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Fouling behaviour for different module formats in membrane filtration applications for surface water treatment

Graeme K. Pearce

Membrane Consultancy Associates, PO Box 4006, Pangbourne, RG8 7WB, UK
Tel. +44 118 984 3106; Fax +44 118 984 5957; email: gpearce@membraneconsultancy.com

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ABSTRACT

Design of a membrane filtration plant requires a careful selection of flux. A low flux will make the plant expensive in terms of capital cost (capex), since the membrane area requirement will increase. A high flux will lead to high operating costs (opex), since fouling rates increase exponentially with flux, and necessitate the use of high driving pressures and frequent chemical cleaning. The design therefore reflects a compromise between capex and opex.

Membrane filtration applications in water treatment use one of three formats, either pressure driven (PD) or submerged, with inside or outside feed configurations. The different formats have different advantages and disadvantages, with all three concepts competitive in most applications. This paper looks at fouling behaviour for two of the module formats, namely PD inside feed and submerged. The data suggest that at a given flux, fouling rates are similar for the same type of feed using either format, though the optimum design flux will vary due to differences in module characteristics. The paper then introduces a method for monitoring plant performance, and quantifying the stability of operation based on two simple indices, evaluated from permeability measurements. The method can be applied to any membrane filtration plant.

Keywords: Membrane filtration; Ultrafiltration; Module format; Fouling rate; Permeability; Monitoring indices

1. Introduction

Fouling in ultrafiltration (UF)/membrane filtration (MF) is complex, with multiple interactions to consider between the various fouling constituents in the feed, and between these constituents and the membrane surface [1,2]. Fouling can be characterized according to the nature of the constituent responsible, the mechanism by which it operates, or by the strategy adopted to control it.

Fouling constituents can be categorized as follows:

- Particulates.
- Organic.
- Inorganic.
- Micro-biological organisms.

Particulates could be inorganic or organic and act as foulants due to their ability to blind or block the surface. The organic category covers dissolved components and colloids which would attach to the surface by adsorption. The inorganic category includes dissolved components which tend to precipitate onto the surface due to a pH change (scaling), or due to oxidation (e.g. iron or manganese oxides). Inorganics may also be present as coagulant residuals. The micro-biological category covers vegetative matter such as algae, and organisms, such as bacteria, which can form colonies and cause bio-fouling.

Fouling occurs due to a combination of chemical and physical interactions. Constituents in the feed can

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become attached to the membrane surface due to chemical binding and/or the interaction of surface properties, such as the degree of hydrophilicity or charge effects. In addition, the fouling constituents will tend to blind the surface physically and block the pores, or hinder transport to the surface by the development of a cake layer. The combination of chemical and physical effects will control the degree of attachment. This will determine how severe the fouling is, and what strategies will be effective in controlling it.

Design of a MF plant for the water industry requires a careful selection of flux in order to achieve a stable cost effective design, in which fouling can be controlled at an acceptable level [3,4]. A low flux will make the plant expensive in terms of capital cost (capex), since a high membrane area will be required to achieve the output. A high flux will lead to high operating costs (opex), since fouling rates increase exponentially with flux, and necessitate the use of high driving pressures and frequent chemical cleaning. The design therefore reflects a compromise between capex and opex [6,7].

This paper reviews two examples of flux vs fouling rate behaviour in the water industry for different membrane formats. The factors involved in selecting an optimum flux for design are discussed. The paper then introduces a method to monitor plant performance, and quantify the stability of operation, based on permeability trends. Monitoring indices can be evaluated from permeability data, and can be used to assess the effectiveness of chemical wash (CW) procedures, and adjust the cleaning protocol, and change parameters such as concentration and frequency to achieve stable long term operation.

2. The influence of module format on plant design

MF applications in the water industry use one of three module formats, namely pressure driven inside feed (PDI), pressure driven outside feed (PDO), and submerged vacuum driven (SUB) (which is also an outside feed format). The different formats have different advantages and disadvantages, with all three formats competitive in most applications. However, distinct advantages arise for some niches based on feed type, feed quality, project size, etc. Indeed, the market is almost evenly split between the three formats, as shown in the Fig. 1 below, which indicates the cumulative share of UF/MF module sales to the water and wastewater market.

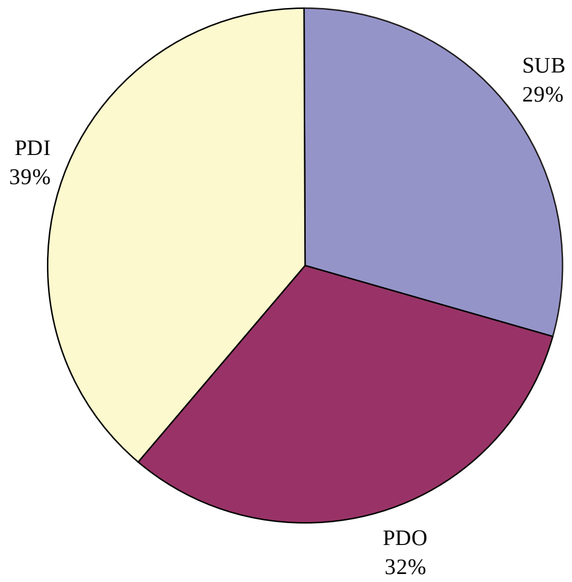

Fig. 1. Market share as a function of module format in the water industry.

Inside feed formats normally use polyethersulfone (PES) membranes, which are characterized by high permeability, and a clear cut UF rating. Outside feed formats are normally based on polyvinylidene difluoride (PVDF). The outside skin confers a surface area advantage, but PVDF has lower permeability than PES, which cancels out most of the advantage. Due to the flexibility of PVDF, air scour can be used for cleaning, which saves backwash usage, but incurs an energy cost for aeration. SUB formats save the cost of encapsulation, but imposes a strict limit on trans-membrane pressure, due to the practical limitation of drawing a vacuum.

The different characteristics of the three module formats results in variation in the optimum flux for commercial plant design. For example, pressure driven (PD) formats often use frequent chemical cleaning, which allows the use of high design flux. In contrast, the absence of containment in SUB increases chemical cleaning volumes and downtime, resulting in an optimized flux at a lower level.

3. Fouling control

MF processes for water and wastewater treatment normally use dead-end or direct-flow designs with intermittent backwash, sometimes combined with air scour either during the filtration and/or backwash cycle. The backwash controls the build up of fouling constituents by expelling particles from the membrane surface on a regular basis. This type of operation is designed to remove loosely attached foulants in a simple inexpensive physical process. Foulants which are not removed by backwash may require the addition of chemicals to improve the efficiency of removal. The

Table 1
Fouling control strategy for commercial systems

Fouling	Strategy	Type	Characteristic	Process seq
Reversible	Prevention	Frequent	Physical	Bw, air, fwd/f, c/f
Irreversible	Maintenance	Intermittent	Chemical	CEB
Persistent	Recovery, cure	Intervention	Chemical	CIP
Irrecoverable	Des/ops changes	Add hardware	System change	Repl membrane

various processes used are described below, and fall into three main categories:

- Prevention – physical, e.g. backwash, air scour, or forward flush.
- Maintenance – CW or chemical enhanced backwash (CEB).
- Recovery – clean-in-place (CIP).

The characteristics of the various processes are described below:

Backwash – regular intermittent process to address particle fouling, normally undertaken 1–4 times/h:

- Reverses the effect of pore plugging due to high velocities.
- Controls the build up of particles at the membrane surface.
- Reduces the particle concentration in the feed channel.
- Reduces the effect of concentration polarization.
- Creates surface shear to dislodge surface attachment.

Air scour – used as part of a maintenance strategy between once/cycle to once/day (NB can be mechanically aggressive to the membrane fibre):

- Improves mass transfer and displacement action.
- Effective for reversing pore plugging, particularly as TMP rises.

Forward flush – can be undertaken during the filtration cycle, or as part of the backwash routine (NB can be expensive in terms of reduced recovery):

- Improves shear.
- Particle concentration build up effectively removed.

CW – used as part of a maintenance strategy on a periodic basis of between several times per day to once per week:

- Alkali (e.g. NaOH) or chlorine soak to combat organic fouling.
- Acid soak (e.g. HCl, H_2SO_4, and citric) to combat inorganic fouling.
- Biocide soak (e.g. Cl_2, H_2O_2, and sodium metabisulfite) to combat bio-fouling.

CIP – used as part of a restoration strategy with heavy or tenacious fouling, normally undertaken between once per week to once in several months, often using the same chemicals as for CW:

- Extended soak and preferably recirculation, also sometimes with heating, to enhance effectiveness of chemicals.

Table 1 summarizes the fouling control strategy described by the processes above. Clearly, the cost increases in progressing from backwash to the use of chemicals. A successful commercial design is one in which a satisfactory compromise is achieved between frequent and inexpensive physical cleaning, and the more expensive chemical cleaning, which incurs chemical cost, downtime, and waste production.

4. Fouling rate case studies

This paper looks at fouling behaviour for two surface water case studies, one using an SUB format, the second a PDI format. In the first example, the PVDF submerged membrane has been used for a low turbidity surface water source. Average turbidity for this source was around 0.8 NTU with a normal maximum rising to 2 NTU. The submerged system was preferred for this duty since the system was relatively large, with a natural head available from the reservoir source to fill the feed tanks. Feed quality and flux data for the first case study are summarized in Tables 2 and 3, respectively.

The membrane system was operated in three distinct phases at different fluxes, providing the opportunity to evaluate fouling rates as a function of flux.

The second case study is for a PDI system using a PES membrane. This feed was also a surface water source, with a normal average turbidity of around 3–4 NTU peaking to 10 NTU, or 15 in one case during

Table 2
SUB case study – feed water quality

Turbidity	0.8–1.0 NTU monthly average 0.6 NTU in summer; winter max 2 NTU
TOC	2.8–3.1 ppm
Hardness	256 ppm $CaCO_3$ (typical)
Alkalinity	119 ppm $CaCO_3$ (typical)
Fe, Mn	Low

the winter. Feed characteristics and operating parameters are summarized in Table 4.

In this case, the PD system was preferred since low winter temperatures necessitated high driving forces, which could be above the vacuum limit of submerged systems, especially during high turbidity episodes.

Flux vs fouling rate behaviour for the two case studies is shown in Fig. 2 below, with fouling rate indicated in terms of the rate of permeability decline in Lmh bar/day. In both cases, fouling rate increases exponentially with flux [5]. It is notable that the two different formats have similar fouling rates at a similar flux. However, it is apparent that for the SUB case, the slope of the fouling rate curve is less, possibly due to the low turbidity of the feed. Also note that the flux range that could be employed for the submerged system was lower, partly due to the TMP limit of the vacuum system, and partly due to the lower permeability of PVDF compared to PES, and longer cleaning interval.

5. Cleaning protocols

Most membrane systems use chemicals in the backwash to maintain performance. This procedure can be carried out automatically, and is inexpensive in terms of chemical consumption, waste produced and downtime. Different companies use different terms to describe this type of process. Two common terms are chemically enhanced backwash (CEB) or CW. Since the cleaning action relies on a short soak period, it is not completely effective. Therefore, from time to time, off-line cleaning is used, sometimes termed clean in place (CIP). CIP often uses similar chemicals and concentrations to CEB, but the extended soak times used, together with recirculation or drain down (depending on system format), ensures greater effectiveness, and normally a full recovery of permeability. Sometimes, the CIP chemicals are used warm, e.g. at 25–35 °C, to improve effectiveness. The limitation of CIP is that the chemical volume is greater and the loss of production due to downtime is significant. It is therefore desirable to restrict CIP frequency as much as possible, and instead rely on CEB.

Table 3
SUB case study – operating fluxes

Temp corrected permeability analysed for three periods
Phase 1 – 80.6 Lmh (47.4 gfd)
Phase 2 – 74.1 Lmh (43.6 gfd)
Phase 3 – 65.6 Lmh (38.6 gfd)

Table 4
PDI case study – operational details

Feed characteristic	
Turbidity	Av 3.5 NTU (max 9 NTU)
Lime softened	SHMP dosing at 0.25 ppm
Process design	
TC flux range	86–118 Lmh (50–70 gfd) (at 20 °C) during pilot
B/w interval	35 min
B/w flux	250 Lmh (150 gfd)
CEB-low flux	2 ppm each cycle, 1 min soak
CEB-high flux	50 ppm, once/day, 15 min soak
CIP	Caustic pH 12/Cl2 50 ppm citric acid 2%
Operation	
180 days	
Temperature	1.5–27 °C

Thus CEB is intended to recover permeability as much as possible. If the CEB is completely efficient, the permeability will be returned to the value after the last CEB. If there is a fouling trend, either the CEB frequency should be increased, the concentration and/or choice of chemicals should be adjusted, or there will eventually be a need for a CIP to recover the permeability loss.

Permeability data can be summarized in two simple parameters which are trended with time, and are termed the *fouling rate index* and the *cleaning index*. The *fouling rate index* measures the rate of permeability loss over the course of a CEB cycle, and is a measure of the

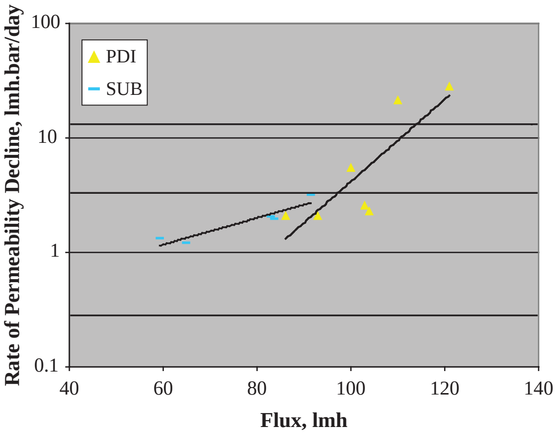

Fig. 2. Flux vs rate of permeability decline for the two surface water case studies.

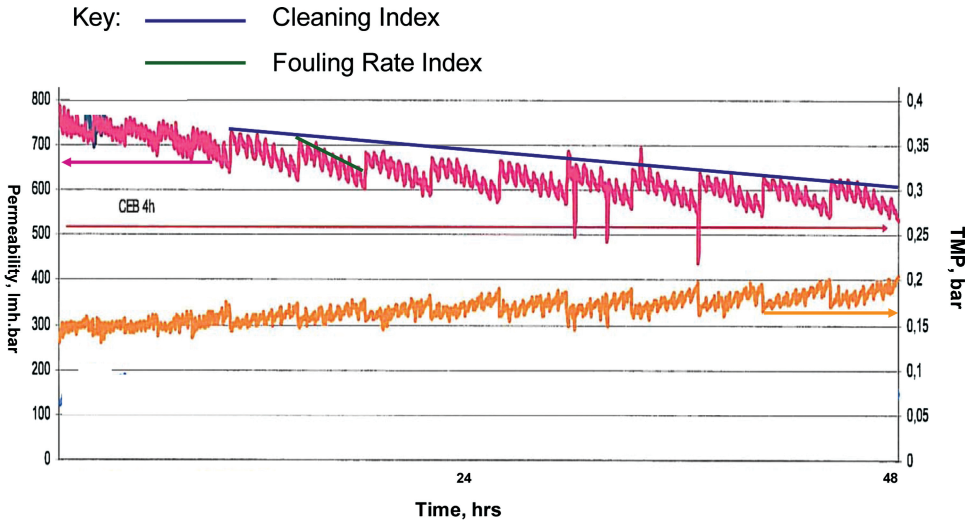

Fig. 3. Monitoring indices for a PD system with a high fouling rate.

fouling propensity of the feed. The *cleaning index* compares permeability from one CEB cycle to the next (Fig. 3).

The two indices are illustrated in the graph above for a permeability trend illustrating rapid fouling. The effectiveness of a single CEB can be measured by:

(Permeability post n^{th} CEB–permeability post $(n+1)^{\text{th}}$ CEB)/time elapsed, weeks.

In order to assess the effectiveness of CEB in an operating period, it is may be useful to relate the permeability recovery to the permeability at the start of the period under review. The CEB effectiveness can be evaluated by a *cleaning index*, which measures the long term stability of operation.

The *cleaning index* for a series of cycles is measured by:

(Permeability post 1st CEB–permeability post $(n)^{\text{th}}$ CEB)/time elapsed, weeks.

The indices can be used in combination with permeability measurements to control CEB frequency, and anticipate the requirement for off-line cleaning (CIP). Also, the comparison of the *cleaning index* between racks can be assessed, highlighting differences in rack performance, perhaps due to valve or pump failure.

Monitoring indices can be combined with target permeability to adjust CEB frequency, and predict CIP intervals. Table 5 below shows typical target permeability for the two case studies discussed in the previous section.

6. Conclusions

Fouling is caused by a complex interaction between various constituents in the feed stream. It can be controlled by a combination of physical processes, such as backwash and air scour, and chemical processes such as CWs and CIP.

The rate of fouling increases exponentially with flux. Commercial plants provide an optimal compromise between flux and fouling rate through the identification of the sustainable flux which provides a trade off between reduced capex at high flux, and reduced opex at low fouling rate.

The Water Industry uses three membrane formats, namely submerged, and PD with an inside, or outside feed configuration. The different formats require different design flux due to trans-membrane pressure and chemical cleaning issues. However, all three formats remain closely competitive in the industry with approximately equal market share.

Table 5
Examples of target permeability for low turbidity surface water

PDI	
Typical clean water permeability	300–400 Lmh bar (12–16 gfd/psi)
Permeability in use	200–300 Lmh bar (8–12 gfd/psi)
CEB should maintain permeability	>200 Lmh bar (8 gfd/psi)
CIP should be performed	>150 Lmh bar (6 gfd/psi)
Typical CIP interval	Once or twice/month
SUB	
Typical clean water permeability	200–250 Lmh bar (8–10 gfd/psi)
Permeability in use	125–175 Lmh bar (5–7 gfd/psi)
CEB should maintain permeability	>100 Lmh bar (4 gfd/psi)
CIP should be performed	>75 Lmh bar (3 gfd/psi)
Typical CIP interval	Once/1–2 months

Plant data from submerged and PDI feed formats show that for a given flux, the two formats exhibit similar fouling rates. Membrane permeability can be used to monitor plants to ensure stable long term performance, and monitoring indices can be evaluated from permeability trends. These indices can be used together with the permeability data to adjust CW frequency and procedures, and predict CIP intervals.

References

[1] C. Liu, Membrane fouling: a physicochemical perspective, Proceedings of AWWA Membrane Technology Conference, GA, 2003, 15 pp.

[2] M.R. Wiesner et al., Processes of particle deposition in membrane operation and fabrication, Water Sci. Technol., 51(6-7) (2005) 345-348.

[3] G.K. Pearce, Membrane fouling guidelines for UF/MF, Proceedings of the IWA Membranes Conference, UK, 2007, Paper 16c.

[4] P. Berubier, Shear forces in an air sparged submerged hollow fibre membrane system, Proceedings of IWA Membranes Conference, UK, 2007, Paper 10b.

[5] G.K. Pearce and R.W. Field, Development of the sustainable flux concept to provide guidelines for fouling control in UF/MF system design, Proceedings of AWWA Membrane Technology Conference, FL, 2007, pp. 1-9.

[6] N. Tangsubkul et al., Environmental life cycle assessment of microfiltration process, J. Membr. Sci., 284(1-2) (2006) 214-226.

[7] K. Parameshwaran et al., Analysis of microfiltration performance with constant flux processing of secondary effluent, Water Res., 35(18) (2001) 4349-4358.