filtration through both types of media but still the product water quality is not sufficient with respect to RO feedwater quality criteria. In addition, the hydrostatic head buildup was minimal in both columns (~0.2 meters water column (MWC)/d). A similar set of reference tests at a flow velocity of 5 m/h was also performed. The reduction in particle counts (particle size range 2–400 μm) was found to be almost at the same level of 65% for both columns. The SDI's from both filtrates were measurable up to 15 min but their values were greater than the acceptable limit of 5. However, there was a great reduction in turbidity between feed water and filtrate from the filtralite or anthracite column. Moreover, the hydrostatic head buildup was minimal in both columns.

Several pilot tests with different coagulant concentrations (0.9, 1.8, 3.5, 5 and 7 mg Al/L) suggested that optimum results regarding the filtration cycle time and filtrate quality parameters were obtained with a PACl concentration of 1.8 mg Al/L. Lower concentrations than this optimum resulted in marginal improvement in filtrate quality in comparison to feed water (producing filtrate with SDI value >5), whereas higher concentrations resulted in too short filter cycle times (see also Fig. 9). Thus, most tests

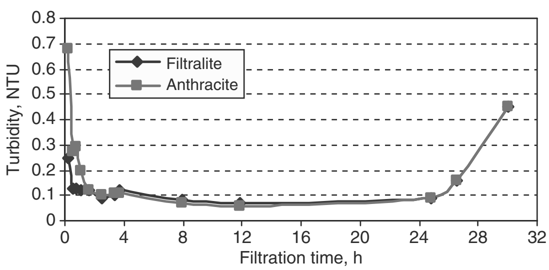

Fig. 8. Effect of filtration time on filtrate turbidity at flow velocity 5 m/h and coagulant dose 1.8 mg Al/L (21/3/2006).

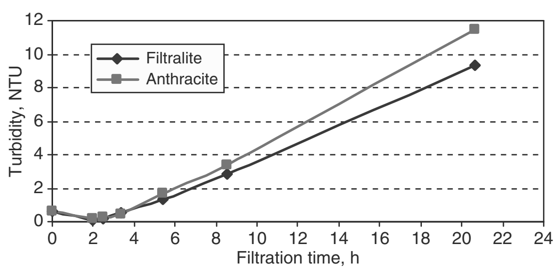

Fig. 9. Effect of filtration time on filtrate turbidity at flow velocity 5 m/h and coagulant dose 7 mg Al/L (2/3/2006).

Table 4
Data for head buildup development above filter columns under various operating conditions

	$U = 10$ m/h				$U = 5$ m/h			
Coagulant dose, mg Al/L	0	1.8	3.5	7	0	1.8	5	7
Sand/filtralite, MWC/d	0.2	0.5	0.8	3.3	–	0.3	0.3	0.7
Sand/anthracite, MWC/d	0.2	0.6	1.0	2.9	–	0.4	0.6	0.9

during the winter testing period and all the tests during the summer campaign, which followed, were performed with the above concentration of coagulant.

Indicative values of measured hydrostatic head buildup are summarized in Table 4. It is shown that in most cases the filtralite filter medium exhibited almost the same or a slightly slower head buildup development in comparison to anthracite filter medium. However, the pilot tests during this period revealed that the filter cycle time is determined by solids breakthrough rather than by any significant buildup of hydrostatic head in the two columns. The likely reason for the observed solids breakthrough is that due to the low prevailing temperatures in the winter, coagulation is not an efficient process to create large aggregates that would be effectively retained in the column. This behavior is in contrast to the one observed during the summer testing period where larger and stronger aggregates could be observed even by naked eye.

In Figs. 7–9 the filtrate turbidity as a function of time is shown for various operating conditions. As may be observed, after a short ripening period, good quality filtrates are obtained for about 24 h at a flow velocity of 5 m/h, whereas the filter cycle time is significantly reduced by increasing either the flow velocity or the coagulant concentration. For this reason it was not possible to perform tests at flow velocities higher than 10 m/h during the winter testing period. Figs. 7–9 also suggest that no significant differences exist between the two types of filter media in terms of turbidity.

An overview of the performance of the two columns is presented in Table 5. This table summarizes the main results, both from the reference

Table 5
Comparison in performance of two filter media under various operating conditions

Conditions	$U = 10$ m/h, no PACl			$U = 5$ m/h, no PACl			$U = 10$ m/h, PACl: 1.8 mg Al/L			$U = 5$ m/h, PACl: 1.8 mg Al/L		
Measured parameter	Feed	F[a]	A[a]	Feed	F	A	Feed	F	A	Feed	F	A
Turbidity, NTU	1.8	0.5	0.6	1.4	0.3	0.3	1.8	0.1	0.1	2.8	0.1	0.1
SDI_{15}	–	8.9[b]	8.8[b]	–	5.3	5.2	–	4.4	4.4	–	3.4	3.4
Particle counts, 2–400 μm, 1/mL	–	–	–	5610	2310	1890	10,422	1544	462	5660	1039	935
Head buildup, MWC/d	–	0.2	0.2	–	–	–	–	0.5	0.6	–	0.3	0.4

[a]F and A refer to the filtralite and anthracite column filtrates respectively.
[b]10 min-SDI.

experiments with no coagulant addition, as well as under conditions where both columns demonstrated near optimal performance.

In the reference tests, the turbidity measurements suggest that the filtration resulted in a significant reduction even with no coagulant addition. Both types of media showed a similar reduction in turbidity. The reduction in particle counts (particle size range 2–400 μm) when operating at 5 m/h with no coagulant was also found to be almost at the same level of 60–65% for both columns. The SDI measurements suggest that the operation at U = 10 m/h with no coagulant resulted in filtrates with SDI's which were measurable up to 10 min, as compared to only 2 min for the feedwater. At 5 m/h the SDI's from both filtrates were measurable up to 15 min but their values were greater than the acceptable limit of 5. Thus, a marked improvement in water quality was obtained after filtration through both types of media, but still the product water was not sufficiently good with respect to RO feedwater quality criteria. Finally, the hydrostatic head buildup was minimal for both columns (~0.2 MWC/d).

With the addition of coagulant at a concentration of 1.8 mg Al/L, there was a greater reduction in turbidity (from ~2 NTU of feed water down to 0.2–0.1 NTU for both filtrates); furthermore, the measured SDI_{15} values were below the acceptable limit of 5 for both columns. The operation at the lower flow velocity of 5 m/h produced filtrates of even better quality as their SDI_{15} values were lower than 4. Moreover, particle count measurements showed that both filtrates had very few particles in a size range 2–400 μm (1544 particle counts/mL for sample from filtralite filtrate, 462 particle counts/mL for sample from anthracite filtrate). Thus, a reduction higher than 83% was achieved in the number of particles present in feed water (10,422 particle counts/mL for that sampling date). A similar reduction in particle counts was observed when operating at 5 m/h flow velocity. Finally, the hydrostatic head at 10 m/h flow velocity in the columns reached the level of 0.5 MWC/d for sand/filtralite bed and 0.6 MWC/d for sand/anthracite bed, whereas it was 0.3 MWC/d and 0.4 MWC/d for filtralite and anthracite column, respectively, at half that flow velocity.

The above results suggest that, under the conditions tested, media filtration assisted by disinfection and cartridge filtration could be a viable option for producing feed waters suitable for membrane desalination operation.

3.2. Tests during the summer campaign

During the summer campaign, operation of the pilot unit took place continuously for a total time of six weeks, from the 13th of June till the 20th of July 2006. Again the operation was continuous throughout each week and was interrupted during the weekends.

As may be observed from Fig. 10, the temperature of the feed water during the experimental period fluctuated from 21.8°C (on the 13th of June 2006) to 37.2°C (on the 20th of June). Shown in the same Fig. 10 is also the feed water turbidity, which ranged from 0.6 NTU (on the 29th of June) to 5.3 NTU (on the 6th of July).

Again, during this testing period the sand/filtralite and sand/anthracite columns operated in parallel with polyaluminum chloride as a coagulant medium. The concentration of coagulant was kept constant in all the tests, whereas the

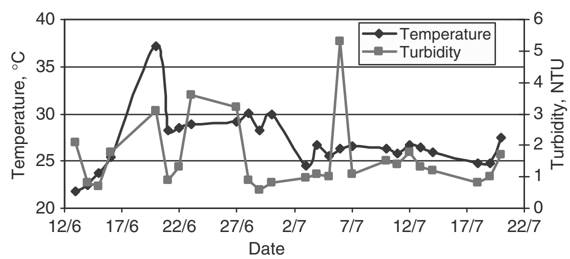

Fig. 10. Feedwater turbidity and temperature variation during experimental period.

variable parameter was the flow velocity in the two columns. Since a concentration of 1.8 mg Al/L was found to give the best results regarding the quality of both filtrates, the same concentration was applied at this period. The flow velocities tested were 5, 10 and 15 m/h in each column.

Reference experiments without coagulant addition were performed first. Operation started at the low flow velocity of 5 m/h in the two columns. The feed water temperatures during the first days of experiments were in the range of 22–25°C. A significant reduction in turbidity was observed and the SDIs were measurable up to 10 min, as compared to only 2 min for the feed water. However, the quality of filtrate water from both columns was not as good as desired, regarding the criteria for feeding RO installations, since 15-min SDI measurements were not feasible, whereas the 10-min measurements gave high SDI values (8.5 for filtralite and 8.8 for anthracite, respectively). In addition, the hydrostatic head buildup was minimal in both columns. The same behavior was observed when the flow velocity was doubled, where 15-min SDI measurements were not feasible and the 10-min measurements were again high (9.2 for filtralite filtrate and 9.3 for anthracite). The hydrostatic head buildup was also minimal in both columns.

As mentioned already, during this testing period a marked improvement in the coagulation behavior of the suspended solids was observed. Evidently, the higher prevailing temperatures resulted in much higher efficiency of the coagulant and the formation of larger and stronger aggregates. Thus, when coagulant dosing was applied, no solids breakthrough was observed under any operating condition, in contrast to the winter testing period. Rather, the filter cycle time was now determined by the hydrostatic head available. Fig. 11 shows the head buildup data (as meters of water column per day – MWC/d), obtained by the operation of the two columns at the three

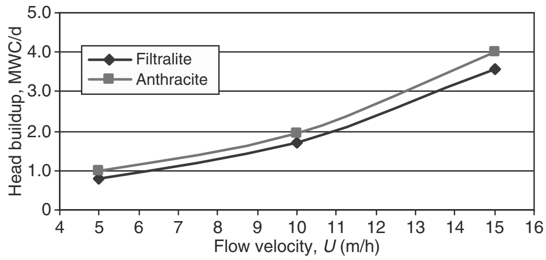

Fig. 11. Head buildup at sand/filtralite and sand/anthracite column at the tested flow velocities (5, 10 and 15 m/h).

different flow velocities tested (5, 10 and 15 m/h). It is evident that the filtralite material exhibits a smaller head buildup compared to the anthracite material for the same duration of filter operation.

Table 6 includes the main measurements for the three flow velocities tested. On the basis of these measurements, the performance of the two columns in terms of filtrate quality and hydrostatic head buildup may be assessed in more detail. Filtrate SDI_{15} indices as low as 3.5 were measured. Thus, both filter media (filtralite or anthracite) showed almost the same performance regarding the capture of particulates, and produced filtrate water with a low SDI_{15} index which is acceptable for feeding RO systems.

For all the operating flow velocities (5, 10, 15 m/h), coagulant addition to the feed water caused a significant improvement in filtrate water quality resulting in low turbidity (<0.2 NTU), and $SDI_{15\,min}$ values usually lower than 4, even after 22 h of continuous filter run for both columns. This is indicative of the fact that no particle breakthrough occurred during the filter cycle for both columns. This fact could be attributed to the better performance of coagulant medium as a result of the high prevailing temperatures compared to winter conditions. Much larger and better adhering flocculates could be formed, thus facilitating their effective capture within the filter media. This is expected since the rate of floc

Table 6
Measured parameters for both columns at 5, 10, 15 m/h flow velocity and 1.8 mg Al/L coagulant

Parameter	Turbidity, NTU			SDI_{15}			TOC, mg O_2/L			Head buildup, MWC/d		
Date	F.W	F	A	F.W	F	A	F.W	F	A	F.W	F	A
				U = 5 m/h and 1.8 mg Al/L								
16/6/06	1.9	0.2	0.1	–	4.6	4.6	11.1	5.7	5.8	–	0.8	0.9
20/6/06	3.1	0.1	0.1	–	3.5	4.4	3.2	1.9	2.0	–	0.8	0.9
21/6/06	0.9	0.2	0.2	–	3.7	3.9	2.9	1.8	1.6	–	0.8	0.8
22/6/06	1.3	0.2	0.2	–	5.7	5.0	2.2	1.7	1.4	–	–	–
23/6/06	3.6	0.1	0.1	–	5.1	3.3	3.7	2.2	2.0	–	–	–
27/6/06	3.2	0.2	0.2	–	4.8	4.1	3.0	1.8	2.3	–	0.7	1.1
28/6/06	0.9	0.1	0.1	–	5.2	4.1	2.9	2.0	1.9	–	0.8	1.0
29/6/06	0.6	0.2	0.1	–	4.4	3.8	2.7	2.3	2.4	–	0.8	1.0
30/6/06	0.8	0.2	0.1	–	4.5	4.3	3.1	2.3	2.6	–	0.8	0.1
				U = 10 m/h and 1.8 mg Al/L								
3/7/06	1.0	0.1	0.1	–	5.4	5.5	2.6	2.2	2.1	–	–	–
4/7/06	1.1	0.1	0.1	–	3.2	3.6	2.0	1.5	1.4	–	–	–
5/7/06	1.0	0.1	0.1	–	3.6	3.3	2.5	2.3	2.0	–	1.7	2.0
6/7/06	5.3	0.1	0.1	–	3.7	3.5	2.8	1.8	1.5	–	–	–
7/7/06	1.1	0.1	0.1	–	4.4	3.7	3.1	2.6	2.5	–	–	–
18/7/06	0.8	0.1	0.1	–	3.8	4.4	2.2	1.9	1.6	–	1.6	NM
19/7/06	1.0	0.1	0.1	–	3.1	3.5	2.5	1.9	1.9	–	1.5	1.8
20/7/06	1.7	0.1	0.1	–	3.4[a]	3.4[a]	3.3	2.8	2.4	–	1.7	1.9
				U = 15 m/h and 1.8 mg Al/L								
10/7/06	1.5	0.1	0.1	–	6.0	5.6	3.1	2.3	–	–	–	–
11/7/06	1.4	0.1	0.1	–	4.6	4.4	2.8	2.1	–	–	3.6	4.5
12/7/06	1.8	0.1	0.1	–	4.8	5.2	2.5	2.1	2.2	–	4.0	4.4
13/7/06	1.3	0.1	0.1	–	3.6	3.3	3.5	2.2	2.4	–	3.4	3.6
14/7/06	1.2	0.1	0.1	–	4.2	3.7	3.0	2.4	2.3	–	3.3	3.6

[a]SDI-10 min.

formation and the efficiency of primary particle removal are found to decrease as the temperature decreases [8].

Significant TOC removal was also measured in both columns. This is attributed to the likely presence of large macromolecules in the feed water that can be effectively aggregated by the coagulant and captured by the filtration media. A rather small reduction in the UV_{254} absorbance was also measured. This measurement is indicative of the aromatic character of the dissolved organic compounds. At a flow velocity of 5 m/h the sand/filtralite column achieved a TOC reduction in the range of 15–40%, and similar was the reduction in the sand/anthracite column (11–46%). At a flow velocity of 10 m/h the TOC reduction was 8–36% in the sand/filtralite column, and 19–46% in the sand/anthracite bed. Finally, when the two filters operated at 15 m/h flow velocity, the TOC reduction ranged from 16 to 37% for the filtralite column and from 12 to 31% for the anthracite column.

4. Conclusions

A pilot unit for testing dual media filtration of raw seawater, under winter and summer conditions, was constructed and successfully operated within the facilities of TATE&LYLE, in Thessaloniki. Seawater, obtained through an open intake and used in the plant for cooling purposes, was made available for the study.

Attention was focused on filtrate quality parameters relevant to feeding RO membrane desalination systems. A range of operating parameters such as flow velocities in the filters, as well as various coagulant types and concentrations were investigated in the laboratory and on site in order to identify conditions for optimal filter performance. It was demonstrated that acceptable filtrate quality for feeding RO systems was obtained by both types of media with the particular type of the raw feed water. It may be mentioned here that the origin of the feed water (being obtained through an open intake) is neither optimal for the design and operation of RO membrane pretreatment systems nor for membrane operation. Indeed, only the 2-min SDI of the particular feed water could be measured, which was very high (in the range of 38). Rough literature guidelines [5] suggest that media filtration alone cannot reduce this parameter by a factor much higher than 2. Thus, it may be argued that it is a significant achievement that very low turbidities and SDI values lower than 5 could be obtained in the present tests.

Polyaluminum chloride (PACl) was found to be the most effective coagulant for this particular feed water. A concentration of 1.8 mg Al/L gave optimal results in terms of filtrate quality and acceptable duration of the filtration cycles. During the winter testing period the filtration cycles were determined by breakthrough of the retained solids in the columns and not by any significant buildup of hydrostatic head. The low quality of the feed water necessitated relatively short filtration cycles in the media filters. For this reason tests at flow velocities higher than 10 m/h were not possible during the winter campaign. In contrast, during the summer testing period, no solids breakthrough was observed. The higher feed water temperatures favoured the formation of large and strong aggregates, resulting in their effective capture in the filter bed. This improved efficiency of the coagulant allowed higher velocities (up to 15 m/h) to be tested. The filtration cycles, at all the flow velocities tested, were now determined by the available free space above filter materials for hydrostatic head buildup.

Both filters, with FILTRALITE MC 1.5–2.5 mm or anthracite media, demonstrated a similar performance in removing particulates from the seawater and the reduction of the SDI_{15} value. Turbidities close to 0.1 NTU and SDI values lower than 4, or even close to 3, could be obtained. During the winter campaign, it was observed that at the higher flow velocity (10 m/h) the filtrate from the sand/filtralite column had almost the same quality as the one from the sand/anthracite column with respect to turbidity and SDI_{15} value. On the other hand, when operating at a lower flow velocity (5 m/h), the sand/filtralite column achieved lower SDI_{15} values and filtrate water of better quality than the sand/anthracite column. During the summer campaign both columns showed a similar behaviour in terms of filtrate quality, which was significantly improved compared to winter conditions. Finally, regarding the hydrostatic head development, it was observed that the sand/filtralite column had a slower head buildup than the sand/anthracite column for the same duration of filter operation.

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References

[1] S.C.J.M. Van Hoof, J.G. Minnery and B. Mack, Performing a membrane autopsy, Desal. Water Reuse, 11 (2002) 40–46.
[2] Permasep Reverse Osmosis Products, Bulletin 4010, Pretreatments for permasep permeators, DuPont, 1994.
[3] V. Bonnelye, et al., Reverse osmosis on open intake seawater: pre-treatment strategy, Desalination, 167 (2004) 191–200.
[4] S.G. Yiantsios, D. Sioutopoulos and A.J. Karabelas, Colloidal fouling of RO membranes: an overview of key issues and efforts to develop improved prediction techniques, Desalination, 183 (2005) 257–272.
[5] Hydranautics, RODESIGN, Hydranautics RO System Design Software, VERSION 6.4 (c), Pretreatment and design limits section of help module, 1998.
[6] Dow Liquid Separations, Ch. 3, Water Chemistry and Pretreatment, in: Filmtec Membranes Technical Manual, 1995.
[7] Osmonics, Pure Water Handbook, Ch. 4, Methods of Water Purification, in: CD entitled Interactive Resource Catalog, 2nd edn., 1991.
[8] American Water Works Association, Water Quality and Treatment, A handbook of Community Water Supplies, Ch. 6, Coagulation and Flocculation, 5th edn., 1999.
[9] Maxit Group, Norway, Internal report, 2005.
[10] S. Lee, et al., Characterization of NOM included in NF and UF membrane permeates, Desalination, 173 (2005) 131–142.
[11] V. Francois, et al., Indicating the parameters of the state of degradation of municipal solid waste, J. Hazard. Mater., B137 (2006) 1008–1015.
[12] APHA: Standard Methods for the examination of water and wastewater, 17th edn., 1989, 2540 D, pp. 2–75 to 2–77, 2540 C, pp. 2–74 to 2–75, 5220C, 5.14–5.15.