Journal of Membrane Science 457 (2014) 1–8

Contents lists available at ScienceDirect

Journal of Membrane Science

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

Performance of a tertiary submerged membrane bioreactor operated at supra-critical fluxes

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ARTICLE INFO

Article history:
Received 2 August 2013
Received in revised form
23 December 2013
Accepted 12 January 2014
Available online 21 January 2014

Keywords:
Submerged membrane bioreactor
Tertiary treatment
Fouling
Supra-critical fluxes
Set-point trasmembrane pressure

ABSTRACT

A pilot-scale submerged aerobic membrane bioreactor (MBR) was run for over 3 months to assess the sustainability to operate at supra-critical fluxes. The MBR was applied as advanced treatment of secondary effluent from a conventional wastewater treatment plant. The system was successfully operated without biomass purge at hydraulic retention time (HRT) of 8.8 h, resulting in a moderate liquor suspended solid concentrations range (MLSS=4.1–7.1 g/l) in the bioreactor, according to the influent organic load fluctuations. Treatment performance was stable and achieved high conversion of ammonium to nitrate (96%) and dissolved organic carbon removal (53%). Short-term tests have been carried out according to a modified flux-step method to determine critical flux and evaluating optimum membrane cyclical aeration frequency. For the long-term tests, an alternative operation mode for backwashing initiation, based on a pre-selected transmembrane set-point, was applied. Under typical specific demand values (SAD_{pnet}=13.7–18.3 N m^3/m^3), continuous operation under different supra-critical filtration fluxes (J=60–80 l/h m^2) and backwashing fluxes (40–80 l/h m^2) can be maintained without any chemical cleaning. Analysis by means of sludge fractionation in lab-scale tests, at similar hydrodynamic conditions, indicated that the contribution of suspended solids to cake membrane fouling was estimated about 86–89%.

1. Introduction

It is widely known that in regions with water scarcity, wastewater reuse is a common practice and competent authorities have promoted many actions to encourage its reuse. In Tenerife island (Spain), since 1993 the secondary effluent obtained in the capital city's wastewater treatment plant (WWTP) is transported a long distance (60 km) by pipe, before being reused for crop irrigation. Biological treatment used in the plant is single-stage aeration and settling, which produces an effluent containing a significant and variable residual organic load and ammonium nitrogen (30–50 mg/l). Current scheme also includes a conventional tertiary treatment train (coagulation, sand filtration, chlorination and desalination). Some of the technical problems found in the treatment scheme have been the production of large quantities of residuals, high consumption of chemical reagents, sulphide generation during transport of the reclaimed water through a long pipe and decreased productivity in the downstream desalination plant due to the mentioned residual organic load [1]. Researching this issue provided some valuable technical solutions, indicating that anaerobic conditions inside the pipe can be inhibited by the presence of low nitrate concentration [2].

Due to their well-known advantages [3], submerged membrane bioreactor (MBR) has turned out as an attractive option for replacing the current tertiary treatment. As it was stated in previous research, the WWTP effluent can be effectively treated in an MBR until it achieves a high dissolved organics removal and complete nitrification [4]. Particularly interesting could be operating at maintenance energy level of the biomass, which significantly reduces sludge production. Under these conditions, the soluble microbial product (SMP) concentration could be minimised and the system was operated successfully at moderate permeate fluxes and low cleaning frequency, without any fouling evidence [5].

Notwithstanding the advantages of MBRs, their implementation is limited by the high costs, both in capital and operating expenditure (CAPEX and OPEX). A key issue regarding CAPEX and OPEX is the selection of the most appropriate permeate flux, which is determined by the classical trade-off problem: at higher fluxes CAPEX decreases while OPEX increases. High fluxes are desirable to reduce the membrane area required (i.e. reduce CAPEX), however, membrane fouling increases with flux, which results in a higher membrane scouring demand and a more frequent cleaning to control membrane fouling (i.e. increase OPEX) [3]. Verrecht et al. [6] have concluded that higher sustainable

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http://dx.doi.org/10.1016/j.memsci.2014.01.027

fluxes lead to lower net present values (NPV), indicating that the higher OPEX are offset by lower CAPEX since less membrane area is required, based on the results of a cost sensitivity analysis for a full-scale hollow fibre MBR. Specifically, an increase in flux from 15 to 30 l/h m^2 decreases NPV by 9%. Nevertheless, the correlation between membrane fouling and flux is influenced by hydrodynamics, cleaning protocols, feedwater characteristics and biological conditions [7]. The subsequent uncertainty has led to conservative plant designs and operation strategies. In addition, an analysis of design and operation of large MBR plants in Europe shows a broad difference between the design and operation flux [8]. For flat-sheet systems, the net fluxes are designed at 14–48 l/h m^2 (mean at 32 l/h m^2) while for the hollow-fibre modules they are 20–37 l/h m^2 (mean at 29 l/h m^2). However, for both systems the operation net flux is of about 20 l/h m^2. Therefore, the general trend is to reduce operational risk by operating at low fluxes (below the critical flux) where fouling is limited [9]. In addition, to maintain the process performance, strategies for fouling mitigation such as air scouring and physical cleaning techniques (i.e. backflushing and relaxation) have been incorporated as a standard [10,11]. Air scouring, expressed as specific aeration demand per permeate volume unit (SAD_p), takes a typical value, for full-scale facilities, between 10 and 50 N m^3/m^3 [10]. Relaxation and backflushing (only for hollow-fibre configuration) cycles with a prefixed duration are commonly applied for 30–130 s every 10–25 min of filtration [10]. However, inflexibility inherent of this time-based operation mode leads to a decrease in productivity when cleaning cycle is applied too often or it can promote irreversible fouling when applied too late [7].

Despite of the experience gained in the MBR operation over the last years, from a great variety of tested conditions, operation strategies are usually based on predetermined values of the key parameters (air scouring, filtration/physical cleaning sequences and permeate flux). However, these pre-set fixed values, based on general background or recommendations of membrane suppliers, lead to under-optimised systems and finally result in loss of permeate and high energy demand.

Special attention has been paid on feedback control to improve filtration process efficiency [7]. A comprehensive review of the achievements, including those related to the biological process, can be found in a recent paper [12]. Among the control systems, Smith et al. [13] have successfully validated a system for backwash initiation by permeability monitoring, automatically adjusting the backwashing frequency as a function of allowable transmembrane pressure increase in each filtration cycle, which results in a reduction of 40% in the required backwashing water. This control system was developed in a previous lab-scale study [14], which showed that membrane fouling can be significantly affected by the value of transmembrane pressure set-point (TMP_{sp}) selected and the cleaning method. However, a deeper investigation in long-term pilot experiments should be carried out in order to assess process sustainability, mainly focused on residual fouling development.

This paper assesses the sustainability of an MBR operated under controlled backwashing at supra-critical fluxes for treatment of secondary effluent. The role of backwashing flux was also investigated.

2. Material and methods

2.1. Feedwater

The pilot MBR was fed with effluent from a conventional activated sludge wastewater treatment plant whose average characteristics are given in Table 1. This is an old WWTP designed only for carbon removal. Due to the short sludge ages and oxygen deficiency in the activated sludge process, frequent episodes of sludge deflocculation or not enough sedimentation usually appear, which results in a high suspended solids concentration in the effluent.

Table 1
Feedwater main characteristics.

Parameters	Units	Mean	Range
COD	mg/l	280	13–2520
DOC	mg/l	14	9–27
N–NH_3	mg/l	26	1–53
N–NO_2^-	mg/l	4	$<$1–13
N–NO_3^-	mg/l	2	$<$1–17
Turbidity	NTU	180	10–1200
TSS	mg/l	280	33–1100

2.2. MBR

A cylindrical 220 l MBR was equipped with ZeeWeed® ZW-10 (GE Water & Process Technologies) hollow-fibre membranes of 0.04 μm rated pore diameter and 1.9 mm outer diameter, assembled vertically, which provide 0.9 m^2 of filtering surface area (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 a constant permeate flux, registering transmembrane pressure as a function of time. Fouling was controlled by coarse bubbling of air flow and by intermittent backwashing. The unit operated in automatic cleaning initiated mode. Each filtration cycle was finished when a pre-established transmembrane pressure was reached (30 kPa), beginning the backwashing cycle immediately afterwards. A programmable logic controller (PLC) system was used to initiate and stop the backwashing by comparison of TMP set-point and instantaneous pressure values. Continuous data logging and plotting of pressure profile evolution were also performed.

Before starting the experimental period, the pilot-scale MBR was seeded with sludge from the activated sludge reactor of the WWTP and operated for over 6 months to ensure that stationary conditions were reached. In this study, the bioreactor was run at HRT values of 8.8 h without sludge removal except for sampling. In order to maintain a constant HRT independent of the permeate flux, the excess of permeate was returned to the tank. Air was supplied through the bottom, providing oxygen and stirring. The dissolved oxygen concentration was always above 1.5 mg/l in the reactor operated at 23 ± 2 °C. Suspensions were characterised by particle size, MLSS, MLVSS, biomass activity, non-flocculating microorganisms [15] and dissolved organic matter of the liquid phase. In order to determine fouling contribution of each sludge components, a filterability test in a lab filtration unit was carried out for the different sludge fractions.

2.3. Short-term flux step trials

The modified flux-step method is based on applying successive flux increments up to a maximum and back analogous, in accordance with the method of Le-Clech et al. [16] and further improved by incorporating relaxation steps for reducing the influence of fouling history [17]. Nevertheless, the modified method proposed in this work substitutes the relaxation steps for short backwashing cycles (30 s) at a fixed flux value of 60 l/h m^2, to be more similar to the conventional operation of an MBR. The results are related to the reversible fouling rate (r_f), given by the change in TMP with time ($dTMP/dt$) at each J. Residual fouling was also assessed by measuring the transmembrane