Journal of Membrane Science 470 (2014) 504–512

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Application of a backwashing strategy based on transmembrane pressure set-point in a tertiary submerged membrane bioreactor

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ARTICLE INFO

Article history:
Received 19 February 2014
Received in revised form
18 June 2014
Accepted 29 July 2014
Available online 6 August 2014

Keywords:
Submerged membrane bioreactor
Tertiary treatment
Fouling
Set-point transmembrane pressure
Wastewater reclamation

ABSTRACT

An alternative backwashing strategy to enhance water productivity in a tertiary submerged membrane bioreactor (MBR) was assayed. This strategy is based on automatically adjustment of the backwashing frequency as a function of the membrane fouling, which is expected to increase the net permeate flux produced. The effect of the key operational parameter (transmembrane pressure set-point, TMP_{sp}) on membrane fouling and process productivity was evaluated on a pilot-scale tertiary MBR. The system was successfully operated for over 4 months with complete sludge retention achieving a high treatment performance with a moderate liquor suspended solid concentration, as a result of carbon substrate limited conditions. The analysis of the membrane fouling at supra-critical filtrate flux of 70 L/(h m^2) with a specific aeration demand identical to that usual at full-scale (SAD_{pnet} = 17 N m^3/m^3) showed that backwashing efficiency (described in terms of residual fouling resistance) was significantly affected by the selected TMP_{sp} value. At high TMP_{sp}, the efficiency decreased and chemical cleaning was necessary for membrane recovery. Nevertheless, moderate set-point values (30–40 kPa) provided high permeate net fluxes of 65–67 L/(h m^2) for more than 2000 h of operation, while the reversible fouling rate was not considerably influenced by TMP_{sp}. This was also confirmed by flux steps trials.

1. Introduction

Due to their well-known advantages [1,2], aerobic membrane bioreactors (MBRs) have become an attractive option for wastewater reuse, being very compact and efficient systems for achieving the highest effluent quality standards. The considerable popularity of the MBRs in the wastewater treatment market, the numerous suppliers, and the upward trend in plant size now reflect the maturity reached by this technology [3]. In fact, MBRs have been implemented in more than 200 countries [4]. Nevertheless, the main limitation to more widespread application is their high energy demand, besides awaiting new strategies to mitigate membrane fouling [5]. In addition, the uncertainty associated with fouling has led to conservative plant designs where the main operating parameters are far from being optimised [1].

As described in a previous research, aerobic MBRs can be effectively applied as an advanced treatment of secondary effluent from a wastewater treatment plant [6,7]. Delgado et al. [7] demonstrated a high conversion of ammonium to nitrate and constant COD removal efficiency in their system, regardless of the influent fluctuations. As a result of carbon substrate limited conditions, a minimal value for the carbon substrate utilisation rate was found and the system successfully operated at moderate permeate fluxes (30–32 L/(h m^2)) and low physical cleaning frequency. In these conditions, the production of soluble microbial products was minimised and higher organisms appeared.

For a submerged MBR, the operation strategy to control membrane fouling frequently includes physical cleaning through backwashing. During backwashing, permeate is used to flush the membrane backwards and it is routinely applied to hollow-fibre configuration. This technique has been successfully proved to remove reversible fouling caused by loosely packed sludge cake [8,9]. Several operating parameters such as frequency, duration and backwashing flux have been identified as crucial in fouling mitigation [10]. However, there is a gap in knowledge regarding the inter-relationships between those parameters and the permeate flux imposed. In fact, due to the complexity of the process, operation strategy is usually time-based and backwashing is commonly applied for 30–60 s every 5.8–15 min of filtration [11]. As a consequence, the systems are not optimised during the whole operational period [1].

Recently, special attention has been paid on feedback control for finding optimal operating conditions in MBRs [12]. Busch and

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http://dx.doi.org/10.1016/j.memsci.2014.07.069
0376-7388/

Marquardt [13] introduced a run-to-run process control approach, in which the manipulated variables are optimised after each filtration cycle. The manipulated variables include the permeate and backwashing fluxes, and the filtration and backwash durations. Smith et al. [14] have proposed a control system for backwash initiation by permeability monitoring, adjusting the backwashing frequency automatically as a function of the permissible increase of transmembrane pressure for each filtration cycle. This operation strategy was capable of achieving higher water productivity than the temporised mode with fixed intervals. The allowable *TMP* increase was fixed at 3% (1.5 kPa) of the maximum permissible value of 50 kPa, which is defined as the point where the fouling can still be removed by backwashing. Vargas et al. [15] used a similar strategy in which backwash is initiated when the flux drops below a predetermined fraction of the maximum value in a sequential membrane bioreactor operated at a constant *TMP*. This approach has been further developed at lab-scale in order to assess the effect of transmembrane pressure set-point (TMP_{sp}) on membrane fouling and water productivity [16]. This backwashing strategy was also validated on pilot-scale, showing that continuous operation can be maintained at supra-critical filtration fluxes without chemical cleaning at moderate TMP_{sp} (30 kPa) [17]. It is therefore desirable to identify the optimal TMP_{sp} value and its effect on membrane fouling over long-term periods in a MBR operated under real feed parameters and temperature fluctuations. This paper continues the discussion about the applicability of this alternative operation strategy, in which backwashing initiation is controlled by the TMP_{sp}. Additional flux step trials have also been carried out in order to assess the effect of TMP_{sp} on reversible fouling and threshold flux.

2. Material and methods

2.1. Feedwater

The MBR was fed with the effluent from a conventional activated sludge wastewater treatment plant. The feed water was analysed three times a week through the whole experimental period and the average characteristics are summarised in Table 1. This is a conventional WWTP designed only for carbon removal. Due to the short sludge ages and oxygen deficiency in the activated sludge process, frequent episodes of sludge de-flocculation or insufficient sedimentation usually appear, resulting in a high suspended solids concentration in the effluent.

2.2. MBR

A cylindrical 220 l MBR was equipped with ZeeWeed® ZW-10 hollow-fibre membranes (GE Water & Process Technologies) of 0.04 μm rated pore diameter, 1.9 mm external diameter and 0.9 m^2 of filtering surface area, assembled vertically (Fig. 1). ZeeWeed® consists of a woven reinforcing braid on which a PVDF membrane is cast. The effluent (permeate) was extracted from the top header of the module under slight vacuum. All experiments were carried out at constant permeate flux (70 L/(h m^2)), registering transmembrane pressure as a function of time. Membrane fouling was controlled by backwashing based on an automatic cleaning initiation mode. Each filtration phase finished when a pre-established TMP_{sp} was reached, beginning the backwashing immediately afterwards. The system was operated at 6 different TMP_{sp} (25, 30, 35, 40, 45 and 50 kPa). A programmable logic controller system was used to initiate and stop the backwashing by comparison of TMP_{sp} and instantaneous pressure values. Pressure profiles were continuously data logged and plotted. Filtration flux (J) and backwashing conditions (flux J_B and backwashing time t_B) were constant throughout the experimental period with $J=70$ L/(h m^2), $J_B=60$ L/(h m^2) and $t_B=30$ s.

Fouling was also controlled by intermittent coarse bubbling of air (10 s on/10 s off) supplied at 1.1 N m^3/h m^2 during the filtration phase, expressed as net aeration rate per membrane area (SAD_{mnet}). Nevertheless, constant air scouring during the backwashing phase was fixed at 3.1 N m^3/h m^2 in order to improve the fouling removal, on the basis of previous results [17].

The bioreactor was run at hydraulic retention time (HRT) of 8.8 h without sludge removal except for sampling. The excess of permeate was returned to the tank in order to maintain a constant HRT independent of the permeate flux. Additional air was supplied at the bottom of the bioreactor, providing oxygen and stirring. The dissolved oxygen concentration in the reactor was always above 1.5 mg/L, operated at 25 ± 2 °C. Suspensions were routinely characterised by particle size distribution, time-to-filter (TTF), MLSS, MLVSS, non-flocculating microorganisms and dissolved organic matter of the liquid phase.

Previous studies were carried out in this pilot-plant for over 3 months in order to evaluate the influence of permeate flux on membrane fouling produced with this novel operation mode based upon TMP_{sp} [17], consequently prior biomass acclimation was not required.

2.3. Short-term flux step trials

The effect of TMP_{sp} on critical flux was assessed by flux-step modified tests. The modified method is based on applying successive flux increments up to a maximum, in accordance with the method of Le-Clech et al. [18] and further improved by incorporating relaxation steps for reducing the influence of fouling history, as described by Van der Marel et al. [19]. The modified method proposed in this work substitutes the relaxation for short backwashing steps along 30 s at a fixed flux of 60 L/(h m^2). These established values are similar to those in conventional operation of MBRs. Intermittent air bubbling (10 s on/10 s off) for membrane scouring was also supplied at $SAD_{mnet}=1.1$ N m^3/h m^2. The other experimental parameters were selected in accordance with previous studies [19,20]: step duration of 15 min, flux-step height of 5 L/(h m^2)and a maximum flux of 70 L/(h m^2).

Results were related to reversible fouling rate (r_f), given by the derivative of the transmembrane pressure ($dTMP/dt$). On the other hand, residual fouling was assessed by measuring the transmembrane pressure after each backwashing (TMP_{if}).

2.4. Membrane cleaning protocol

After the long-term test, the fouled membrane was cleaned by a specific protocol that includes the following steps: (1) rinsing with Milli-Q water; (2) backwashing with Milli-Q water at a flux of 60 L/(h m^2); (3) chemical cleaning with a solution of sodium hypochlorite (500 mg/L) for 24 h; (4) chemical cleaning with a solution of citric acid (6000 mg/L) for 24 h; and (5) chemical cleaning with sodium hypochlorite (500 mg/L) for 24 h. After each

Table 1
Feedwater main characteristics ($n=63$).

Parameters	Units	Mean	Range
COD	mg/L	55	12–205
DOC	mg/L	23	10.5–125.0
$N–NH_3$	mg/L	15	1.4–22.7
$N–NO_2^-$	mg/L	6	< 1–12.8
$N–NO_3^-$	mg/L	9	< 1–18.5
Turbidity	NTU	69	14–177
TSS	mg/L	156	27–316