

Sustainability and membrane processing of wastewater for reuse

Anthony G. Fane

School of Civil & Environmental Engineering, Nanyang Technological University, Singapore, Singapore

email: agfane@ntu.edu.sg

UNESCO Centre for Membrane Science & Technology, University of New South Wales,

Sydney, NSW 2052, Australia

email: a.fane@unsw.edu.au

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Abstract

Sustainability has various meanings in the context of water reclamation and reuse. In one sense it acknowledges that to sustain our water supplies we must develop technologies that can efficiently reclaim wastewater to augment natural supplies. Membrane technology is playing a vital role in this application. However a largely unasked question is how well do the membrane technologies we use and the way we operate them stand up to scrutiny based on ‘sustainable development’ criteria? Finally at the technical and operational level we have the age-old problem of fouling and its impact on ‘sustainable’ long-term operation. This paper addresses the three levels of sustainability in the context of membrane technology and water reclamation.

Keywords: Membranes; Water reuse; Sustainability; Fouling

1. Introduction

To sustain is ‘to continue without lessening’ and ‘to allow to flourish now and in the future’. This is a vital concept for the water industry, as well as having special meaning for the application of membrane technology to that industry. This paper discusses sustainability and membrane processing for wastewater reuse, at three levels from the macro to micro. Firstly the existing and potential role of membrane technology in

sustaining our water supplies is discussed. Secondly, we consider how this technology stands up to scrutiny in terms of *sustainable development* criteria. Finally we address the concept of long-term *sustainable* flux in applications such as membrane bioreactors, where the challenge is to maintain operation in the presence of membrane fouling. This paper is based in part on some of the authors previously published works (see refs. [1,3,4,7,8,9,11]).

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2. Membrane technology and sustainable water supply

The traditional sources of water are increasingly stretched. The problem is being exacerbated by urban growth and, in many regions, by decreasing rainfall due to climate change. This crisis has accelerated the use of waters from less traditional sources, namely seawater and wastewater, which are effectively limitless. Desalination by reverse osmosis is now preferred over thermal processing due to cost reductions and significant savings in power demand. The application of the dual membrane process to convert ‘used water’ (secondary effluent) to potable quality is also seeing dramatic growth. Over the past decade this approach has gone from a few iconic applications, such as Water Factory 21 in Orange County, to many plants around the world [1]. The largest reclaimed water plant to date is located in Kuwait and has a capacity of 340 ML/d, which is significantly larger than the biggest RO seawater desalination plant. In the future it is likely that direct processing of wastewater in MBRs followed by RO will be favoured due to potentially better feed to the RO. The growth in applications of MBRs opens up more opportunities for reuse for a range of purposes. The key drivers for membrane-based reclamation for sustainable water supply are

- (i) the cost of processing wastewater to the standard for high quality use is about 50% of that for seawater desalination [2];
- (ii) reclamation and reuse can be done locally which favours decentralized processing and this could avoid long distance transfers of the product water;
- (iii) the need to find new protected catchments, usually distant from the users, is avoided.

The main impediments to this approach include lack of acceptance for indirect potable reuse in large reclamation schemes, the cost of dual reticulation in existing communities and institutional

and regulatory constraints to small-scale onsite decentralized systems. The impediments most easily overcome are probably the constraints to onsite decentralized systems once they are shown to be reliable and readily monitored [3].

3. Membranes and sustainable development

Sustainability, or sustainable development, has become an important environmental benchmark for both process industries and the service industries, such as the water industry. In this context the use of membrane technology for water supply, including reclamation, needs to be scrutinized in terms of ecological sustainability. The dilemma is that current economic frameworks may not necessarily lead to systems or modes of operation that satisfy sustainability criteria [3]. Table 1 shows how membrane technology, and more specifically MBRs, meet a range of sustainability criteria; this ranking was developed by a group of experts (the Bellagio team [4]). The criteria are from Balkema et al. [5].

A more detailed assessment of the criteria is given in Ref. [3]. However Table 1 suggests that the overall sustainability is good. The areas that require improvement are all linked to the issue of membrane fouling and the trade-off between capital and operating cost (a function of energy usage). This leads to considerations of what flux is acceptable and desirable, and brings us to the concept of sustainable flux.

4. Sustainable operation of membrane processes

The stable, long-term, operation of membrane processes is imperative. Performance decline is both inconvenient and costly. There is a well-established link between imposed flux and fouling, and this is most clearly illustrated by the concept of critical flux [6]. The critical flux concept says that in principle, for a given feed and crossflow hydrodynamics, there is a flux

Table 1
The MBR and its ranking on sustainability criteria (adated from Ref. [4])

Criteria	Indicators	Improvement needed	Good now
Economic	Cost and affordability	X	
Environmental	Effluent water quality		
	Microbes		X
	Suspended solids		X
	Biodegradable organics		X
	Nutrient removal		X
	Chemicals usage	X	
	Energy	X	
Technical	Land usage		X
	Reliability		X
	Ease of use	X	
	Flexible and adaptable		X
	Small-scale systems		X
Socio-Cultural	Institutional requirements	X	
	Acceptance	X	
	Expertise	X	
Overall sustainability good			

below which fouling/deposition is negligible and above which fouling/deposition occurs. This definition has been shown to be applicable to some simple feeds, such as latex suspensions, but is not strictly applicable to complex feeds, such as in the MBRs.

Fig. 1 (from Ref. [7]) illustrates a feature of MBR operation at fluxes below the ‘critical’. In this example the critical flux was determined as about $50 \text{ L/m}^2 \text{ h}$.

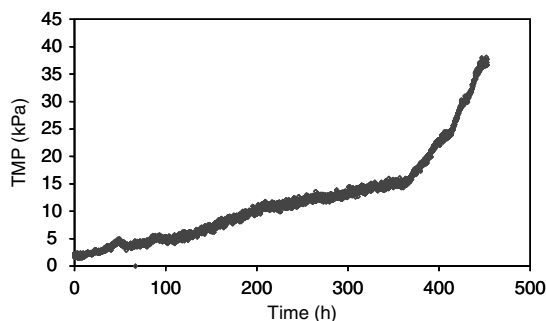


Fig. 1. (from Ref. [7]) Transmembrane pressure for crossflow MF of UASB overflow, at an imposed flux of $30 \text{ L/m}^2 \text{ h}$; where measured critical flux was $50 \text{ L/m}^2 \text{ h}$.

The TMP rise over an extended period was very slow, and about 0.04 kPa/h . Then at approximately 370 h the TMP suddenly started to increase at more than 0.3 kPa/h . This slow TMP rise, followed by a TMP transient or jump, was qualitatively reproducible. While gradual changes in TMP may be manageable the sudden TMP rise requires an immediate response in terms of cleaning. The ‘TMP jump’, or transient, has been observed in the author’s laboratory under various conditions and this implies that more than one mechanism could lead to this self-accelerating phenomena. It appears to be a feature of constant ‘subcritical’ flux processing, and as we shall see it is delayed as flux is reduced. This encourages the idea of ‘sustainable flux’ as that flux which delays the need to stop filtration to perform a major cleaning operation. There will be a trade-off in terms of imposed flux and cleaning frequency to minimize lifecycle costs.

Some of the mechanisms that could lead to the TMP transient are discussed briefly below.

- (i) The inhomogeneous fouling (area loss) model. This was proposed to explain the observed TMP profiles in nominally sub-critical processing of a UASB effluent [7] (Fig. 1). The TMP jump appeared to coincide with a measured loss of local permeability at different positions along the membrane, due to slow fouling by EPS. It was argued that the flux redistribution (to maintain the constant average flux) resulted in regions of supercritical flux and consequent rapid fouling and TMP rise.
- (ii) The inhomogeneous fouling (pore loss) model. Similar TMP transients have been observed for the crossflow MF of a model biopolymer (alginate) [8], as shown in Fig. 2. These trends are qualitatively similar to Fig. 1 and show that the TMP transient can occur with relatively ‘simple’ feeds. It is also evident that as imposed flux is increased the slow TMP rise is faster and the TMP transient is sooner. The data obtained have been explained by a model (see darkened lines) that involves flux redistribution among open pores, allowing for the pore size distribution. Local pore velocities eventually exceed the critical flux of alginate aggregates that rapidly block the pores. The difference between the two models is that ‘area loss’ is a macroscopic redistribution of flux and ‘pore loss’ is a microscopic redistribution. It is

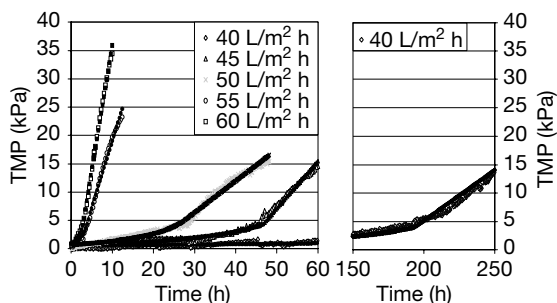


Fig. 2. Experimental TMP data and model (---) for alginate MF in crossflow at various imposed fluxes [8].

quite possible that both mechanisms can occur simultaneously.

- (iii) The critical suction pressure model. Using a fine colloid, filtered in deadend mode, onto an immersed hollow fibre we have observed that the anticipated gradual TMP rise may be followed by a rapid increase in TMP. Both autopsy and modeling suggest a critical suction pressure at which coagulation occurs at the base of the cake [9]. A rapid increase in resistance leads to the TMP jump; a very thin dense layer is observed next to the membrane. Although this ‘model’ was observed with deadend rather than crossflow operation there is no reason why this mechanism could not apply in crossflow. A requirement is that fouling continues to occur over time until the critical suction pressure is reached, and that the deposit has the potential to coalesce.
- (iv) Percolation theory. As a fouling layer develops it provides resistance that increases the necessary TMP. According to percolation theory the porosity of the deposit can gradually be reduced by filtration within the deposit layer. At a critical condition the cake loses connectivity and resistance, and TMP, increase rapidly. This has been proposed for MBRs [10], but the modeling showed a very rapid change (within minutes) not seen in practice. However, it is plausible that the percolation theory approach combined with the inhomogeneous fouling (area loss) model (i above) could satisfy the more gradual ‘kinetics’ of the typical TMP transient.
- (v) The inhomogeneous fibre bundle model. Another manifestation of the TMP transient has been observed in a model fibre bundle [11] where the flow from individual fibres was monitored. The bundle was operated under suction at constant permeate flow, giving constant average flux, and initially this was evenly distributed amongst the

fibres. However over time the flows became less evenly distributed so that the standard deviation of the fluxes of individual fibres started to increase from the initial range of 0.1–0.15 to 0.3–0.4. The suction TMP was adjusted to maintain the average flux across the fibre bundle and it can be seen from Fig. 3 that the TMP rise mirrored the increase in the standard deviation of the fluxes. At some point both TMP and standard deviation showed a rapid rise. This is believed to be due to flow maldistribution within the bundle leading to local blockages between fibres and membrane fouling. The profiles of the standard deviation and the TMP were made more steady when the flow regime around the fibres was more vigorous (more liquid or bubbling).

The fact that a number of phenomena can lead to an unsustainable TMP rise is cautionary. In all cases the TMP jump occurred in response to a self-accelerating phenomena. The application of a fixed permeate flow is the driver for this, in contrast to a fixed pressure (declining flux) process which becomes self-limiting. However fixed product flow is a commercial reality and our analysis points to the need for guidelines as well as on-line monitors that can initiate preventive action in these membrane applications. In

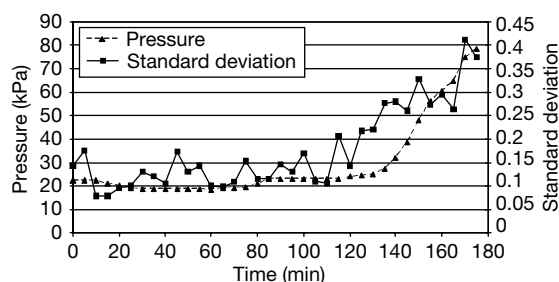


Fig. 3. Performance of a model submerged hollow fibre bundle operated at an average flux of 20 L/m² h with a 5 g/L yeast suspension. Suction pressure (TMP) and standard deviation of individual fibre fluxes versus time.

order to identify sustainable fluxes it is clearly necessary to consider long-term trials to assess the likelihood of TMP transients. Finding strategies and system designs that improve the sustainable fluxes in membrane applications for wastewater reuse remain goals for the membrane industry.

5. Conclusions

Membrane technology is playing an increasing role in sustaining water supplies by freeing up compromised sources such as wastewater. When the technology is evaluated in terms of the criteria for sustainable development it gets a favourable ranking. The major limitation is membrane fouling and that influences the selection of conditions for long-term sustainable operation. For the commonly used constant flux operation fouling phenomena tend to be self accelerating so that TMP transients occur. Strategies to control this involve intermittent filtration, adequate two phase flow and module design to encourage homogenous filtration.

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