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DRFM hybrid model to optimize energy performance of pre-treatment depth filters in desalination facilities☆

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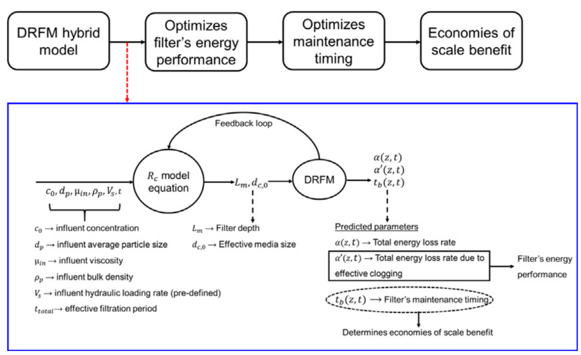
HIGHLIGHTS

- DRFM predicts filter's energy loss rate values due to effective clogging.
- DRFM hybrid model optimizes filter's energy performance a priori.
- Simulated filter's energy cost lower than the current industrial value of 0.39 kWh/m^3.
- Iterative approach estimates optimal timing to backwash the clogged filters.
- Economies of scale generally reduces the unit energy cost of desalinated water.

GRAPHICAL ABSTRACT



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ABSTRACT

Rapid depth filtration is the dominant pre-treatment technology in seawater desalination industry today. Optimizing the pre-treatment filter's energy performance provides economies of scale in the total energy usage of desalination facilities on a broader sense. However, this objective remains difficult to achieve by far. In this study, we develop a numerical algorithm, termed as Dynamical Rapid Filtration Model (DRFM), to simulate the effective clogging dynamics occurring inside a depth filter which depends on a multitude of controlled and non-controlled operating parameters. DRFM quantifies the filtration kinetics with a modified Yao's model to represent the particle removal mechanisms occurring within the simulated filter. A unique length scale is also introduced to account for the particle size effect on the filter's energy loss rate incurred, i.e. its energy performance, during its effective filtration stage. Concurrently, we performed an experimental study with a lab-scale depth filter to develop a model equation for measuring its total contaminant mass removal rate (R_c) due to effective clogging conditions. For a predicted R_c transient profile, good agreement is obtained between the experimental results and predicted values from DRFM. We then extensively discuss on a novel DRFM hybrid model to optimize the filter's energy performance which subsequently affects the filter's optimized backwashing timing for achieving economies of scale. The simulation results from the hybrid model demonstrates on how various filter configurations can result in lower energy cost to effectively pre-treat each unit volume of intake seawater as compared to the current industrial average of 0.39 kWh/m^3. Finally, we include a cost analysis to demonstrate on how the obtained economies of scale alleviates a portion of the total energy cost for each unit volume of desalinated water.

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Nomenclature

c_0	initial concentration of turbidity particles suspension
c	concentration scalar
$D_{c\%,max}$	maximum clogging degree percentage of filter
$D_{c\%}$	clogging degree percentage
$d_{c,0}$	effective size of grain under clean filter conditions
d_c	effective size of grain under clogging filter conditions
d_p	average diameter of particle
EC_1	energy cost associated with the pre-treatment filtration of intake seawater volume
EC_2	chemical cost associated with treatment of produced backwash waste
EC_3	energy cost associated with management of treated backwash waste
EC_4	energy cost associated with RO treatment step
F	theoretical filter capacity
$\widehat{G}$	total molar generation rate per unit volume
g	gravitational acceleration
J	hydraulic gradient
k_1	attachment coefficient
k_2	detachment coefficient
L_m	media depth
m	number of backwash cycles for filters adopting the 48 h operational period
n	number of computational nodes
Q	assumed seawater intake rate
q_{in}	inlet hydraulic loading rate
R_c	total mass removal rate of the contaminants per unit volume of fluid
TEC	total energy cost incurred by SWRO facilities
Tur_{in}	influent turbidity value
TSS	total suspended solids concentration
t_b	filter's breakthrough timing
t_{HRT}	hydraulic retention time of experimental filter
t_{total}	total effective filtration period
t	time
t'	normalized timing
UC	uniformity coefficient
$\vec{u}$	molar-averaged velocity vector
V_s	superficial velocity
V_1	volume of intake seawater
V_2	volume of backwash waste
v	velocity
y	downward displacement parameter
z	filter depth

Symbols

α_b'	filter's breakthrough energy loss rate (dimensionless)
α_p'	energy cost to pre-treat per cubic metre of intake seawater
α_{48}'	filter's energy loss incurred at the 48 h time mark (dimensionless)
α	filter's total energy loss rate (dimensionless)
α'	filter's energy loss rate due to clogging (dimensionless)
β	total energy cost for each unit volume of desalinated water
σ	specific deposit
λ_c	filter coefficient under clogging conditions
ε_c	filter's clogging average porosity
ε_0	filter's clean average porosity
η_c	effective filtration efficacy
η_G	gravitational sedimentation efficacy
η_I	interception efficacy
η	filter's average removal efficacy for simulation runs
ρ_p	bulk density of turbidity particles suspensions
μ_{in}	fluid dynamic viscosity
υ	fluid kinematic viscosity
γ	indicator for economies of scale analysis
θ_A'	length scale

1. Introduction

1.1. Background

At present, the number of desalination plants stands at 18,426 providing an approximate 86.8 million cubic metres of desalinated water per day to more than 300 million people globally [1]. Substantial amount of energy is usually consumed by the multiple treatment steps deployed within a typical medium- or large-scale seawater reverse osmosis (SWRO) desalination plant (see Figure A supplementary) which contributes to climate change [2]. Studies have also confirmed that each unit volume of desalinated water consumes the most energy among the other potable water producing technologies [3]. Currently, the average total energy usage for desalinated water is 3.10 kWh/m^3 and the average unit cost is \$1.1 USD/m^3. The total energy usage/cost is generally distributed directly and indirectly among the multiple treatment steps in desalination facilities. For example, energy is utilized to produce chemicals for use during the pre- and post-treatment steps (indirect energy), and to manage the produced sludge subsequently (direct energy). On the other hand, the RO treatment step contributes most directly to the total energy usage [3,4]. This intricate relationship between the desalinated water produced and the required energy usage can broadly be defined as water-energy nexus [4–6].

To ensure that desalinated water remains affordable to an increasing urban population, optimization of the different treatment systems in desalination facilities is desirable to minimize the expected growth rate in the total energy cost. For example, desalination technology using renewable energy has been studied [7,8]. While the desalination technology continues to be innovated to achieve optimization, limitations may arise due to thermodynamics consideration. Hence, optimizing the other treatment technologies (pre- and post-treatment) deployed in desalination facilities becomes necessary [4,9] as they also contribute to the total energy cost as discussed. In this paper, the focus is on the pre-treatment depth filtration technology which is deployed to remove turbidity particles for mitigating particulate fouling in the downstream RO operating membranes [10,11]. Many medium- and large-scale desalination facilities today are still deploying this pre-treatment technology. An example is the current largest facility located in Sorek, Israel which operates at around 624,000 m^3/d [12,13]. Generally, the pre-treatment step (during its effective clogging stage) is the second-largest energy consumer, at around 0.39 kWh/m^3 on average [3], among the other treatment technologies in desalination facilities [9,14]. It is worth noting that the above-mentioned value is only an average and varies among the different desalination facilities.

Recent studies have underlined that the volume capacity treated by rapid gravity filters provides economies of scale in the energy intensity of water treatment facilities [15]. Directly, it indicates that extended production rate from the operating filters is effective to gradually offset a portion of the treatment plant's total energy cost. This aligns with the optimization objective of pre-treatment depth filters in desalination facilities which is to maximise the production rate of quality effluents into the downstream RO membranes before the filters' energy loss rate due to effective clogging conditions reaches their pre-defined allowable value. Generally, this energy loss rate parameter indicates the optimization level in the pre-treatment filter's energy performance on a