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Ripening of granular media filters for pretreatment of seawater in membrane desalination

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ABSTRACT

The successful operation of a seawater reverse osmosis desalination plant depends greatly on the performance of the pretreatment step. The start-up of a pretreatment filtration process usually begins with a dynamic part called ripening, during which the filter media increases its adsorption ability and improves the removal of foulants from the seawater. In that period (typically lasting 30–60 min, depending on the system's conditions) the effluent often does not meet the quality requirements of the RO membranes and must often be disposed of. An observation and analysis of the ripening phenomena was performed using lab scale acrylic filter columns containing granular activated carbon. The seawater originated from the Yellow Sea in Korea and an inline coagulation was performed prior to filtration using an optimal dose of $FeCl_3$ based on a jar test. The turbidity, total suspended solids concentration and dissolved organic carbon were measured before and after filtration with the goal of assessing the filtration performance. The filter media, which was cleaned and dried before filtration showed distinct ripening characteristics. The measurements were then used for parameter identification of a typical filtration model. Based on the fitted model one can predict the optimal filter depth that would reduce the waste stream production of the plant.

Keywords: Desalination; Pretreatment; Media filtration; Granular activated carbon; Ripening

1. Introduction

Granular media filters, often in the form of pressurized or gravity rapid filters, usually serve as the core of many water treatment processes. This is especially true for surface water treatment in drinking water production as these filters combine efficient turbidity, silt and organics removal with high production rates and economy of operation. In seawater reverse osmosis (SWRO) desalination the issue of RO membrane fouling requires the seawater to be of high quality. Since most SWRO plants rely on open intakes, the seawater is usually of inadequate quality (SDI, NTU) to be fed directly into the RO stage. An efficient pretreatment which will reduce the fouling potential of the feed water is required. Media Filtration is the most common pretreatment step in SWRO and usually involves coagulation as a pre-conditioning step [1]. The filtration mechanism is referred to as deep bed filtration and involves the adsorption of water-borne particles on to the filter media grains, or "collectors".

The depth filtration phenomenon is a dynamic process often characterized by the filtration curve which shows the effluent particle concentration (C_{out}) as a function of

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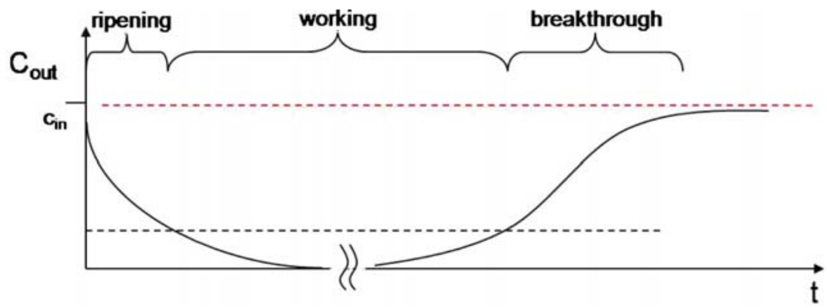

Fig. 1. Filtration curve.

time (Fig. 1). It is composed of three main stages: Ripening (approx. 10–60 min), working zone (approx. 12–24 h) and breakthrough [2]. During ripening, the filter bed is increasing its removal efficiency. The attachment of the first particles to the collectors increases the collectors' surface area and makes the bed denser and rougher. This increases the number of collectors, allowing for even more particles to be catched, thus improving the overall removal capability [2]. During this bed conditioning phase, the filter effluent is usually not of good enough quality to be used as RO feed. As a result the stream is being disposed of and is often referred to as a "filter to waste" stream. For efficient pretreatment the ripening stage should therefore be kept as short as possible.

At some point this increasing attachment effect is evened out by particles leaving the collectors (due to shear stress and collisions) and a pseudo steady state removal is achieved. This is the main filtration working zone, where the effluent quality meets the RO requirements (SDI<3, NTU<1) and the best removal is achieved.

As time passes the filter bed eventually becomes so saturated that the removal of the particles from the water greatly losses its effectiveness when compared to the detachment and influent effects. Consequently the effluent concentration then sharply rises to high levels in a stage usually referred to as "breakthrough". Before reaching that point the filtration needs to be stopped and the filter media should be cleaned by backwashing (and possibly air scouring) in order to retrieve the original removal capacity of the media. Once the backwash sequence ends, forward filtration once again commences resulting in a short intermediate stage (not discussed here but analyzed in [3]) which concludes with an exponential ripening effect similar to the one shown in Fig. 1 that marks the beginning of the next cycle.

Since a well designed media filter is expected to operate in the working zone for as long as possible, a better understanding of the other operation phases might help in doing just that. The issue of media conditioning and ripening during the beginning of the filtration phase of seawater was yet to be thoroughly explored in the literature. Since some of the physical mechanisms of that phase are not well understood, a phenomenological, more empirical approach is usually used to model it [4].

The mass balance on a differential element of the bed gives:

$$\frac{\partial \sigma}{\partial t} = -v_f \frac{\partial c}{\partial z} \tag{1}$$

which means the dynamic change of the adsorbed particle concentration in the filter bed, also known as the specific deposit σ, is changing according to the mass balance of the particles in the water flowing through the differential element in the bed (the filtration flux is v_f in m^3/m^2h and the suspended solids concentration is c in kg/m^3). Furthermore, the classic Iwasaki depth filtration equation describing the suspended concentration decrease along the filter bed also applies:

$$\frac{\partial c}{\partial z} = -\lambda c \tag{2}$$

with λ being referred to as the filtration coefficient, a time dependent factor which increases during the ripening phase and decreases during the breakthrough phase. It depends on the specific deposit, σ, and can be empirically described during ripening using the following function [4]:

$$\lambda(\sigma) = \lambda_0 + \kappa\sigma \tag{3}$$

with κ referred to as the ripening coefficient. The three equations form a PDE system which can be solved numerically.

By experimentally observing the ripening of media filters using seawater we have identified the model's coefficients, κ and λ_0, and were able to preliminary forecast the behavior of larger systems.

2. Materials and methods

A lab scale filtration apparatus was built for the experimental part of the research. It is depicted in Fig. 2. It is composed of a 20 l feed tank, T-01, a small 20 l/h feed pump, P-01, a flow meter and two acrylic glass columns

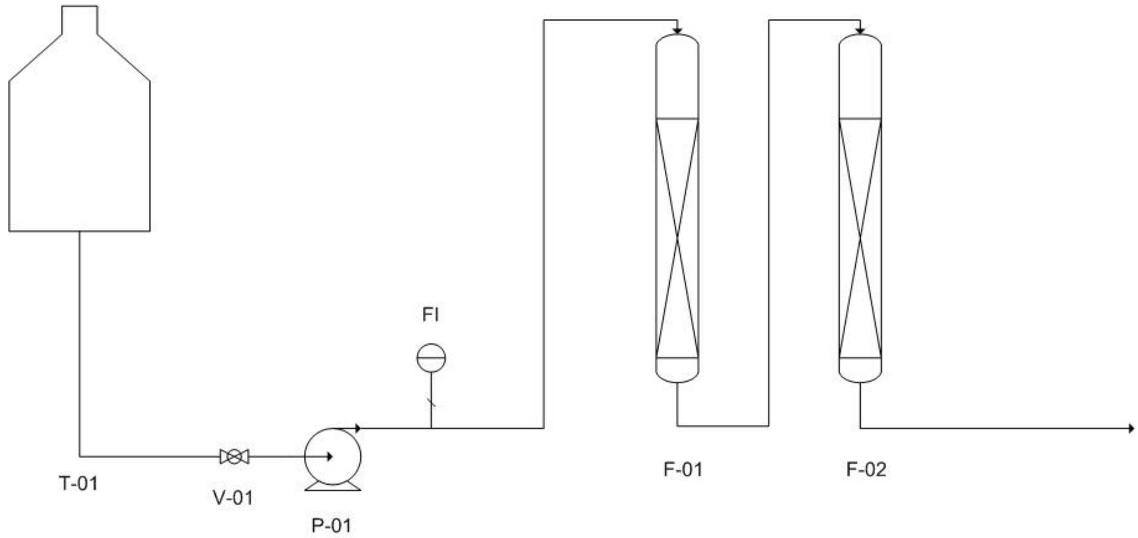

Fig. 2. Process flow diagram of the laboratory system.

1 m in length and 6.5 cm in diameter, F-01 and F-02. During the filtration experiments the use of one column at a time was enough to identify the desired parameters.

The feed seawater used was collected from the Yellow Sea on the shoreline of Mokpo, South Korea. The main water quality parameters are shown in Table 1.

The media used for filtration is granular activated carbon (GAC). The GAC's main properties are given in Table 2. GAC was shown by Shon et al. [5] and Chinu et al. [6] to hold a promising potential for seawater pretreatment in RO desalination, especially concerning the removal of organic material, a major cause for fouling and bio-fouling on RO membranes.

For the experiments the GAC was washed with acid (HNO_3) and repeatedly rinsed with deionized water to remove ash and scale from the grain and pore surfaces. It was then dried at room temperature for 72 h. Both filtrations with and without coagulation were explored with media depths of 0.1 m and 0.5 m and an average filtration head of 0.15–0.2 m above the media. The filtration rate was kept at 7 m/h. Coagulation was based on a jar test and included a dosing of 2 mg/l of $FeCl_3$ as Fe, followed by 20 s of rapid mixing and immediate filtration. Each filtration experiment was started with new, dried media and lasted for about 30 min. It was then repeated to improve the statistical accuracy. Effluent samples were taken from the bottom of the filter every 0.5–3 min and measured for turbidity (using a portable LED turbiditimeter) and dissolved organic carbon levels (using IR liquid chromatography after 0.45 μ filtration). Since the mass transfer model utilizes concentration rather than turbidity as the main variable, an assumption was made that a linear correlation between turbidity and total suspended solids concentration exists in the filtrate solution (based on [7]).

Table 1
Raw seawater properties

Temperature, °C	18.5
pH	7.86
DO, mg/l	5.97
Turbidity, NTU	4.78
TOC, mg/l	9.2
TSS, mg/l	49

Table 2
Granular activated carbon properties

Parameter	Value	Deviation
Particle size, mesh	12×30	
Bulk density, g/l	0.51	±0.03
Specific area, m^2/g	100	±0.5
Suspended solids reduction potential, %	92.9	±0.5
Turbidity reduction potential, %	93	±5
Fixed carbon, %	95	±5
Maximum ash content, %	7	±3

3. Results and discussion

The ripening effect of the GAC media is shown in Fig. 3 by the filtration turbidity results of seawater without coagulation using 0.1 m and 0.5 m media depths. The error range for most points was 10–20%. As one can see the results show an exponential decline during the first 10 min, followed by almost steady state levels. The

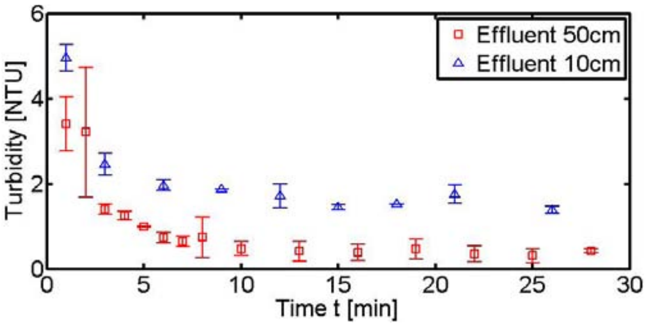

Fig. 3. Seawater turbidity reduction by 10 and 50 cm of GAC without coagulation.

improvement in particle removal due to a bigger bed depth is already sufficient in producing filtrate of high enough quality: The steady state turbidity values after 20 min for the 50 cm case are around 0.5 NTU. However, comparing it with the results shown in Fig. 4, obtained from the filtration of coagulated solutions, it is obvious that the short coagulation contributes a great deal to the filter's efficiency.

After only 2 min, the turbidity is already within specified requirements for both 0.1 m and 0.5 m bed depths, with the steady state levels of the deeper bed reaching well below 0.1 NTU. The coagulation appears to have very little effect on shortening the time needed to reach the steady state zone.

The dissolved organic carbon levels dropped to 2–4 mg/l after approximately 20 min for both beds regardless of the use of coagulant. This corresponds to approximately 60–80% reduction in DOC levels.

In all cases, the effluent turbidity experienced an initial spike-like peak at $t = 0$ which often exceeded the feed water turbidity (except for the 50 cm bed with coagulation: effluent's turbidity at $t = 0$ was 5.34 NTU). This could possibly be explained by a wash out of remaining residuals of carbon powder from the media, a recurring phenomenon even after very thorough pre-rinsing. That seemed to be a more prominent problem when no coagulant was used: In the 0.5 m bed case, the effluent turbidity at time zero had a turbidity of 20.5 NTU (not shown in Fig. 3 due to the different scales of magnitude). This could have also been the cause for what appears to be a larger measurement error range in the coagulation-free case (10–20% as opposed to <10% when using coagulant).

The correlation between turbidity and total suspended solids was found based on measuring the TSS levels of some of the filtration samples while comparing them to their NTU values. The method used was UV spectral absorption and not the more common filter paper weighing because the samples were very small in volume: only 10–20 ml. None the less a reasonable linear correlation was obtained as can be seen in Fig. 5. The correlation (TSS = 11.77 × NTU – 0.153) is not ideal ($R^2 = 0.82$) but under the circumstances it was assumed to be good enough to determine the concentration of suspended particles that was used in the filtration model.

The numerical solution of the previously mentioned partial differential equation system [Eqs. (1)–(3)] followed using Matlab. The boundary conditions were the feed water concentration of suspended particles at $z = 0$ (assumed to be constant on the filter's top surface) and zero at the end of the filter's length, assuming complete removal for a very deep filter in order to avoid numerical complications. The initial condition was set as the Iwasaki filtration equation with the use of λ_0 as the constant filtration coefficient and the mesh was set as 100 ppm. For the coagulation case, utilizing the least squares method for parameter estimation (which minimizes the distance between measured and simulated data points) yielded the parameter values of: $\lambda_0 = 1.84$ 1/m; $\kappa = 35$ m^2/kg.

The simulation results using these parameters are shown in Fig. 6.

The comparison of the fitted filtration curve with the measurements (after the NTU–TSS correlation) at bed depths of 0.1 m and 0.5 m is given at Fig. 7. As one can see from the top diagram, the fit for $L = 0.1$ m is poor, resulting from numerical limitations: When one further increases the ripening factor, κ, oscillations begin to appear in the solution around $L = 0$, the beginning of which can already

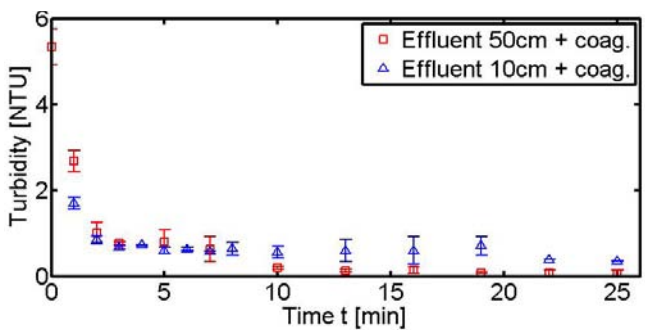

Fig. 4. Seawater turbidity reduction by 10 and 50 cm of GAC after short coagulation.

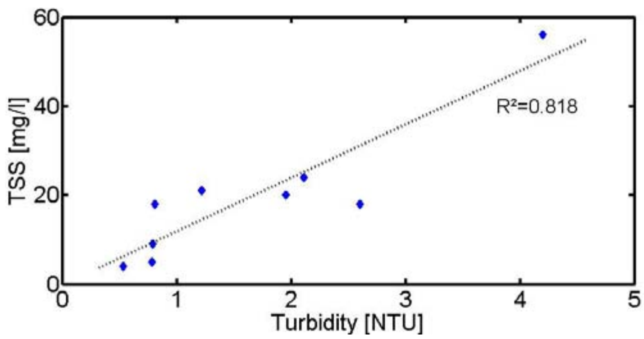

Fig. 5. A linear correlation between turbidity and total suspended solids.

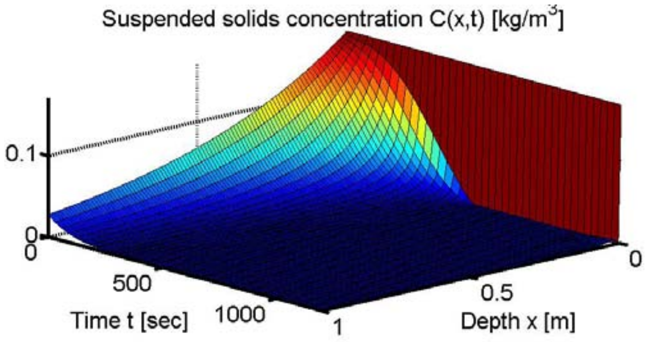

Fig. 6. Suspended particles removal after coagulation as a function of time and depth.

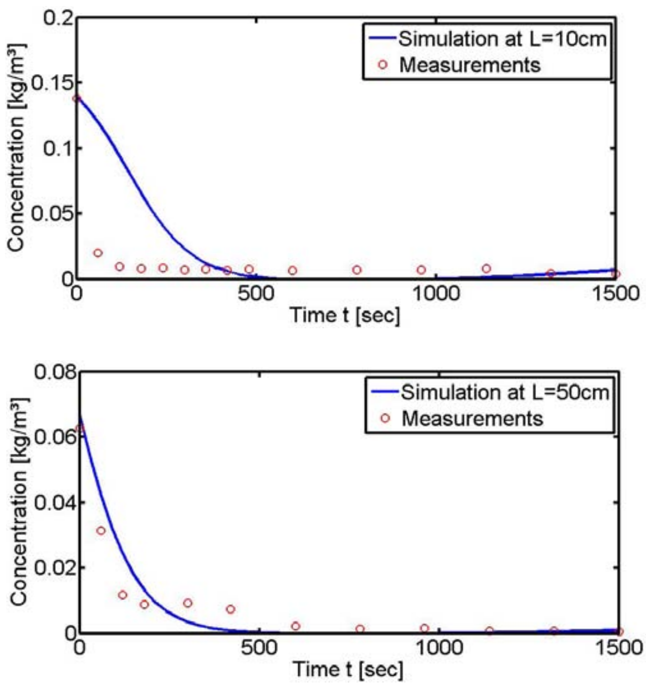

Fig. 7. Fitting the filtration model to the coagulated measurements at $L = 0.1$ m (top) and $L = 0.5$ m (bottom).

be seen at the right end of curve. They appear because for high κ values, the immediate transition from the harsh boundary condition of constant feed concentration at the top of the filter to practically zero concentration only a short distance inside the filter is too abrupt for the implicit numerical solver to handle even when using very small step sizes. Furthermore the current model's structure is faulty in the sense that it cannot explain the fact that for very thin beds 100% solids removal is not possible even with very long filtration times. As one can see from Figs. 3 and 4, the steady state concentration in the 0.1 m cases is not zero and it is most likely that a breakthrough will occur before the concentration further drops. These limitations are however limited to close-to-the-surface layers of filter and as one can see from the bottom of Fig. 7, the fitting for $L = 0.5$ m is distinctly better, making the prediction potential for filters of that depth or more much better. Since most industrial filters have a bed depth of 0.8–1.2 m, the current model should provide sufficient accuracy however a new approach concerning the calculation of the filtration coefficient, λ, should be considered if one wants to account for the dynamic ripening of all parts of the filter.

It is at this point that the model can be used for basic design ideas. For example the minimal depth at which the initial ripening no longer results in a filtrate to waste stream (i.e. the theoretical depth at which the effluent's initial turbidity peak will be below 1 NTU) can easily be assessed from the current simulation results: 1.55 m. Never the less, one should keep in mind that this model only applies for the narrow filters used in the experiments. Such filter columns were used because they are faster, cheaper and easier to operate and control than large commercial filters. The model needs further validation and modifications, as some of the systems' assumptions and characteristics are expected to change when scaling-up: dispersion along the horizontal axis, wall effects and other friction forces, pressure loss etc. In a more advanced step, one could think of utilizing online model-based control and optimization strategies for the operation of commercial filters (for example controlling the effluent's turbidity by using the filtration speed, v_f, as a manipulated variable).

4. Conclusions

This research has evaluated the ripening of GAC rapid filters using seawater from the Yellow Sea. It was shown to be a quick process, taking approximately 10–15 min resulting in filtration that meets the pretreatment requirements for SWRO desalination in terms of turbidity levels both with and without coagulation. The following conclusions have been made:

- The use of iron coagulant greatly reduces the ripening effects of the GAC filters, reaching lower effluent NTU levels in shorter time.
- The validation of a typical ripening model was performed with identified parameter values of $\lambda_0 = 1.84$ 1/m and $\kappa = 35$ m²/kg.
- The model showed better prediction capabilities for deeper filter beds and should be modified for thin beds by changing the way the filtration coefficient, λ, is calculated.
- The minimal predicted filter depth at which no filtrate to waste stream will be produced is 1.55 m.

Further validation and a possible revision of the model's assumptions using bigger filters are called for. The further development of model based control and optimization strategies in the media filtration part of an SWRO pretreatment process will be explored.

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