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Performance of a sand filter in removal of algal bloom for SWRO pre-treatment

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ABSTRACT

The present study has two main purposes: to investigate the performance of a first-stage sand media filter in a case of several reconstituted algal blooms and to better understand fouling mechanism of sand filter due to micro-algae. The retention efficiency of the filter obtained for 30,000, 50,000 and 145,000 cells/ml alga suspensions of *Chlorella vulgaris* is respectively above 90, 90 and 80% only during the first hours of filtration and drop at 74, 78 and 48% after 7 h. The fouling investigation reveals that the number of micro-algae captured in the filter is much higher in the first 30 cm of the bed. The ratio between the volume occupied by micro-algae retained in the filter and the total pore volume does not exceed 0.015% and suggests a minor effect of straining filtration mechanism. The effect of the micro-algae size (*C. vulgaris* (2–8 μm) and *Heterocapsa triquetra* (17–18 μm)) seems not to have a significant impact on the retention efficiency which is encouraging the idea that the adsorption mechanism has a higher affect on the retention than the straining filtration.

Keywords: Sand media filter; Algal bloom; Seawater pre-treatment; Fouling mechanism

1. Introduction

As freshwater resources become limited due to global changes, seawater desalination will play an important role in the world's future water supply.

The emergent market of desalination has to struggle against a serious threat known as harmful algal bloom [1–4]. Indeed, during a bloom event, desalination plants have some difficulties to supply a good fresh water quality, especially owing to the clogging of intake filters, the irreversible fouling of reverse osmosis (RO) membranes or other operational problems generated by the blooms [5,6]. Pre-treatment strategies in seawater reverse osmosis (SWRO) desalination plant become all the more crucial in this case [7,8].

The granular media filter (GMF) is the largest process used as pre-treatment in the SWRO desalination plant [9] even if the membrane pre-treatment process is wide-spreading in the desalination plant designs [10–12]. GMF remains simpler and more economic [9] whereas membrane systems provided a better outlet seawater quality [13,14]. GMF is a part of a conventional pre-treatment system, which is composed of several main units as follows: screening, coagulation/flocculation/sedimentation or flotation and granular

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media filtration. Screens are designed to remove from large debris and marine organisms to silt, plankton, sand as small as 80 μm. Coagulation/flocculation step enables to enhance removal of particulate and colloidal foulants, before the sedimentation. A flotation step could be used instead of the sedimentation, which is a better way to eliminate for instance algal cells [15–17].

Typically, the conventional design of granular filter is a single dual media (anthracite and sand) unit. According to the quality of feed water, the level of organics content, a single media (sand or anthracite) stage could be added upstream from the dual media filter. The most common characteristics encountered in the SWRO desalination plant is presented in Table 1.

Even with more drastic chemical pre-treatment such as chemical pre-oxidation [18], the filter still has some difficulties to provide a good enough seawater quality for RO feed during a bloom event. Several fouling mechanism can occur during filtration: cake deposit, straining filtration and adsorption [19] (Fig. 1).

Particles can be captured on the bed surface of the filter (cake deposit), trapped through the media in pores where there is no velocity (straining filtration) or attracted and deposited on the sand grain surface (adsorption). Cake deposit and straining filtration are dependent on the particle size and mechanical way whereas adsorption mechanism is more linked to physico-chemical properties.

The present work is a preliminary study and is part of a project concerning the research of an optimal SWRO pre-treatment process system by investigating step by step the performance of each pre-treatment unit and the fouling impact on them in case of algal bloom. This study is focused on the first-stage sand media filter unit alone first without chemical pre-treatment with a height of bed included in those used in SWRO desalination plant and a lower mean grain diameter than usual (392 μm). Several blooms have been reconstituted from a light one (30,000 cells/ml algae suspension) to a more severe one (145,000 cells/ml algae suspension) of the alga *Chlorella vulgaris* (2–8 μm). The retention efficiency of the filter will be investigated as well as an attempt of better understanding the fouling mechanism of sand filter due to micro-algae. Assays will be performed with another alga *Heterocapsa triquetra* (17–18 μm) in order to compare the effect of the micro-algal size on their retention efficiency.

Table 1
Granular media filtercharacteristics for SWRO desalination plant [9]

	First stage: single media filter	Second stage: dual media filter
Filtration rate ($m^3 m^{-2} h^{-1}$)	12–30	8–15
Filter media	Anthracite or Sand	Anthracite & Sand
Anthracite		
Depth (m)	0.4–1	1.9–2.6
Diameter (mm)	1 –2	0.8–2
Sand		
Depth (m)	0.4–1	1.4–2.6
Diameter (mm)	0.8–2	0.5

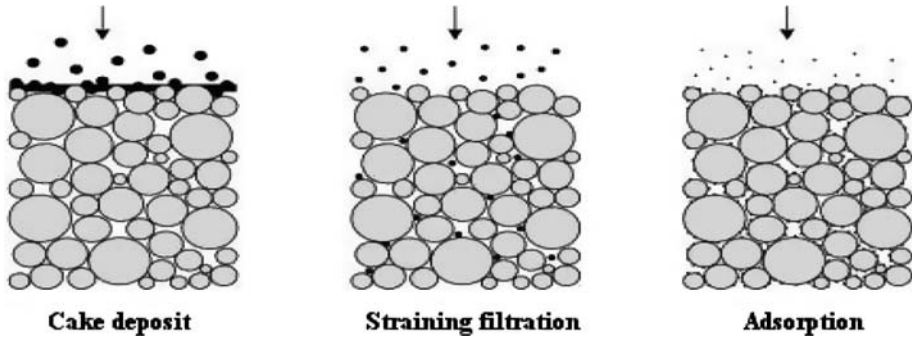

Fig. 1. Fouling mechanisms at stake in the granular filtration [19].

2. Materials and methods

2.1. Experimental set-up

Fig. 2 shows a schematic diagram of the experimental set-up used for tests. The sand is contained in a plexiglass column (60 mm inner diameter). Porosity was determined after packing the column, prior to experiments. It was calculated by measuring the volume of the solid phase needed to pack a column of known total volume and was found to be 0.45 ± 0.01. The water was circulated in the downward direction through the fixed bed using a volumetric displacement pump. The liquid flow rate was measured by a rotameter.

All the experiments were carried out with a fixed superficial velocity of $3.5\,m\,h^{-1}$ during seven hours and two bed heights (75 and 100 cm) were attempted.

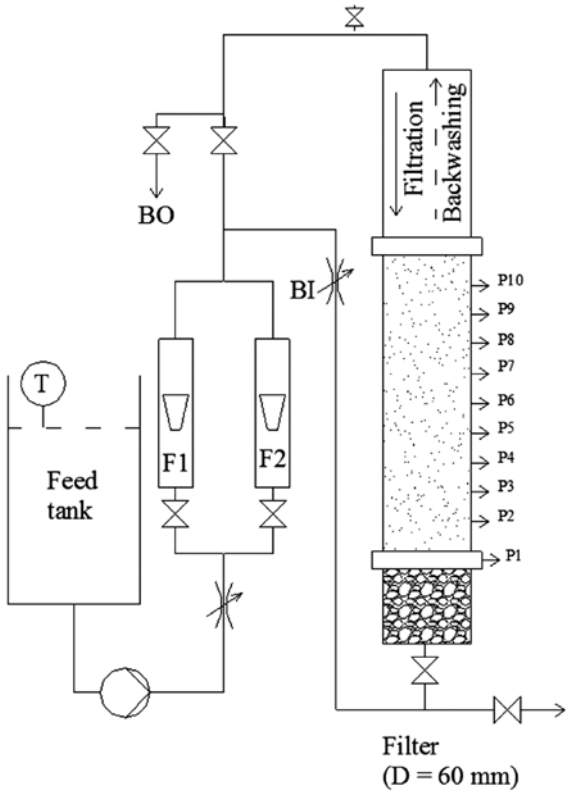

Fig. 2. Diagram of sand filter system used in laboratory scale.

2.2. Sand characterization

Silica sand was used as the filter medium, its chemical composition is given in Table 2.

The sand used in this work was sifted from 300 to 425 μm and has a mean diameter of 392 μm with a minimum and maximum diameter respectively of 38 and 599 μm. Its distribution size was characterized in a former study [20] by image analysis and is represented in the Fig. 3.

2.3. Feed water and micro-algae suspensions

Two micro-algae species were used for the experiments: *C. vulgaris* and *H. triquetra*.

C. vulgaris is a spherical fresh water micro-alga which has a size range from 2 to 8 μm (Fig. 4). *C. vulgaris* (211–19 strain) culture has been provided from our own laboratory, realized in a 1L photobio reactor and fed with a culture medium which has the following composition for 1L: NH_4Cl, 1.45 g; $MgSO_4{\cdot}7H_2O$, 0.281 g; $CaCl_2{\cdot}2H_2O$, 0.05 g; KH_2PO_4, 0.609 g; $NaHCO_3$, 1.68 g and 1 ml of Hutner solution [21]. For sand filtrations, samples of this culture were diluted in tap water in order to reconstitute algal blooms at different concentrations. A 30,000 cells/ml suspension was considered to a light algal bloom and a 145,000 cells/ml suspension to a more severe one. A 50,000 cells/ml suspension was also realized (Table 3).

The dinoflagellate *Alexandrium minutum* [22] is one of the main micro-e which occur in bloom form all over the world and which can be seen near desalination plants [23–25]. *A. minutum* is a PSP (Paralytic Shellfish Poisoning) toxic micro-alga. The Dinoflagellate *H. triquetra* (Ehrenberg) [26] species has been selected in this study for its morphological and size similarities with *A. minutum* and for its easy handling due to its harmless character. Batch cultures of *H. triquetra* (HT99PZ strain) are realized in 10L tanks fed

Table 2
Chemical composition of the sand used

SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	Na_2O	K_2O	SO_3
87%	6.61%	0.11%	0.07%	0.45%	1.10%	3.51%	0.03%

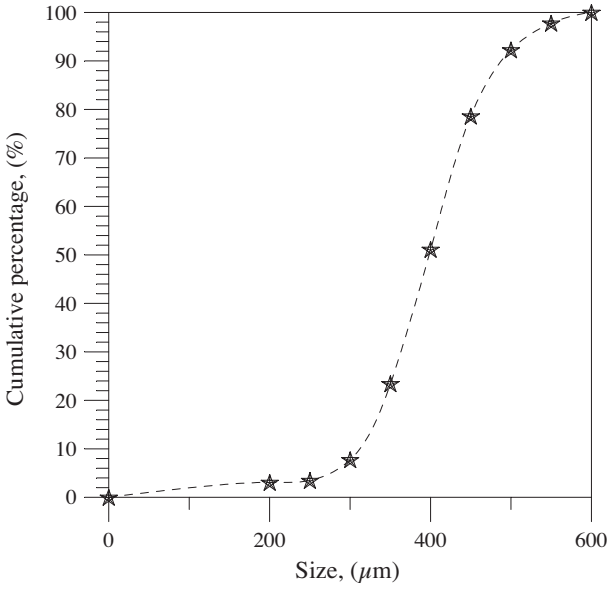

Fig. 3. Representative particle size distribution of 392 μm mean diameter sand.

with "L1 medium" [27]. The seawater used for the culture medium is pre-filtered through 0.2 μm cartridge filter. For each test, the cultures are diluted up to 30,000 cells/ml with pure water, then salinity is adjusted to 35 g NaCl/L. This cell concentration corresponds to a natural red tide of *H. triquetra* [28] and *A. minutum* (REPHY: French data network monitoring phytoplankton, 1992, [29]). Micro-algae images are shown in Fig. 4.

2.4. Filtration process

Before the filtration step, sand beds are first fluidized by back-washing to fill the whole pipeline of water and remove the air bubbles trapped in the hydraulic system. Then they fall by sedimentation without compaction. The bed is not homogeneous; the different types of particles are fluidized at different minimum velocities. This creates a change in the structure of the packing along the filter. The finer particles are located in the upper section of the bed, while the larger ones are found at the bottom.

After the fluidization and sedimentation steps, the packing is slightly compacted to get the height corresponding to a porosity of $\varepsilon = 0.45 \pm 0.01$, knowing the mass of poured sand in the column.

$$\varepsilon = \frac{V_{\text{pore}}}{V_{\text{column}}} = 1 - \frac{V_{\text{sand}}}{V_{\text{column}}} = 1 - \frac{M/\rho}{\pi(D/2)^2 H} \quad (1)$$

where V_{pore} is the pore volume (m^3), V_{column} the total volume occupied by the sand bed (m^3), V_{sand} is the volume occupied by the sand grain (m^3), M (kg) and ρ (2,353 kg m^{-3}) are respectively the mass and the density of the sand, D is the diameter of the column (0.06 m) and H the height of the bed (m).

In order to determine the effectiveness of the filter, filtrate samples were taken every 30 min during the filtration cycle to monitor the evolution of turbidity and cell concentrations. The capacity of the filter to capture particles is expressed in terms of efficiency E which is given by:

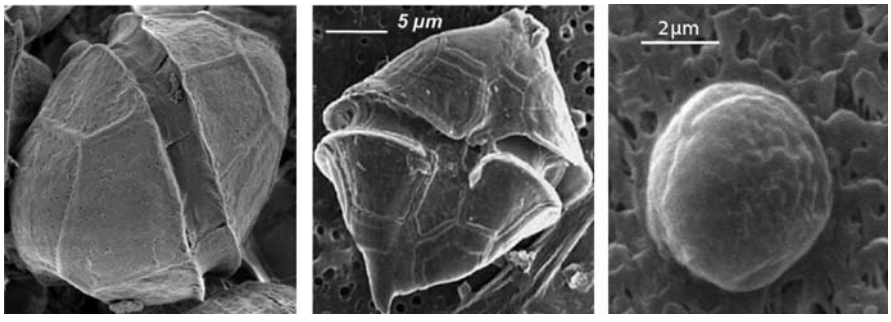

Fig. 4. SEM (scanning electron microscopy) of *A. minutum* (mean size: 20–23 μm) (left), *H. triquetra* (mean size: 17–18 μm) (middle) and *C. vulgaris* (mean size 2–8 μm) (right) (*A. minutum* and *C. vulgaris* photos: GEPEA-UMR CNRS 6144 *H. triquetra* photo: CNRC-NRC ISBN 0-660-96057-5).

Table 3
Experiments characteristics

Micro-algae	*H. triquetra* [20]	*C. vulgaris*			
Concentration (cells/ml)	30,000	30,000	30,000	50,000	145,000
Bed height (cm)	100	100	75	75	75

$$E = \frac{C_e - C_s}{C_e} \quad (2)$$

where C_e and C_s are respectively the particle concentrations of the inlet and outlet filter media.

Characteristics of each performed experiment are presented in Table 3.

2.5. Water analytical methods

Cell concentrations in feed water and filtrates were determined with a QICPIC particle analyser using image analysis (Sympatec, Clausthal—Zellerfeld Germany).

3. Results

3.1. Effect of different concentrations of micro-algae on filter performance

Results obtained for the filtration of *C. vulgaris* at different bloom concentrations are presented in Fig. 5.

For the same fixed medium height of 75 cm, the effect of three different *C. vulgaris* bloom concentrations (30,000, 50,000 and 145,000 cells/ml) was investigated. For the first 3 h of filtration, the efficiency of micro-algal removal was steady at respectively 90, 90 and 80%. Then a decrease was observed the more drastically the higher the initial algal bloom concentration was.

It can also be noticed that the difference of efficiency between feed water at 30,000 and 50,000 cells/ml of *C. vulgaris* is not significant and supposes that a slight variation of this range of micro-algae concentration does not have a serious impact on retention efficiency. However the more the feed water is concentrated in micro-algae (from 30,000 to 145,000 cells/ml) the faster the filter efficiency will drop. This may be explained by a saturation phenomenon of the narrower pores in the filter and after 3 h of filtration, the filter is no longer able to retain micro-algae.

For a fixed concentration of micro-algae, two experiments were carried out with different heights of bed, one at 75 cm and the other at 100 cm. Trends of the efficiency plot are similar and imply that at this stage 15 higher centimeters have less impact on the filter algae removal efficiency.

In the pre-treatment strategy, when an algal bloom occurs, it seems that adding a second single-stage upstream from a classical dual media filter is only efficient for the first hours of filtration and becomes useless for a common 24 h of filtration encountered in SWRO pre-treatment.

3.2. Micro-algae transport behaviour

The number of cells retained during the filtration is calculated from the mass balance of micro-algae between input and output of the filter.

$$N_{acc} = C_e Q_e \int_{t_0}^{t_1} \left(1 - \frac{C(t)}{C_e}\right) dt \quad (3)$$

where C_e is the initial concentration in the feed (cells/ml), Q_e is the feed flow rate (ml/min), $C(t)$ is the outlet concentration at time t (min), t_0 and t_1 are respectively the time the filtration starts and ends (min).

The number of particles accumulated (N_{acc}) during each filtration of *C. vulgaris* is shown in Fig. 6. The more severe the algal bloom, the greater the number of accumulated particles in the filter. Most of particles are accumulated during the first hours of the filtration. This result is consistent with a saturation phenomenon which triggers the drop of the efficiency after 3 h of filtration. The ratio between the number of particles accumulated (N_{acc}) and the total number of particles entered in the filter (N_0) during filtration time was calculated (Fig. 7). It seems that it decreases

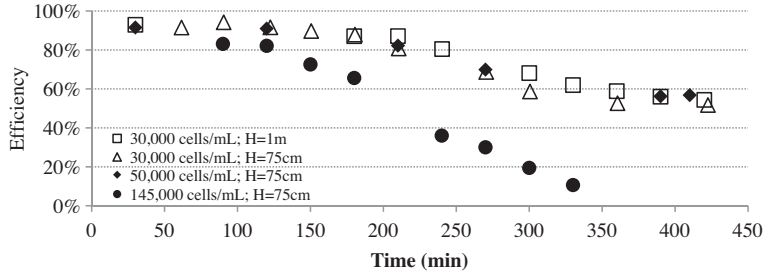

Fig. 5. Efficiency of the sand filter during 7 h of filtration for different initial concentrations of *C. vulgaris* with a feed flow rate of 150 ml/min (3.5 m h^{-1}).

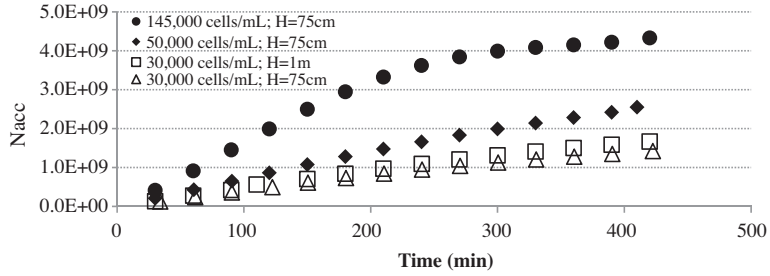

Fig. 6. Number of particles retained in the filter vs. time for different concentrations of *C. vulgaris* and two heights of bed.

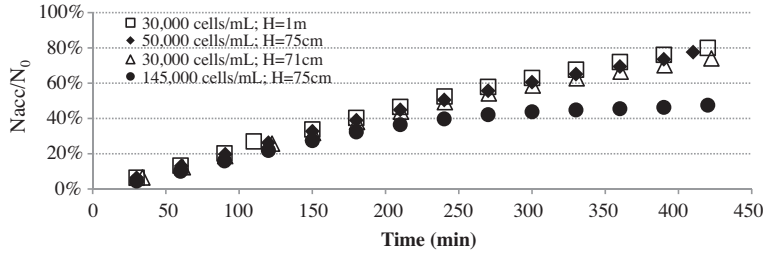

Fig. 7. Ratio between the number of particles accumulated in the filter (N_{acc}) and the total number of particles entered in the filter during the cycle of filtration (N_0) vs. time.

Table 4
Ratio volume occupied by micro-algae retained in the media on the total pores volume initially present in the porous medium

Concentration (cells/ml)/height of bed (cm)	30,000/100	30,000/75	50,000/75	145,000/75
V_{occ}/V_{pore}(%)	0.012	0.006	0.009	0.015

meaningfully with increasing feed concentration. At the end of the filtration this ratio is respectively equal to 48, 74 and 78% for 145,000, 30,000 and 50,000 cells/ml.

This reveals that despite the fact the accumulation for the more concentrated suspension is higher, the total removal efficiency drops.

The saturation phenomenon is observed as well in Fig. 6. It is also noticed that in the beginning of the filtration all suspensions have a similar normalized accumulation rate even for the higher initial concentration suspension before reducing significantly.

3.3. Fouling media mechanism

The volume occupied by micro-algae retained in the media (V_{occ}) during filtration calculated from a mass balance was compared to the total pores volume initially present in the porous media (V_{pore}). The ratio between these two volumes does not exceed 0.015% considering a mean diameter of 4 μm for *C. vulgaris* (Table 4). This result shows that the pore size of the filter remains much greater to catch algal particles (130 vs. 4 μm) and this algae trap only occurs in few filter pores which are not enough to capture all micro-algae.

This result can be linked to the ratio d_g/d_p where d_g is the mean sand grain diameter and d_p the particle diameter. According to McDowell-Boyer et al. [19], if $d_g/d_p = 50$, only 0.05% of the pore volume is occupied. Here, $d_g/d_p = 92$, and the occupied pore volume does not exceed 0.015%. Benamar et al. (2007) [30] has established that with a $d_g/d_p > 20$, mechanical way could be ignored which leads here to the conclusion that the straining filtration is not the main fouling mechanism at stake.

Furthermore, in order to better understand the sand filter fouling along the medium, sand slices of 10 cm were taken after the filtration. Each slice was washed and the micro-algae concentrations contained

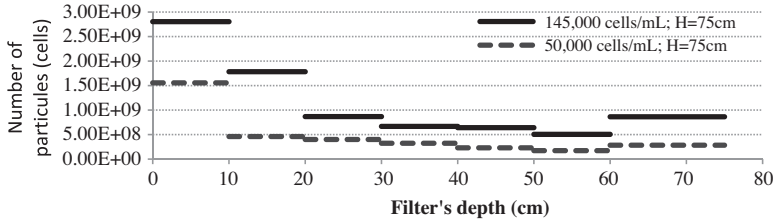

Fig. 8. Number of particles retained in the media filter vs. its depth for two different concentrations of *C. vulgaris*.

Table 5
Ratio number of particles accumulated in each slice of the filter on the total number of particles entered in the filter during the filtration (%) for initial concentration of 145,000 and 50,000 cells/ml of *C. vulgaris*

Depth (cm)	0–10	10–20	20–30	30–40	40–50	50–60	60–75
145,000 cells/ml (%)	31	20	10	7	7	6	9
50,000 cells/ml (%)	47	14	12	10	7	5	9

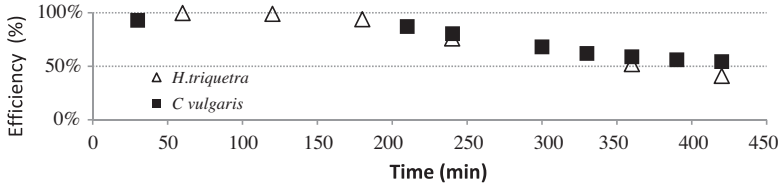

Fig. 9. Efficiency of a solution of *H. triquetra* and *C. vulgaris* at 30,000 cells/ml, for a height media bed of 100 cm during the cycle of filtration.

in wash waters were quantified. Fig. 8 shows the number of particles captured through the filter's bed for the filtration of a *C. vulgaris* suspension at 145,000 and 50,000 cells/ml.

The fluidization step could explain the fact that the first 30 cm of medium retains more particles than the rest of the medium. Indeed after fluidization, the upper medium layer contains the finest particles and this creates narrower pores encouraging the straining filtration mechanism as well as the other fouling mechanism. The fact that the first 10 cm of the filter contain more particles in both cases could reveal the existence of cake deposit mechanism.

It can also be observed that the rest of the filter layer retains around 5–10% (Table 5), which proves that a deep-bed filtration occurs as micro-algae are captured all along the filter bed.

3.4. Effect of micro-algae size on the performance of the filter

Two filtrations were carried out in the same conditions with different algae. Two main differences can be noticed: The first one is that micro-alga is a marine species (*H. triquetra*) whereas the other one lives in fresh water (*C. vulgaris*). The second difference is their sizes; *C. vulgaris* is smaller (2–8 μm) than *H. triquetra* (20–30 μm). Despite these differences, retentions of these micro-algae by the filter remain similar (Fig. 9). This tends to imply that micro-algae size has unexpectedly no impact on the retention mechanisms which occurred during filtration. Micro-algae with a larger size and cultivated in marine water were expected more to be retained by mechanical way ($d_g/d_p = 16$, [30]) than chemical way all the more the effect of adsorption mechanism is reduced by salt concentration. At this stage, it is not possible to conclude either for the smaller size micro-algae cultivated in freshwater the effect of adsorption is not reduced and may compensate the reduced effect of mechanical way, or that the mechanical way could also be ignored in the larger size micro-algae and only adsorption mechanism occurs.

4. Conclusion

The present study has two main purposes: to investigate the performance of a first-stage sand

media filter in a case of algal bloom, with a height of bed included in the one used in SWRO desalination plant and a lower mean grain diameter than usual (392 μm) and to better understand fouling mechanism of sand filter due to micro-algae.

The filtration of light (30,000 cells/ml) and severe (145,000 cells/ml) algal blooms shows retention efficiency respectively above 90 and 80% only during the first hours of filtration even with a smaller sand mean diameter than the one currently used. After 7 h, the overall efficiency obtained is 74% for a light bloom and 48% for a severe one. This leads to the conclusion that for a 24 h-filtration cycle, as usually encountered in the SWRO desalination plant, adding second single-stage upstream from a classical dual media filter without chemical pre-treatment is only efficient for the first hours of filtration.

The fouling investigation reveals that the number of micro-algae captured in the filter is much higher in the first 30 cm of the bed (70%). This can be explained firstly by the existence of a cake deposit on the surface of the bed. Secondly the sand bed has been fluidized, which leads to the retention of the smallest sand particles at the top of the bed and narrower pore trapping more particles than the rest of the bed. Results also show that the 30% remains of particle retention is homogeneously spread along the rest of the bed.

The low value of the ratio between the volume occupied by micro-algae retained in the filter and the total pores volumes available does not allow to conclude if particle straining is a minor mechanism involved during filtration or if there are too few pores to trap particles. A determination of pore size distribution all along the filter bed should enable to better estimate the volume of tight pores present in the filter and to learn more about the straining mechanism.

The fact that the size of micro-algae does not seem to have a significant impact on the retention efficiency will be more investigated by studying the retention efficiency of sand filter with a small-size marine micro-algae (2–8 μm).

Further tests will also be carried out such as the effect of coagulation/flotation before the sand filtration, the performance of the filtration with different flow rates. The process is planned to be combined with a second dual media filter stage followed by ultrafiltration.

Acknowledgement

Specials thanks to Thi-Dong-Phuong NGUYEN and Antoine SOULIES for providing *Chlorella vulgaris* culture samples.

List of symbols

ε	—	porosity
V_{pore}	—	pore volume, m^3
V_{column}	—	total volume occupied by the sand bed, m^3
V_{sand}	—	volume occupied by the sand grain, m^3
V_{occ}	—	volume occupied by the micro-algae retained in the media, m^3
M	—	mass of the sand, kg
ρ	—	sand density, kg/m^3
D	—	column diameter (0.06 m)
H	—	height of bed, cm
E	—	retention efficiency, %
C_e	—	upstream filter particle concentration, cells/ml
C_s	—	downstream filter particle concentration, cells/ml
$C(t)$	—	output particle concentration at time, cells/ml
N_{acc}	—	number of particles accumulated in the filter during the filtration, cells
N_0	—	total number of particles entered in the filter after 7 h of filtration, cells
Q_e	—	feed flow rate ($3.5\,m^3\,m^{-2}\,h^{-1}$)
d_g	—	mean sand grain diameter (392 μm)
d_p	—	mean micro-algae diameter (4 μm)
t, t_0, t_1	—	time, starting time and ending time of the filtration, min

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