



Engineering advance

The application of electromagnetic fields to the control of the scaling and biofouling of reverse osmosis membranes - A review



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ABSTRACT

Scaling and biofouling are two major problems in the operation of reverse osmosis (RO) membranes. A variety of control measures are employed in practice, including the use of pulsed electromagnetic fields (EMF), which can avoid the use of chemical anti-fouling agents (e.g. halogen-based biocides) that may be toxic to humans or the environment. This is a fairly recent and controversial technology and, from the available documentation and literature, it is clear that the scientific basis for its purported effectiveness is not yet firmly established, although some studies suggest that beneficial effects could be possible. In particular, the various conditions under which EMF technologies are likely to be effective for real world applications have not been scientifically established. This review collates the relevant literature on the problem of scaling and biofouling in RO membranes and heat exchanger systems (e.g. cooling towers), with a particular focus on the application of pulsed EMF technologies, including the broad documentation, relevant scientific studies, proposed mechanisms of action and further research directions. This review demonstrates that a lot more systematic scientific research is needed in order to validate the application and commercialization of EMF technologies as a pretreatment to control fouling in RO membrane systems.

1. Introduction

Desalination is a general term that refers to the removal of salts from saline or brackish water to produce fresh water [1–4]. Desalination may be achieved via thermal processes based on distillation [5,6], ion exchange methods [2] and membrane-based processes [7,8]. Membrane technology has played a crucial role since the mid 1970s [9] and it is now widespread [10–13], with RO now accounting for more than 60% of the world's desalination capacity [3]. Macedonio, et al. [14] and Amjad [15] summarize and compare thermal and membrane-based desalination technologies and state that RO tends to be favored over distillation - due to better system performance, user friendliness and economic feasibility [16,17].

RO technology, which produces water essentially free of pathogens and pollutants [18–23] is often categorized into brackish water reverse osmosis (BWRO) and sea water reverse osmosis (SWRO) [24–26]. BWRO membranes generally have higher product water flux with lower salt rejection, whereas SWRO membranes have higher salt

rejection but need to be operated at higher pressures [1]. A typical membrane desalination process is composed of intake, pre-treatment, RO and post-treatment [26]. Spiral-wound RO modules are more commonly employed [27] than plate/frame and hollow-fiber modules due to the balance between ease of operation and better fouling control - and the spiral wound module has been standardized amongst many membrane companies ensuring competitive pricing [28,29]. In the spiral-wound module, the semipermeable membranes are separated by feed spacers and permeate spacers and are wound around a central porous tube in a spiral fashion. Due to the separation by the feed spacers, turbulence in the tangential cross-flow is enhanced and the product water which permeates through the membrane is collected into a central permeate tube [30]. In addition to desalination, RO membranes are also used in wastewater treatment applications [31–35].

Fouling is an issue in the operation of RO systems [18,36]. Expenditure associated with membrane fouling can include direct costs such as periodic cleaning, feed water pretreatment, and increased energy demand, as well as indirect costs such as product loss due to

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down time and shortened membrane life [37–40]. Berenchko and co-workers [39] have stated that the fluid dynamics of spiral wound membrane elements combined with their large exposed surface areas render them especially prone to microbial attachment followed by biofilm formation.

When product water continuously passes through the membrane, rejected dissolved solutes and suspended solids accumulate in a viscous sub-layer (i.e. boundary layer) near the membrane surface, a process referred to as concentration polarization (CP) [41]. Within this boundary layer, salts may exceed their solubility limits and precipitate from solution resulting in mineral scaling on the membrane surface. Suspended solids can undergo adsorption to the membrane surface [42], forming a gel-like fouling layer that can act as a secondary membrane [18,43–46]. The resulting fouling layer can limit membrane performance [47–50] by reducing permeate flux and increasing solute passage (via CP) into the permeate [43,51–53]. Goosen [54] includes scale formation, cake formation and biofilm formation as being external fouling or surface fouling because the various substances comprising the fouling layer do not penetrate into the membrane substructure. Internal fouling or fouling within the membrane material can result in a change in membrane structure due to physical compaction or chemical (solute) interactions, altering solute and solvent transport. RO membranes are considered to be non-porous since they appear as homogeneous polyamide (PA) networks even under high-resolution transmission electron microscopy. Thus, fouling is considered to be localized mainly at the membrane surface [1]. Many authors have discussed the fouling of RO membranes, including a critical review by Goosen et al. [54]. Table 1 summarizes the different types of fouling that may occur on RO membranes. Notably, different kinds of fouling can occur simultaneously [55–57].

Metal oxide and colloidal fouling tend to occur in lead elements, whereas mineral and polymerized silica scaling tend to be more common in the last stage [39]. Biological fouling can occur at any stage [57] and on all surfaces [44] in an RO facility [20]. Armstrong et al. [58] state that organic fouling and biofouling contribute the most to RO membrane fouling and further details of RO fouling can be found in Malaeb and Ayoub [59].

1.1. Scaling

Scaling or precipitation occurs wherever the solubility of any sparingly soluble salt in the feed water is exceeded [60,61]. Antony et al. [61] have published an excellent review on scale formation and its control in high pressure membrane water treatment systems. This review includes discussion on scale forming mechanisms, factors affecting scale formation and types of scale. These authors categorize

Table 1
A summary of the different types of foulants in RO membranes.

Fouling category	Symptoms	Representative references
Mineral scaling (Inorganic fouling or scaling)	Flux decline	[3,33]
	Damage to membrane	
	Loss of solute rejection	
Particulate fouling or colloidal fouling	Increase of salt passage into the permeate	[42,58]
	Flux reduction	[3,33]
Organic fouling	Increase or decrease of salt passage	[42]
Biological fouling or biofouling	Increases the resistance to water permeation through the membrane	[3]
	Increased pressure differentials	[2]
	Flux reduction	
	Damage to the membrane	[33]

the types of scale in RO membranes as being alkaline (e.g. calcium carbonate), non-alkaline (e.g. calcium sulfate) and/or silica based. Calcium carbonate, CaCO₃, is the most common scale-forming mineral, which originates in the form of calcium and bicarbonate ions in industrial water, seawater or groundwater sources. When the water temperature increases, the solubility of calcium carbonate decreases which results in precipitation onto heated surfaces [62]. However, heated surfaces are not required for calcium salts to form scale [63], but scale can occur whenever the solubility concentration is exceeded [64]. It should be noted that barium and strontium salts often co-precipitate with calcium carbonate [1]. Some workers [65–67] have reported that trace amounts of Zn can significantly inhibit the nucleation rate of CaCO₃ and promote the formation of aragonite.

When dissolved or suspended minerals precipitate they are attracted to the membrane surface due to their natural charges [68,69] and crystallize [70]. Once a nascent scaling layer develops, it can exacerbate CP near the membrane surface by reducing fluid convective forces proximal to the membrane surface [42]. Conway [71] and Antony et al. [61] have constructed flow diagrams that attempt to explain such scale formation. Mineral scaling results in permeate flux decline and crystals can damage the active membrane layer [57]. In addition, harsh chemical cleaning cycles can also damage the membrane and shorten its lifetime [71]. Fig. 1 summarizes the key steps in scale formation.

Calcium carbonates, iron and silica can be present naturally in water in dissolved form [62,72]. Calcium carbonate is usually the main precipitate in seawater RO [1,71] and crystallizes in three different crystal forms: calcite, aragonite and vaterite. Calcite usually gives rise to hard scale whereas aragonite and vaterite give rise to softer types of scale that are more easily removed [70]. Calcium sulfate scale is much harder than calcium carbonate, and calcium phosphate scale is common when treating wastewaters. Metal oxides and hydroxides can occur due to oxidation of soluble metal ions or aluminum-based coagulants [57]. Silica is a general term which refers to crystalline, amorphous, hydrated or hydroxylated forms of silica [72–74]. The highest silica levels are typically found in ground waters [74]. Super-saturation and polymerization of soluble silica can form a silica gel coating which is very difficult to remove. This is different from ‘silica-based colloidal foulants’, which may be associated with either metal hydroxides or organic matter [57]. Ca²⁺ and Mg²⁺ ions have a strong influence on the formation of filterable silicate and on the kinetics of formation of silicate species [73].

1.2. Biofilms and biofouling

In addition to scaling, biofilm formation is a major concern for RO system performance [75–77]. Biofilm is the general term for accumulation of bacteria on a surface [4,44,72], while ‘biofouling’ is when a biofilm becomes problematic in the context of an operational definition [56]. A biofilm is a structured community [47,77,78] containing multiple layers of living, inactive, and dead bacteria along with their associated extra-cellular polymeric substances (EPS). EPS is important for the development and maintenance of biofilm structure [79] and accounts for roughly 50–90% of the total organic carbon of biofilms [79]. It is composed primarily of polysaccharides and proteins and is often accompanied by nucleic acids, lipids or humic substances [80]. The quantity and composition of a biofilm may change according to the environment [81]. It tends to be a slimy material [82] that may or may not uniformly cover the membrane surface [83]. A biofilm stability study by Mayer et al. [79] showed that electrostatic forces, hydrogen bonds and interactions such as van der Waals forces were possible molecular interactions responsible for the gel structure in a biofilm. Biofilm can also trap other deposits [20,84] resulting in a diffusion-transport barrier that limits the penetration of antimicrobial agents into the deeper layers [83]. This makes the biofilm essentially irreversible under a variety of environmental conditions [81] such as low flow [47]. Biofilm population and dynamics can also be affected by permeate flux

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