Separation and Purification Technology 96 (2012) 147–153

Contents lists available at SciVerse ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Influence of backwashing, flux and temperature on microfiltration for wastewater reuse

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ARTICLE INFO

Article history:
Received 19 February 2012
Received in revised form 22 May 2012
Accepted 23 May 2012
Available online 1 June 2012

Keywords:
Microfiltration
Fouling rate
Flux
Backwash
Water quality
Municipal wastewater

ABSTRACT

Microfiltration (MF) and ultrafiltration (UF) membranes, widely used for pre-treatment of reverse osmosis (RO) processes in wastewater recovery, are nonetheless subject to fouling which considerably reduces the process throughput. In this study, reversible and irreversible fouling of a pilot MF process treating secondary wastewater effluent were measured over an 18 month period and data pertaining to common feedwater quality determinants collated. Fouling rates were quantified as a function of the key operating parameters (flux and backwash interval) and water quality determinants (turbidity and temperature).

Fouling was found to increase exponentially with turbidity. Irreversible fouling was promoted only by increased flux and backwash interval, while reversible fouling rate depended on flux, turbidity and temperature. Some residual fouling, following the same exponential or power relationship with the flux as that manifested at different turbidities, was observed at zero turbidity. Operation above the so-called critical flux was sustained through appropriate backflushing. It was concluded that the sustainable flux concept was a more appropriate basis for process control and optimisation than critical flux, since the latter does not take into account process economics.

1. Introduction

Microfiltration (MF) and ultrafiltration (UF) membranes are widely used for pre-treatment of reverse osmosis (RO) processes in wastewater recovery for Indirect Potable Reuse (IPR) [14]. However, a major drawback of such systems is the fouling of the MF/UF membrane which considerably reduces the process throughput.

Membrane fouling is determined both by feedwater quality and process operating parameters; numerous studies have attempted to identify key membrane foulants in wastewater effluent treatment [32,9,12]. Fouling is usually defined as reversible, if removed by physical cleaning such as backflushing, or irreversible if removed only through applying chemicals. Whist precise foulant speciation is abstruse it is often generally be categorised as "particulate" or "organic", though these are obviously not mutually exclusive.

Particle concentration, as total suspended solids (TSSs), has been shown to proportionally diminish membrane flux and increase transmembrane pressure (TMP), over the filtration cycle [9,6]. Bourgeous et al. also showed irreversible fouling to become prevalent at higher TSS concentrations, where higher TSS loads on the membrane were not completely removed by physical cleaning. Moreover, smaller particles have been found to more tenaciously adhere to the membrane surface, since the shear forces they are subject to are lower than those of larger particles. On a mass basis, fouling resistance has been reported to increase by 50% on decreasing particle diameter fivefold [6]. Whilst fouling by particles is normally associated with cake formation at particle sizes below that of the membrane pore size, pore blocking may also take place [22,11]. Hwang et al. [11] demonstrated that internal membrane fouling can contribute significantly more to total filtration resistance than the cake layer. Thus, whilst particle fouling is generally expected to be removed by physical cleaning [26], the more tenacious and generally smaller particles apparently contribute most significantly to irreversible fouling.

Organic fouling is generally understood to comprise colloidal and dissolved organic material, and is thus may be differentiated from particulate fouling only by size for entirely organic matter. Several studies have sought to identify the constituent primarily responsible for membrane fouling through employing fractionation. Jarsutthirak et al. [12] concluded that organic hydrophilic colloids of >3500 Dalton size range, such as polysaccharides, contributed more to fouling of PA–UF membranes than the hydrophobic (humic and fulvic acid) and transphilic fractions. Zheng et al. [32] found dissolved organic compounds in the 0.45–0.26 μm size range, identified as biopolymeric, to provide the highest organic fouling propensity compared to large colloids (>0.45 μm) and components smaller than the UF pore size.

Fouling by organic matter is mechanistically more complex than that by particles. Natural organic matter (NOM) fouling, for

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http://dx.doi.org/10.1016/j.seppur.2012.05.030

Table 1
Membrane module specifications according to the supplier.

Manufacturer	Siemens Water Technologies Memcor Ltd.
Membrane type	XS CMF-S S10 V
Materials	PVDF, 0.08 μm pore size
Area/module	25.3 m^2
Configuration	1 cell of 24 submerged hollow fibre modules
Filtration mode	Out-in
Design flux	27–37 LMH
Design backwash	Backwash interval: 15–45 min Air (0.40 m/h for 55 s) + water (0.06 m/h for 15 s) for downtime 300 s downtime
Operating temperature	>0–40 °C (max 45 °C)
Operating pH	2–10.5
Standard CIP (Clean in place)	Recommended interval of 15 days 600 L NaOCl (540 mg L^{-1}, 30 °C) followed by 600 L H_2SO_4 (pH 2.5, 30 °C)

example, relates to NOM heterogeneity, membrane type, pH, ionic strength and multivalent cations concentration [17]. Extracellular polymeric substances (EPS), generated through microbiological activity, enhance bacteria attachment to membrane surfaces and so significantly contribute to irreversible fouling; EPS and soluble microbiological compounds from secondary treatment have been observed as being the major contributor to the gel layer [23].

Membrane fouling can be suppressed by operation under sub-critical conditions, i.e. under conditions sufficiently benign for fouling to be significant [3]. Critical fouling conditions may be defined with respect to the operating flux [4,16] and/or the amount of material. The latter include the filtered volume between physical cleans [21], the solute osmotic pressure [5] or the critical deposit formation related to the contaminant mass transfer [2]. This critical condition can be identified experimentally by plotting the fouling rate or some other fouling index as a function of the condition, criticality being observed as a deviation from linearity.

Whilst progress continues to be made in elucidating fouling mechanisms pertaining to the foulant character, studies of operating conditions impacts have been largely constrained to flux and have been conducted mainly at laboratory scale. It has been acknowledged that such studies do not fully capture the water quality conditions typically encountered during wastewater treatment plant operation, or full-scale membrane module properties such as fibre length and packing density [9]. The aim of this study was to determine fouling behaviour under conditions replicating those of a full-scale plant, and specifically, the impact of both operating parameters (flux and backwash interval) and water quality (turbidity and temperature) on irreversible and reversible fouling rates.

2. Materials and methods

2.1. Microfiltration unit and pilot plant overview

The pilot plant has been described elsewhere [27]. The MF technology (Memcor *CMF-S*, Table 1) was supplied by Siemens. The skid employed 24 *S10V* hollow fibre modules, forming part of a 600 m^3 d^{-1} demonstration plant treating secondary wastewater effluent and including a 500 μm pre-filter, the microfiltration unit, a reverse osmosis (RO) unit and an advanced oxidation process (AOP). The plant was fully automated and data recorded on a SCADA system. The average water quality (measured online) of the MF feedwater for 2008–2010 is reported in Table 2.

2.2. Data analysis

The plant was operated continuously for 18 months other than stoppages for the routine maintenance cleaning, general plant maintenance, or automatic shutdown arising from out-of-spec conditions. Flow and TMP, from which operating fluxes and permeabilities were calculated, were collated for common determinant values of feedwater quality, primarily turbidity and temperature, and plant operation, principally flux and cleaning interval. Fluxes were viscosity corrected to 20 °C [29]. Values of the MF reversible and irreversible fouling rate, i.e. the rate of pressure increase, were calculated for each filtration cycle, i.e. between backwashing (BW)) and each cleaning cycle, i.e. between each cleaning in place (CIP), over the entire 18 months period. Values were obtained by simple linear regression, as employed in previous studies [10].

The 18 months of operational data generated fouling data (d(TMP)/d*t*, under constant flux conditions) from approximately 32,760 backwash cycles (representing reversible fouling rate) and 32 cleaning cycles (representing irreversible fouling rate). A macro was applied to spreadsheet files to identify those fouling data pertaining to common feedwater quality, as defined by temperature and turbidity. These were then averaged and correlated with operating determinants such as fouling rate and permeability.

Data points for single datum are depicted without error bars in figures provided. For those referring to multiple data the error bars relate to the 95% SD limit.

3. Results and discussion

Results show the mean irreversible fouling to depend both on flux and backwash interval (Fig. 1), whereas reversible fouling apparently depended only on flux (Fig. 2). Excessive irreversible fouling at 63 LMH and a 45 min BW cycle made sustainable operation impossible.

Decreased fouling at lower fluxes and backwash intervals is intuitive and supported by literature data from previous studies. Liu et al. [20] showed the rate of TMP increase for fluxes of 75 LMH (the critical flux) and 150 LMH (supra-critical flux) for a pressurised MF membrane to be more rapid at the higher flux by 10–70% depending on feedwater quality. A previous study of backwash intervals of 30–120 min by Wang et al. [30] revealed higher backwash intervals (30–60 min) to provide a less rapid the increase in initial TMP for each filtration cycle, and thus irreversible fouling, than that encountered at lower backwash interval (60–120 min). Moreover, the time to reach the threshold TMP was found to decrease by 25% when the backwash interval was increased from 60 to 120 min.

Shorter backwash intervals thus allow longer intervals between chemical cleans, due to suppression of reversible fouling, whilst the contribution from irreversible fouling has been reported to increase with increasing operating flux [19]. At high fluxes and/or longer backwash intervals, the efficacy of backwashing is apparently reduced, since reversible fouling becomes consolidated and more irreversible and so demanding more frequent chemical cleaning.

3.1. Feedwater quality

Feedwater quality obviously strongly influences membrane fouling, with turbidity and UV-254 shown to be as important as flux and backwash interval in promoting MF fouling [20]. In the

Table 2
Mean feedwater quality (2008–2010).

Parameter	Average	Min	Max
Turbidity (NTU)	6.18 ± 3.35	0.37	100
TOC (mg/L)	7.18 ± 0.82	5.82	8.88
Temperature (°C)	16.7 ± 1.97	8.56	26.54
pH	7.09 ± 0.35	6.55	7.85
Conductivity (μS cm^{-1})	1048 ± 90	630	1862
UV_{254}	0.196 ± 0.018	0.175	0.256
Specific UV absorbance (m^{-1} mg^{-1} L)	2.82 ± 0.45	2.14	4.35