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A grand challenge for membrane desalination: More water, less carbon

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ABSTRACT

The decarbonisation of membrane desalination is a grand challenge due to the competing demands of more water for a thirsty world and the urgent need to reduce carbon emissions to mitigate climate change. This paper is a review of some developing strategies that could lead to lower energy use and thereby reduce the carbon foot print of desalination. Each strategy brings benefits along with technical challenges that are research opportunities.

The use of very low energy 'engineered biofilms' coupled with biomimicry control of biofouling could almost eliminate pretreatment energy. Improved membranes based on 'water channels' could contribute to reduced energy demand but high flux operation will need novel mass transfer control and will be constrained by module engineering. Significant energy benefits could come from combining seawater RO with wastewater reclamation using forward osmosis and pressure-retarded osmosis (PRO), although fouling by the wastewater stream requires special attention. The overall potential of the novel pretreatments, membranes and post-treatments is to more than halve the net energy of RO desalination. However there would be significant trade-offs to achieve this level of decarbonisation. The application of renewable energy is considered in the context of a membrane-enabled osmotic battery using PRO for discharge and advanced RO for recharge. Finally, low energy desalination for agriculture is being developed using novel applications of forward osmosis.

1. Introduction

There is overwhelming agreement that emissions of greenhouse gases (GHGs) must be reduced significantly, and eventually to zero, over the next few decades to mitigate climate change. Decarbonisation will be required over all sectors, including water supply. At the same time our increasingly thirsty world is turning to seawater and brackish water desalination to augment supplies. Desalination of seawater by reverse osmosis (SWRO) is now the dominant technology and over the past 50 years the energy demand has dropped by a factor of 5 so that the reverse osmosis step is currently approaching 2 times the thermodynamic minimum [1,2]. However as the total installed capacity approaches 100 megatonnes/day (currently > 60 Mte/day with 10 to 15% annual growth rate) the total energy usage approaches 100 TWh/year (assuming an energy demand of 3.0 kWh/m^3 for state of the art SWRO [2]). In terms of GHG emissions this is in the range 60 to 100 Mte CO_2 per year, potentially growing at 10 to 15% p.a. While this is currently a modest component of the global separation technology impact it could change as other industries decarbonise and SWRO continues to grow in application. Clearly 'business as usual' for SWRO desalination is not an option. In response this paper discusses various strategies to lower energy demand and to decarbonise RO desalination. It is a selective review based largely on the author's experience and interests; more comprehensive reviews of the status and future of desalination and membranes are available elsewhere (for example [1–4]).

2. Desalination RO energy and strategies to decarbonise

Modern seawater RO plant produce water at an overall energy demand of 3.0 to 3.5 kWh/m^3 where the RO step is of the order 2.2 kWh/m^3 [2] and low pressure membrane pretreatment is of the order 0.3 kWh/m^3 [5], that is the membrane components are about 2.5 kWh/m^3. As we will see it should be feasible to halve that value by current developments and changes to the process. The topics of interest are as follows:

(i) mitigation of RO membrane fouling, particularly biofouling, by low energy 'bio'-pretreatment and biomimicry control;
(ii) improvements in RO membranes and modules; and
(iii) low energy processing by hybridisation with FO/PRO using alternative water sources.
(iv) Related topics also discussed are;

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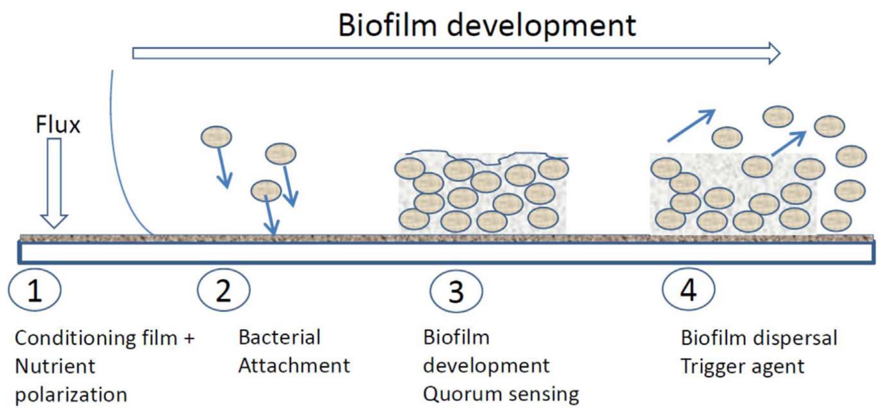

Fig. 1. Evolution of biofouling on a membrane – steps 1 to 4.

(v) a membrane-enabled osmotic battery to facilitate renewable energy usage;
(vi) low energy desalination for agriculture exploiting osmotic gradients.

2.1. Mitigating fouling of RO membranes

Membrane fouling increases the energy required for desalination either by decreasing productivity (flux) or increasing the required driving force (transmembrane pressure and feed channel deltaP); biofouling is a major issue [6]. The biofouling process involves several steps depicted in Fig. 1 that provide hints to (partial) prevention and cure. Nutrient concentration at the membrane surface (step 1) can be controlled by limiting the feed nutrients and its flux-induced polarization. Bacterial attachment (step 2) depends on incoming bacterial load although this is less important than the nutrient load that drives growth. Biofilm development is facilitated by quorum sensing trigger chemicals (step 3) and other triggers promote dispersal (step 4). Bioenabled fouling strategies being developed tackle steps 1, 3 and 4.

2.1.1. Low energy pretreatment

Pretreatment of seawater prior to RO desalination is considered essential. Potentially the most effective current approach is to use beachwells and recent developments and improved designs for beach and seabed galleries [7] make them more attractive at larger scale. However in some locations beachwells may not be feasible. Beachwells remove turbidity and, importantly, much of the assimilable organic carbon (AOC) [8] is removed by biological action within the beachwell matrix. The presence of nutrient AOC in RO feed water leads to biofouling (step 1) and related inefficiencies. We have shown in lab studies a direct correlation between organic nutrient concentration (enhanced by concentration polarization) and permeability decline [9]. Conventional SWRO pretreatment could involve media filters, low pressure UF and possibly dissolved air flotation (DAF). As currently operated none of these methods favours AOC removal by promoting 'engineered' biofilms. The industry is moving to UF pretreatment as it promises greater security [5]. However, as operated, UF involves frequent backwash and significant energy use ($\sim$0.3 kWh/m^3) contributing to the total energy demand for SWRO desalination. Conventional UF requires chemical cleaning, membrane replacement and/or maintenance. Its ability to remove turbidity is good but the extent of AOC removal is limited.

One approach to a low energy 'bio' pretreatment is depicted in Fig. 2 using gravity driven membranes (GDM). This is based on previous studies on river waters at EWAG [10]. Under gravity-driven deadend flow the flux stabilizes owing to a beneficial biofilm on the UF membrane surface and this is achieved without backwash or chemicals. We have found similar results are possible with seawater feed [11] and this gives water of low fouling potential at an energy demand of the order of 0.01 kWh/m^3. Fig. 2 also summarizes pilot-scale RO fouling and shows that the GDM can outperform commercial UF as a biofouling control. Of particular interest is the stabilized GDM flux of almost 20 l/m^2 h with a driving force of only 0.4 m (40 mBar) head due to control of the GDM biofilm structure by eukaryote predation [12]. One potential limitation of GDM pretreatment could be the larger footprint required, although our preliminary analysis suggests that it is not the case. Indeed due to the simplicity of the GDM it would be feasible to locate this type of pretreatment off-shore on barges. Similar beneficial 'bio' pretreatment for SWRO appears to be offered by biofiltration [13,14]. The bottom line could be an energy saving of the order of 0.3 kWh/m^3 in the overall desalination process.

2.1.2. Biomimicry control

However some degree of biofouling on the RO membrane is inevitable and another strategy, or partial cure, is to employ 'biomimicry' to interrupt biofilm growth on the membrane. Various chemical triggers are involved in biofilm development and this can be exploited to reduce biofouling. Quorum quenching has been successfully applied to disrupt quorum sensing triggers, such as AHL (Fig. 1, step 3), and control fouling in membrane bioreactors [15] and in recent studies on RO [16] we have shown that quorum quenching bacteria (QQB) and their enzymes can also delay fouling in a constant flux 'biofouling' RO system. Similarly biofilm dispersal (Fig. 1, step 4) is chemically triggered by agents such as nitric oxide and NO donors introduced into a biofouling RO system can also delay transmembrane pressure (TMP) rise [17]. Neither of these biomimicry strategies eliminates biofouling but such methods promise to improve biofouling control in RO, with consequent energy savings. One approach to strengthening biomimicry would be to combine it with other biocidal agents that act synergistically, as demonstrated in previous work [18].

2.2. Improvements in RO membranes and modules

The past decade has seen several innovations that promise to vastly improve the water permeability (A) of desalination membranes. These potential 'ultrapermeable membranes' (UPMs) include incorporation of Aquaporins [19,20], carbon nanotubes [21] and graphene materials [22]. The relevance of UPMs to desalination energy has been illustrated by the MIT group [23] who conclude that a 3 fold increase in A could decrease SWRO energy by $\sim$15% (this is conservative and the potential could be $\sim$20%) and brackish water energy by $\sim$40%. In addition higher fluxes would decrease the number of modules, and by implication, the deltaP of the process train, thereby lowering pumping energy. To achieve the full benefit of high permeability it would be necessary to operate UPMs at 'close to osmotic pressure' and this would require multistaging [1] or some form of batch operation with increasing feed pressure, such as Closed Circuit Desalination (CCD) [24].

The basis of the proposed UPMs are materials that provide selective