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Sustaining membrane permeability during unsteady-state operation of anaerobic membrane bioreactors for municipal wastewater treatment following peak-flow

K.M. Wang, B. Jefferson, A. Soares, E.J. McAdam*

Cranfield Water Science Institute, Vincent Building, Cranfield University, Bedfordshire MK43 0AL, UK

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ABSTRACT

In this study, the impact of peak flow on anaerobic membrane bioreactor operation is investigated to establish how system perturbation induced by diurnal peaks and storm water flows will influence membrane permeability. Good permeability recovery was attained through increasing gas sparging during peak flow, which was explained by the transition in critical flux of the suspension at higher shear rates. However, supra-critical fluxes could also be sustained, provided peak flow was for a short duration. We suggest longer durations of supra-critical operation could be sustained through introduction of reactive fouling control strategies (e.g. TMP set-point control). An initial flux below the critical flux, prior to the introduction of peak flow, was advantageous to permeability recovery, suggesting membrane 'conditioning' is important in governing recoverability following peak flow. The importance of conditioning was confirmed through analysis of multiple peak flow events in which the loss of permeability following each peak-flow event was increasingly negligible, and can be ascribed to the arrival of a steady-state in membrane surface deposition. Whilst responding to peak flow with increased gas sparging has been shown effective, the energy demand is considerable, and as such a pseudo dead-end filtration strategy was also evaluated, which required only 0.04 kWh m^{-3} of energy for gas sparging. Comparison of both filtration modes identified comparable fouling rates, and the feasibility of a low energy gas sparging method for peak flow management that has successfully enabled supra-critical fluxes to be achieved over long-periods in other MBR applications. Importantly, membrane area provides the highest contribution toward capital cost of AnMBR. The potential to turn-up flux in response to peak-flow has been identified in this study, which suggests membrane area can be specified based on average flow rather than peak flow, providing substantial reduction in the capital cost of AnMBR for municipal wastewater treatment.

1. Introduction

Anaerobic membrane bioreactors (AnMBRs) are a promising alternative to conventional aerobic biotechnology for municipal wastewater treatment, as the combination of organic degradation without the demand for aeration, coupled with energy recovery from biogas production, offers the potential to realise energy neutral wastewater treatment [1]. The key challenges limiting full-scale application of AnMBR for municipal wastewater treatment, are the membrane investment cost and energy demand associated with membrane fouling control [2]. Numerous previous studies have focussed on sustaining membrane operation through application of various hydrodynamic conditions (e.g. gas sparging rate, physical cleaning frequency and duration). In each of these studies, a steady-state influent flow rate is assumed, with the membrane fixed at constant flux [1,3]. However, at full-scale, MBR must be designed to manage diurnal peaks and storm water flows [4]. Installation of equalisation tanks can serve to ameliorate peak flow and improve flow regulation [5]. Nevertheless, in a survey of 17 full-scale municipal aerobic MBR plants in Europe [6], half were reported to have peak ratios (peak flow to average flow) between two and three, due to the diurnal flow pattern and connection to combined sewer systems. The membrane must therefore be designed to cope with an increased flow without incurring substantial long-term fouling. This can be facilitated by sustaining an average flux at peak flow, through an increase in membrane surface area, or by temporarily increasing flux during periods of peak flow. This latter option will constrain capital investment in membrane surface area by up to three times, but its viability is impingent upon permeability not being compromised in the long-term from the short-term turn-up in flux.

A peak ratio of 1.4–1.5 is recommended for full-scale aerobic MBR

* Corresponding author.
E-mail address: e.mcadam@cranfield.ac.uk (E.J. McAdam).

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which assumes that a maximum sustainable flux (defined as the flux required to limit fouling and avoid or limit the demand for reactive chemical cleaning) can be achieved during peak flow that is 40–50% higher than the average flux [7–9]. Some full-scale aerobic MBR plants have adopted more conservative design, instead specifying the membrane surface area to match peak flow, which ensures a considerably lower operating flux during flow variation [8,10], but introduces a tremendous penalty in capital cost. This is significant since it is estimated that membrane area will comprise the largest proportion of capital cost (61–72%) for a full-scale municipal wastewater AnMBR [11,12]. Furthermore, by specifying membrane surface area based on peak flow, severe membrane under-utilisation has been reported [8]. To illustrate, in several surveys of full-scale municipal aerobic MBRs [13,14], the average flow was typically less than 50% of the peak flow used for design. This also incurred an increased operational cost of around 54%, due to the excess specific aeration demand per unit membrane area (SAD_m) required [8]. In the context of AnMBR for municipal wastewater treatment, this increase in energy demand and operational cost may reduce the attractiveness of investment, since the core aspiration is to facilitate energy neutral wastewater treatment [15].

Whilst the implications of peak flow on AnMBR design and operation are yet to be reported, laboratory and pilot scale evaluation of aerobic MBR have been conducted, in which the capacity for the membrane to withstand an increase in flux, in response to peak flow, has been determined using a constant SAD_m [5,16,17]. Lebegue et al. [17] identified no significant difference in transmembrane pressure (TMP) before and after a 2 h peak flow event in a lab-scale aerobic MBR treating synthetic municipal wastewater, which increased flux from 10 to 30 L m^{-2} h^{-1} for two hours on a daily basis. However, Metcalf [9] observed a significant membrane permeability decline in a pilot scale aerobic MBR treating settled municipal wastewater, when the flux returned to the average flux of 20 L m^{-2} h^{-1}, from a peak flux of 25 L m^{-2} h^{-1} that was sustained for 24 h. The authors attributed the increased fouling to the operating flux exceeding the critical flux during peak flow. In recognition of such behaviour, several studies sought to identify fouling control strategies that could be deployed during peak flow, such as increasing SAD_m, shortening filtration cycle time, or increasing backwash flux [4,14]. Following evaluation of a laboratory scale aerobic MBR treating synthetic settled municipal wastewater, Howell et al. [18] concluded that membrane fouling introduced by a temporary increase in flux could be controlled by an increase in SAD_m, with the residual foulant removed following flux restoration to a sub-critical level. Hirani et al. [4] tested five different pilot-scale submerged aerobic MBRs treating settled municipal wastewater, and demonstrated that a reduction in membrane permeability of 22–32% following the introduction of a peak flux ratio 1.6–3.2, was reversible, indicating that the reactive implementation of physical cleaning strategies during peak flow, were effective to cope with peak flow [4]. Importantly, such observations suggest that membrane surface area can be specified based on average flow rather than peak flow, which would help constrain membrane capital investment.

In AnMBR, the bulk sludge matrix is considerably more complex than in conventional aerobic MBR, leading to significantly higher membrane fouling [7,19]. As such, the reported flux for AnMBR is ordinarily between 5 and 12 L m^{-2} h^{-1} [1,20], which is considerably below the flux of 20–30 L m^{-2} h^{-1} typically specified for full-scale aerobic MBR [7]. The membrane area required for AnMBR will therefore be greater than for aerobic MBR, with the membrane cost inevitably increasing when membrane area is specified to sustain average flux at peak flow. The aim of this paper is therefore to evaluate the impact of a temporary increase in AnMBR flux, in response to peak flow, to ascertain whether AnMBR membrane surface area can be specified based on average flow rather than peak flow in order to diminish capital investment. The specific objectives were to: (i) evaluate the parameters governing permeability recovery (initial flux, peak flux to initial flux ratio, peak length); (ii) investigate the impacts of peak flow and strategies of increased gas sparging during the peak to enhance permeability recovery; and (iii) compare the conventional and alternative hydrodynamic conditions, to sustain permeability recovery whilst minimising energy demand.

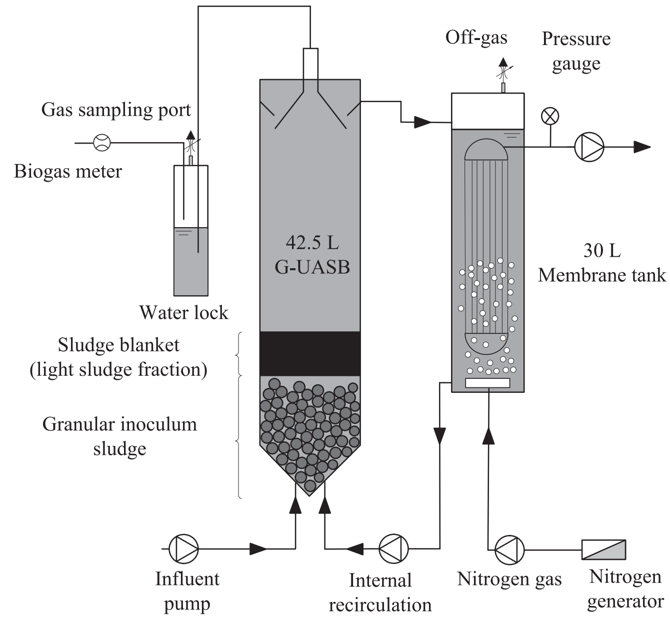

Fig. 1. Schematic of the pilot granular anaerobic membrane bioreactor (G-AnMBR).

2. Material and methods

2.1. Anaerobic MBR pilot plant

The AnMBR pilot plant was configured as a granular upflow anaerobic sludge blanket (G-UASB) reactor with a submerged hollow fibre membrane cited downstream (Fig. 1). The UASB was 42.5 L in volume, and was fitted with a lamella plate clarifier for solid/liquid/gas separation (Paques, Balk, The Netherlands). Granular sludge (16 L) from a mesophilic UASB designed for the pulp and paper industry, was used for inoculum, and was left to acclimate for 360 days before experimentation commenced. Settled sewage from Cranfield University's sewage works with COD_t, TSS and volumetric loading rate (VLR) of 320 ± 124 mg L^{-1}, 157 ± 66 mg L^{-1} and 1.0–2.2 g COD $L_{reactor}^{-1}$ d^{-1} respectively was fed into the AnMBR at the flow rate of 134–290 L d^{-1} (Flux = 6–13 L m^{-2} h^{-1}) under normal conditions with a peristaltic pump (520 S, Watson Marlow, Falmouth, UK), to fix HRT at 3.5–8 h for normal flow conditions. A dispersed-growth sludge fraction accumulated above the granular bed [21], and was withdrawn occasionally once washout occurred into the downstream membrane tank. No granular biomass was withdrawn from the G-UASB during the 120-day trial. Average temperature of sewage and AnMBR reactor during experimentation was 19.5 ± 3.4 °C.

The 30 L membrane tank was fed with G-UASB effluent and a recycle from the membrane tank to the base of the G-UASB was employed to sustain the upflow velocity. The resultant upflow velocity in the G-UASB was 0.8–0.9 m h^{-1} [22], which provided granule bed expansion of around 40% of total column height. The hollow-fibre membrane module (ZW-10) (GE Water & Process Technologies, Oakville, Ontario, Canada) comprised four elements, each with 54 polyvinylidene fluoride (PVDF) hollow fibres (0.72 m in length and 1.9 mm outer diameter), providing a total surface area of 0.93 m^2. The hollow-fibres had a nominal pore size of 0.04 μm. Permeate was removed by suction using a peristaltic pump (520U, Watson Marlow, Falmouth, UK). Pressure