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Effect of mean cell residence time on transmembrane flux, mixed-liquor characteristics and overall performance of a submerged anaerobic membrane bioreactor

Author names and affiliations

Santiago Pacheco-Ruiz^{*}, Sonia Heaven^{*} & Charles J. Banks^{*}

^{*}Faculty of Engineering and the Environment, University of Southampton, Southampton, UK

Abstract

Kinetic control of Mean Cell Residence Time (MCRT) was shown to have a significant impact on membrane flux under steady state conditions. Two laboratory-scale flat-plate submerged anaerobic membrane bioreactors were operated for 245 days on a low-to-intermediate strength substrate with high suspended solids. Transmembrane pressure was maintained at 2.2 kPa throughout four experimental phases, while MCRT in one reactor was progressively reduced. This allowed very accurate measurement of sustainable membrane flux rates at different MCRT, and hence the degree of membrane fouling. Performance data were gathered on chemical oxygen demand (COD) removal efficiency, and a COD mass balance was constructed accounting for carbon converted into new biomass and that lost in the effluent as dissolved methane. Measurements of growth yield at each MCRT were made, with physical characterisation of each mixed liquor based on capillary suction time. The results showed membrane flux and MLSS filterability was highest at short MCRT, although specific methane production (SMP) was lower since a proportion of COD removal was accounted for by higher biomass yield. There was no advantage in operating at an MCRT <25 days. When considering the most suitable MCRT there is thus a trade-off between membrane performance, SMP and waste sludge yield.

Keywords: anaerobic membrane bioreactors; membrane fouling; mean cell residence time; wastewater treatment; kinetic control

1 Introduction

There is growing interest in the anaerobic membrane bioreactor (AnMBR) as a promising technology for municipal and industrial wastewater treatment, due to its potential for energy recovery from dilute nutrient sources [1, 2]. The energy product is a biogas which is rich in methane, a flexible energy source for fuel and power applications. Net energy production is potentially possible because biomass retention is highly effective, allowing decoupling of the solids retention time (SRT) from the liquid hydraulic retention time (HRT), and thus providing a means of controlling the mean cell residence time (MCRT) of the system [3]. This is an important parameter as through it the growth rate of the system and its metabolic activity and energy conversion efficiency can be controlled [4]. The use of a membrane also effectively separates the biomass from the effluent, resulting in a high quality product very low in suspended solids. AnMBR can operate at HRTs similar to their aerobic counterparts, and research over recent years has shown they can successfully adapt to low temperatures [5, 6, 7] resulting in potential net energy gains. AnMBR operation at higher temperatures is also of interest for the treatment of industrial effluents that are at a higher temperature such as brewery, chemical, dairy and paper industries [8, 9, 10], for which full-scale plants are already in commercial operation [10]. Further advantages of these anaerobic systems include their small footprint and their low biomass yields, although the latter need to be fully quantified, especially when they are operated at high growth rates.

There are still considerable technical challenges to be overcome before full-scale application of the technology becomes widespread: these include recovery of dissolved methane from the effluent, and reductions in membrane fouling and/or the high energy consumption of membrane cleaning systems [1, 3, 11]. Membrane fouling is considered to be the main limitation in all membrane processes, and design approaches have included both in-situ cleaning systems and periodic chemical cleaning or membrane replacement [12, 13]. The objective is usually to maintain a high transmembrane flux with a low transmembrane pressure (TMP), while minimising energy and chemical inputs for operation over prolonged periods. In this respect the submerged anaerobic reactor (SAnMBR) may have advantages over externally-configured membrane cartridges as the former are reported to have a lower energy demand, although this has still to be confirmed on larger-scale installations [11]. Research to investigate the controlling factors that lead to different degrees of membrane fouling could lead to more practical solutions through prevention and minimisation.

Control of MCRT through proportional biomass wastage is the simplest way to exert kinetic control over biological wastewater treatment systems, as well as over the physical characteristics of the mixed liquor [14]. In the case of AnMBR both membrane fouling and reactor performance are likely to be directly affected by MCRT as the mixed liquor characteristics and biomass concentration both depend upon this parameter [7, 13], which also controls the microbial growth rate and metabolic activity [15]. The production of extracellular polymeric (EPS) materials and soluble microbial products, which are known to influence membrane fouling, has also been shown to be related to MCRT and HRT [11, 12] and may be particularly important where the membrane is directly submerged in the mixed liquor [13]. There is considerable debate in the literature, however, concerning methods for

analysing EPS and soluble microbial products, and this lack of consistency makes it difficult to interpret results or make comparisons between different studies [16, 17]. At present the strategy appears to be to operate MBRs at long MCRT, since research on aerobic systems has shown that decreasing the MCRT tends to increase the concentration of soluble microbial products and EPS, both of which may have a greater effect on membrane fouling than the concentration of mixed liquor suspended solids (MLSS) alone [11, 13, 18]. The evidence in the case of AnMBR is less clear: in work using a flat sheet SAnMBR to treat low strength synthetic wastewater, Huang *et al.* [6] found that a long MCRT resulted in higher fouling; yet a more recent paper by the same authors showed more fouling at very short MCRT when treating domestic wastewater in the same reactor type [7]. The relationship between operational parameters, treatment performance and membrane fouling is recognised as being complex and poorly defined [3]; and it is clear that further research is needed to understand fully how MCRT impacts on reactor performance, and in particular the relationship between this and membrane fouling.

The aim of the current research was to assess the impact of changes in MCRT during long-term operation of AnMBR upon a range of key performance indicators including: membrane flux at constant TMP; Chemical Oxygen Demand (COD) removal; specific methane production (SMP), MLSS, and mixed liquor filterability.

2 Materials and methods

2.1 Reactor design and function

Two SAnMBRs designated A and B (Fig. 1), each with a working volume of 9.6 L and a headspace of 2.1 L, were operated with the TMP applied by gravitational head, as described by Pacheco-Ruiz *et al.* [19]. The membranes used were type 203 cartridge flat plate chlorinated polyethylene (Kubota Co., Japan) with a nominal pore size of 0.4 μm and an effective surface area of 0.113 m^2 , giving a membrane packing density of 0.012 $\text{m}^2 \text{L}^{-1}$. The reactors were fed by a constant head device through which substrate was continuously circulated from a cooled storage tank (Grant FH15 and CC25, Germany). Flow through the reactors was achieved by maintaining a head differential between the constant head device and a syphon outlet from the lumen of the membrane cartridge. Flow was measured by recording the weight of the collected permeate at 5-minute intervals, using a laboratory scale with a capacity of 32 kg and a readability of 1.0 g (Adam Equipment CBK 32, UK).

Transmembrane pressure could be kept constant, in which case the membrane flux varied relative to the degree of fouling; alternatively the membrane flux could be adjusted by increasing or decreasing the head differential. The back pressure in the reactor headspace was maintained at approximately 0.3 kPa using a fermentation gas-lock through which the biogas produced escaped into a gas collection bag.

The membrane was cleaned by recirculating the headspace biogas through a stainless steel sparger at a rate of approximately 0.57 L L^{-1} of reactor min^{-1} (equivalent to 48.5 $\text{L min}^{-1} \text{m}^{-2}$ of membrane surface) using a diaphragm pump (AIRPOTM, UK). This provided a gas lift which kept the mixed liquor in homogeneous suspension. Reactor temperature was

maintained at 36 ± 0.5 °C by an internal stainless steel heat exchanger coupled to a thermo-circulator system (Grant FH15V and FC15, Germany). Reactor and feed temperatures were recorded continuously using solid-state IC temperature probes (Texas Instruments LM35DZ, USA) connected to a data logger (model U3-LV, Labjack, USA).

2.2 *Inoculum and substrate*

Both reactors were inoculated with digestate from a mesophilic digester treating municipal wastewater biosolids (Millbrook wastewater treatment plant, Southampton, UK), as recommended by Akram and Stuckey [20]. This was diluted to 50% with tap water, and after filling of the reactor the headspace was purged with nitrogen. Substrate was prepared fresh each day, to an average COD concentration of 890 mg L^{-1} and an average TSS concentration of 360 mg L^{-1} during the main experimental period. It was made from a mixture of: sterilised yeast to give a biosolids component; milk and dried blood as sources of protein and fat in soluble and colloidal form; sugar as a readily utilisable soluble carbon source; urea as a further source of organic nitrogen; and a mixed mineral supplement. The mix has been previously reported as a synthetic wastewater (SWW) [19], as the C:N:P ratio and ratio of solids components is based on typical values for European municipal wastewaters when used at a lower strength.

2.3 *Performance and stability*

The experiment ran for 245 days including a start-up period and four experimental phases (EP) during which the reactors were operated at different MCRTs as shown in Table 1. The MCRTs evaluated were based on the range previously tested by Huang *et al.* [6,7] with intermediate values chosen to give a significant increment in each case.

Membrane performance was assessed based on the membrane flux at constant TMP. Membrane flux was calculated using Equation 1; TMP was calculated from Equation 2, based on the head differential between the inlet and outlet taking into account the back pressure of the biogas produced.

$$J = \frac{Q}{A_M} \quad (1)$$

Where:

J = membrane flux ($\text{L hour}^{-1} \text{ m}^{-2}$)

Q = reactor effluent flow (L hour^{-1})

A_M = membrane area (m^{-2})

$$TMP = ((H_{wl} - H_e) + (P_b)) g \quad (2)$$

Where:

TMP = transmembrane pressure (kPa)

H_{wl} = surface level of the mixed liquor inside the reactor (m)

H_e = level of the effluent outlet (m)

P_b = estimated gas-lock pressure-head (m)

g = acceleration due to gravity (9.80665 m s^{-2})

The biochemical characteristics and stability of the reactors were assessed based on COD conversion, SMP, pH, MLSS, volatile suspended solids (MLVSS) and capillary suction time (CST; Triton Electronics, UK). COD was measured using the closed tube reflux method with titrimetric determination of the end point [21] for fresh feed, feed after 24 hours of cooled storage, and reactor effluent. Gas production was measured using a weight-type gasometer, and reported at a standard temperature and pressure (STP) of 0 °C and 101.3 kPa according to Walker *et al.* [22]. Biogas composition was measured using a gas chromatograph (Varian GP-3400, USA) and compared to standard biogas of 36% CO₂ and 64% CH₄ (v/v) (BOC, UK). The average COD of fresh and stored feed was used in the calculation of organic loading rate (OLR) and SMP. Reported SMP values include both methane produced in the headspace and methane dissolved in the effluent to ensure comparability between reactors operating with different membrane fluxes. Dissolved methane in the effluent was estimated using Henry's Law with the saturation concentration at 36 °C, giving a value of 22.9 mL CH₄ L⁻¹. This value was confirmed by experimental measurement, based on the method of Walsh and McLaughlan [23]. Mixed liquor pH was measured with a pH meter (Jenway 3310, UK) calibrated with buffers at pH 4, 7 and 9.2 (Fisher Scientific, UK). The MLSS and MLVSS concentration in the reactor was measured according to Standard Method 2540-D [24]. A COD mass balance was carried out in which the influent COD was considered as the only input to the system and the outputs were COD_{effluent}, COD_{gaseous CH₄}, COD_{dissolved CH₄}, and COD_{biomass growth}. The latter was estimated from the biosolids removed daily (g MLSS day⁻¹) divided by the average mixed liquor COD/SS ratio (g COD g⁻¹ MLVSS). Biogas H₂S content and changes in the biomass stored in the reactor were not included in the mass balance calculation.

3 Results and discussion

3.1 Operational performance

The performance of the two reactors over the 245-day experimental period is shown in Fig. 2, and summary results are given in Table 2. Key parameters are discussed below in relation to operational changes during each of the four experimental phases

3.1.1. Membrane flux in response to MCRT with observed changes in OLR, HRT and MLSS

Start-up. Both reactors were started with a TMP of 6.0 kPa and daily biomass wastage aimed at giving an MCRT of 96 days. The membrane flux in both Reactor A and B was initially very high at 17.5 and 19.2 L m⁻² hour⁻¹ respectively, but decreased and converged throughout the start-up period resulting in fluxes of 11.0 and 11.3 L m⁻² hour⁻¹ at the end of start-up (Fig. 2). Because of the high initial flux, a more dilute feed was used during start-up with an average COD concentration of 427 ± 27 mg COD L⁻¹. As a consequence of the declining flux the initial OLR dropped from 2.10 and 2.31 g COD L⁻¹ day⁻¹ to 1.35 and 1.38 g COD L⁻¹ day⁻¹ in Reactor A and B respectively, and the initial HRT increased from 5.0 and 4.5 hours to 7.7 and 7.6 hours. The initial MLSS concentration of 17.3 g L⁻¹ showed some variation, but by the end of start-up had fallen to 16.2 g L⁻¹ in Reactor A and 16.9 g L⁻¹ in Reactor B.

EP-1. The TMP was deliberately reduced from 6.0 to 2.2 kPa at the beginning of this phase to establish a more consistent flow regime by stabilising the membrane flux around a target value of $6 \text{ L m}^{-2} \text{ hour}^{-1}$ (Fig. 2). This was successful: the flux in both reactors stabilised almost immediately at around 6.1 and $6.6 \text{ L m}^{-2} \text{ hour}^{-1}$ and by the end of this phase had only dropped to $5.8 \text{ L m}^{-2} \text{ hour}^{-1}$ and $6.1 \text{ L m}^{-2} \text{ hour}^{-1}$ for Reactor A and B, respectively. The overall effect was an almost constant OLR of $1.56 \pm 0.03 \text{ g COD L}^{-1} \text{ day}^{-1}$ for Reactor A and $1.67 \pm 0.18 \text{ g COD L}^{-1} \text{ day}^{-1}$ for Reactor B, with correspondingly stable HRTs of 14.0 and 13.1 hours. Operation of both reactors at an MCRT of 96 days continued and by the end of this phase the MLSS concentration had fallen to 15.1 and 15.6 g L^{-1} in Reactor A and B respectively.

EP-2. Both reactors were kept at a TMP of 2.2 kPa. MCRT in Reactor A was reduced to 40 days while in Reactor B it remained at 96 days. Despite the difference in MCRT both reactors maintained a similar membrane flux during the first 30 days of this phase (Fig. 2), although a gradual decline was seen in both, resulting in fluxes around day 90 of 4.5 and $4.2 \text{ L m}^{-2} \text{ hour}^{-1}$ in Reactors A and B respectively. After this the flux rates diverged, with Reactor B falling further and then stabilising at an almost constant flux of $3.7 \pm 0.1 \text{ L m}^{-2} \text{ hour}^{-1}$, whilst the flux in Reactor A gradually increased to $5.4 \text{ L m}^{-2} \text{ hour}^{-1}$ around day 130 and remained at this value until the end of EP-2. These changes in flux resulted first in an increase in HRT in both reactors, then a reduction in Reactor A to 15.9 hours and a further increase to 22.8 hours in Reactor B. As a result the OLR in Reactor A initially fell to $1.07 \text{ g COD L}^{-1} \text{ day}^{-1}$ and then rose to $1.34 \text{ g COD L}^{-1} \text{ day}^{-1}$ by the end of EP-2; while in Reactor B OLR fell from $1.51 \text{ g COD L}^{-1} \text{ day}^{-1}$ and stabilised at around $0.93 \text{ g COD L}^{-1} \text{ day}^{-1}$. MLSS concentrations also reflected the changes in MCRT and OLR, with Reactor A stabilising at around $6.3 \pm 0.2 \text{ g L}^{-1}$, while the fall in MLSS in Reactor B, which was maintained at a constant MCRT, simply reflected the decreasing organic load applied.

EP-3. A TMP of 2.2 kPa was maintained in both reactors. MCRT in Reactor A was reduced to 25 days and in Reactor B remained at 96 days. This resulted in an initial increase of the membrane flux in Reactor A from $5.5 \text{ L m}^{-2} \text{ hour}^{-1}$ (day 145) to $6.3 \text{ L m}^{-2} \text{ hour}^{-1}$ (day 169), after which it remained constant at $6.3 \pm 0.1 \text{ L m}^{-2} \text{ hour}^{-1}$. The flux in Reactor B showed a slight increase during this phase, with a final value of $4.3 \text{ L m}^{-2} \text{ hour}^{-1}$ (Fig. 2). Changes in HRT and OLR corresponded to the changes in flux, while any expected increase in MLSS in response to the increased load in Reactor A was counteracted by the shorter MCRT which results in higher microbial activity. As a consequence the MLSS in Reactor A decreased to $5.5 \pm 0.1 \text{ g L}^{-1}$ whereas in Reactor B it remained at $10.5 \pm 0.3 \text{ g L}^{-1}$.

Technical difficulties on days 180-2 resulted in feed lines blocking and disruption to feeding. This resulted in some loss of membrane flux over this period, but the flux returned to its previous value when the problem was resolved and the lines cleaned.

EP-4. Both reactors remained at a TMP of 2.2 kPa. MCRT was reduced to 15 days in Reactor A and maintained at 96 days in Reactor B. Reactor A showed no further increase in membrane flux, which remained constant around $6.3 \pm 0.1 \text{ L m}^{-2} \text{ hour}^{-1}$ (Fig. 2). Further

improvements in the membrane flux in Reactor B were observed, giving a final flux of $5.1 \text{ L m}^{-2} \text{ hour}^{-1}$ over the last three days of operation. Apart for the flux-related changes to OLR and HRT, which were as expected, the MLSS concentration in Reactor A reduced to $3.7 \pm 0.1 \text{ g L}^{-1}$ during the last 10 days of the experimental run. MLSS in Reactor B increased slightly to 11.2 g L^{-1} reflecting the increased load applied as a result of the slightly higher flux.

3.1.2 COD removal rate

The first measurement of COD removal rate made on day 6 showed 82% removal in Reactor A and 69% in Reactor B, although these values were not reflected in biogas production which was low in both reactors. During start-up COD removal declined. The reactor headspaces were found to contain a high proportion of nitrogen; this was attributed to equilibration of dissolved atmospheric gases in the influent, which was maintained at 10°C and continuously ‘aerated’ through the constant head feed before being fed into the reactors at a high dilution rate. The feeding set-up may thus have led to some respiratory oxidation of COD, and the presence of residual oxygen may possibly have been toxic to strict anaerobes in the reactors. To overcome this problem the feed temperature was raised to 20°C on day 11 to reduce atmospheric gas solubility. From this time onward a significant increase in biogas production was observed, with no more than 10% (v/v) atmospheric gases present in the headspace. Coupled with the slightly longer HRT this resulted in COD removal rates of 96% in Reactor A and 83% in Reactor B, with the mass balance (Fig. 3) showing a substantial proportion of this being converted to methane.

As can be seen in Table 2 and in Fig 2, the COD removal rate remained at 96-97% in both reactors throughout EP-1 to EP-4. This result indicates that under the loading and hydraulic conditions applied MCRT does not have any effect on COD removal rates in mesophilic operation. This suggests that similar metabolic activity can be maintained at a MLSS of 3.7 g L^{-1} at a MCRT of 15 days as at a MLSS of 11.2 g L^{-1} at the longer MCRT of 96 days.

3.1.3 Specific methane production

Biogas composition was stable throughout the four experimental phases with 76% CH_4 , 14% CO_2 and 10% atmospheric nitrogen. SMP expressed as $\text{L CH}_4 \text{ g}^{-1} \text{ COD}_{\text{removed}}$ followed a very similar pattern in both reactors despite the considerable differences in MCRT and biomass concentration (Fig. 2 and Table 2). There were, however, differences in the SMP value, which tended to decrease slightly at shorter MCRTs, reaching its lowest value of $0.27 \text{ L CH}_4 \text{ g}^{-1} \text{ COD}$ in Reactor A during EP-3 and 4; whilst during the corresponding period in Reactor B the value remained around $0.30 \text{ L CH}_4 \text{ g}^{-1} \text{ COD}$. The SMP may be lower under short MCRT operation as more carbon is lost from the system through biomass growth and subsequent wastage, and is therefore not available for reduction to methane [25]. The importance of biomass turnover in interpreting SMP is further highlighted by the COD balance (Fig. 3) which shows that the COD output was higher than the input during phase 1 and 2: this discrepancy may be due in part to endogenous decay of the high MLSS inoculum used, as well as to changes in the stored biomass within the reactor. This extra methane production from an endogenous source rather than exogenously supplied substrate might account for the higher SMP values recorded during these early phases of operation (Fig. 2).

The estimated COD used in observed biomass growth is shown in Fig. 4a where it can be clearly seen that the fraction of the total COD input used for biomass production under pseudo-steady state conditions is greater at shorter MCRTs, supporting the conclusion that the lower methane production is associated with high growth rate. If the SMP is normalised to the MLSS (SMP_{MLSS}) (Fig. 2), the SMP per unit of biomass increases with reducing MCRT, clearly indicating a higher metabolic activity which is consistent with kinetic theory. Huang *et al.* [6] also reported that SMP increased with increasing MCRT when treating low strength SWW in SAnMBRs, giving average values of 0.13, 0.20 and 0.22 L CH₄ g⁻¹ COD_{removed} at 30, 60 and infinite days MCRT, respectively. Their explanation for this phenomenon was that the longer MCRT would benefit methanogenesis and lead to more biogas generation; this, however, does not account for almost identical COD conversion efficiencies. The later study by Huang *et al.* [7] also shows increasing SMPs of 0.04, 0.09, 0.09 L CH₄ g⁻¹ COD removed at 30, 60 and 90 days MCRT respectively when fed at an OLR of 1.02 g COD L⁻¹ day⁻¹. These SMP values are 3-8 times lower than those in Huang *et al.* [6], where SWW was used rather than domestic wastewater.

Whilst the SMP values reported in this experiment are generally higher than those reported by Huang *et al.* [6] and Huang *et al.* [7], it must be remembered that the reported SMP in this experiment includes the theoretical methane loss in the effluent to enhance comparability between reactors. Nonetheless, the trend of lower SMP at shorter MCRTs is still consistent between their studies and the outcome of this experiment. The trends in SMP_{MLSS} calculated from the data reported by Huang *et al.* [6] contradict those found here, however, and suggest that the methane productivity per unit of biomass is higher at long MCRTs and hence low growth rates. In future work specific methanogenic activity tests should be used to establish metabolic activity to further clarify this point.

3.2 Membrane performance and fouling phenomena

Throughout the four experimental phases both reactors maintained a sustainable membrane flux as defined by WEF [12] at a constant transmembrane pressure, although the value of this was different at each MCRT, as seen in Fig. 2 and reported above. It is clear that MCRT can affect membrane flux, and that this is not necessarily just as a function of the MLSS concentration. Earlier research has suggest that membrane fouling may result from constituents such as EPS and soluble microbial products, the production of which is related to growth and hence MCRT [11]. The relationship between these factors is still unclear, however, and studies in AeMBRs [18] and anoxic/anaerobic membrane bioreactors [26] have shown more fouling at shorter MCRTs; whilst in the current SAnMBR study fouling appears worse at longer MCRTs. This is in agreement with one of the studies by Huang *et al.* [6] in which performance decreased with increasing MCRT: this was attributed to higher production of soluble microbial products inducing more pore blocking in the membrane and enhanced surface biofilm/biocake development. Later work by Huang *et al.* [7] showed biofouling increased at both long and short MCRTs, with maximum flux rates being achieved at 60 days. Recent studies on two stage SAnMBRs treating palm oil mill effluent [27] showed that cake layer formation was directly linked to MLSS concentrations, and hence increased at

longer MCRT, with a negative impact on membrane flux. Studies to investigate the effect of MCRT on membrane fouling and overall performance in AnMBR are scarce, however, and none has previously evaluated this using a gravitationally-mediated constant transmembrane pressure as reported here with the capacity for continuous measurement of flux rate. Physical examination of the membrane cassettes (Fig. 5) showed that the shorter MCRTs in Reactor A resulted in a lower biocake formation on the membrane surface, when compared to Reactor B which operated at longer MCRT. The possibility that this could be due to differences in the performance of the membrane air scouring system was discounted, as both reactors performed equally well when operated under the same conditions during the start-up and EP-1 phases.

3.3 *Mixed liquor characteristics*

3.3.1 *Filterability*

Results from the capillary suction time test (Fig. 6a and Table 2) show that MCRT has a large effect on the ability of the mixed liquor to hold water, with samples at shorter MCRT giving up their water much more readily than those at long MCRT. During start-up and EP-1 when Reactors A and B were operated as replicates, similar increases in CST time were seen in both reactors. When the MCRT in Reactor A was reduced in EP-2 the CST time also decreased, giving a more than 3-fold difference in CST by the end of this phase. This could not be attributed simply to a change in MLSS concentration as, when normalised against MLSS (CST_{MLSS} , Fig. 6b), a significant change can be seen from day 100 onwards. This trend of reduction in both CST and CST_{MLSS} continued through EP-3 and EP-4 with CST times of < 25 seconds being achieved at MCRT of 25 and 15 days, compared to an average close to 800 seconds for an MCRT of 96 days. The CST_{MLSS} results confirm that the MCRT has a considerable effect on the mixed liquor filterability and therefore on membrane fouling, independently of the MLSS concentration.

3.3.2 *Microbial growth yield*

Besides having a major effect on MLSS characteristics, manipulation of MCRT controls the growth rate of a microbial population and hence its potential growth yield. This is shown in **Error! Reference source not found.4b** where it can be seen that the amount of biomass produced during the start-up and EP-1 followed the same trend in both reactors. With each reduction in MCRT in phases EP-2, EP-3 and EP-4 there was a sharp increase in the apparent biomass yield at the beginning of each stage, followed by a gradual decrease until a stable value for MLSS was reached. This stable biomass yield at the end of each phase was considered to be the most representative value for that MCRT and was equal to: 0.111 ± 0.004 g VSS g⁻¹ COD_{removed} for 40-day MCRT; 0.132 ± 0.008 g VSS g⁻¹ COD_{removed} for 25-day MCRT; and 0.143 ± 0.006 g VSS g⁻¹ COD_{removed} for 15-day MCRT. In contrast, the constant MCRT of 96 days showed a long-term growth yield from day 180 onwards of 0.092 ± 0.009 g VSS g⁻¹ COD_{removed}. These results further reinforce the above argument that at the shorter MCRT a larger proportion of the available carbon is diverted away from methane production into cellular growth, thus reducing the SMP of the substrate.

Membrane flux and transmembrane pressure are direct indicators of membrane performance as fouling results in a reduction in flux which has to be compensated for by an increase in transmembrane pressure. Several papers have tried to relate membrane fouling to the presence of EPS [11-13] but there are only very limited indications as to what conditions may control EPS formation in membrane systems, and still no firm evidence as to how this affects membrane fouling. The current work, however, shows a clear link between shorter MCRT and improved filterability of the MLSS as measured by membrane flux and CST; and also shows that this improved CST at shorter MCRT is independent of MLSS concentration. This is the first time this behaviour has been reported, in a study with the reactors allowed to stabilise for periods close to 3 MCRT to ensure pseudo steady state operation, and at retention times typical of those used in high rate anaerobic reactors. There are thus clear advantages in running these systems at short MCRTs, but this has to be balanced by the fact that this will also generate a higher biomass sludge yield which at the shortest MCRT used was as high as might be expected from an extended aeration activated sludge plant. These growth yields were again taken under steady state conditions and show the range over which anaerobic systems can operate with respect to this important parameter. The higher growth yields at shorter MCRT indicate that anaerobic systems can operate at metabolic rates similar to those of aerobic plants, as similar COD reductions and rates of conversion can be achieved at roughly equal biomass concentrations expressed as MLSS.

4 Conclusions

Long-term operation of two SAnMBR on a substrate of low to intermediate strength with a high suspended solids content was achieved without change in the transmembrane pressure throughout four experimental phases, during which the MCRT in one reactor was progressively reduced. This allowed very accurate measurements to be made of the membrane flux rates associated with different MCRT, with determination of COD removal efficiencies and a COD mass balance, as well as estimation of biomass yield and physical characterisation of each mixed liquor using CST. The results showed that membrane flux was significantly affected by MCRT, with shorter MCRT giving the best performance and greatly enhancing both the relative and the absolute MLSS filterability. Operation at short MCRT, however, resulted in lower specific methane production, although overall COD removal was not affected. Short MCRT also led to greater waste sludge production and no further improvement in membrane flux or MLSS filterability was seen at MCRT < 25 days. There is clearly a trade-off to be made between membrane performance, digestate filterability, specific methane production and sludge yield when considering the most suitable operational MCRT.

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Tables

Table 1. Start-up and experimental phases

Phase	Duration (days)	Objective	Reactor	TMP (kPa)	MCRT (days)
Start-up	25	Acclimate the digestate to the reactor and substrate, and pre-foul the membrane for the TMP reduction	A	6.0	96
			B	6.0	96
EP-1	25	Couple both reactors to establish a common baseline for the next stages	A	2.2	96
			B	2.2	96
EP-2	95	Evaluation of MCRT effect on membrane flux, reactor performance and mixed liquor characteristics	A	2.2	40
			B	2.2	96
EP-3	55	Evaluation of MCRT effect on membrane flux, reactor performance and mixed liquor characteristics	A	2.2	25
			B	2.2	96
EP-4	45	Evaluation of MCRT effect on membrane flux, reactor performance and mixed liquor characteristics	A	2.2	15
			B	2.2	96

Table 2. Experimental results; main parameters summary table

Parameter	Reactor A				Reactor B			
	EP-1	EP-2	EP-3	EP-4	EP-1	EP-2	EP-3	EP-4
MCRT (days)	96	40	25	15	96	96	96	95
TMP (kPa)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
Membrane Flux (J)* (L m ⁻² hour ⁻¹)	6.2 ± 0.2	5.8 → 4.3 → 5.4	5.5 → 6.3	6.3 ± 0.1	6.5 ± 0.2	6.1 → 3.7	3.8 → 4.3	4.4 → 5.1
Feed COD (mg L ⁻¹)	901 ± 19	872 ± 33	898 ± 20	911 ± 19	901 ± 19	872 ± 33	898 ± 20	911 ± 19
Effluent COD (mg L ⁻¹)	29 ± 6	25 ± 5	31 ± 4	31 ± 5	107 → 31	28 ± 5	32 ± 5	33 ± 3
COD removal (%)	97% ± 1%	97% ± 1%	97% ± 1%	97% ± 1%	83% → 97%	97% ± 1%	96% ± 1%	96% ± 1%
OLR (g COD L ⁻¹ day ⁻¹)	1.56 ± 0.03	1.43 → 1.07 → 1.34	1.58 ± 0.07	1.67 ± 0.02	1.67 ± 0.18	1.51 → 0.90 → 0.93	1.05 ± 0.05	1.15 → 1.33
HRT (hours)	14.0 ± 0.4	14.8 → 20.0 → 15.9	13.9 ± 0.5	13.6 ± 0.2	13.1 ± 0.4	14.0 → 23.5 → 22.8	22.6 → 19.6	19.3 → 16.6
MLSS (g L ⁻¹)	16.2 → 14.7	15.1 → 6.2 → 6.5	5.5 ± 0.1	5.6 → 3.6 → 3.7	16.9 → 17.9 → 15.9	15.6 → 10.8	10.5 ± 0.3	10.9 → 11.2
MLVSS (g L ⁻¹)	11.8 → 11.3	11.6 → 5.6	5.0 ± 0.3	5.1 → 3.3 → 3.4	12.5 → 13.3 → 12.2	12.1 → 9.1	9.1 ± 0.3	9.5 → 9.9
CH ₄ in biogas** (%)	84% ± 1%	84% ± 1%	85% ± 1%	85% ± 1%	84% ± 1%	84% ± 1%	84% ± 1%	84% ± 1%
SMP*** (L CH ₄ g COD rem. ⁻¹)	0.30 ± 0.02	0.32 ± 0.01	0.27 ± 0.02	0.27 ± 0.01	0.30 ± 0.01	0.33 ± 0.03	0.30 ± 0.02	0.29 ± 0.01
CST (seconds)	509 → 761	768 → 798 → 338	312 → 34	33 → 23	555 → 745	778 → 1211 → 952	1012 → 824	810 → 760
pH	6.9 ± 0.1	6.9 ± 0.1	7.0 ± 0.1	6.9 ± 0.0	6.9 ± 0.1	6.9 ± 0.1	6.9 ± 0.1	6.9 ± 0.1

(→) Variable trend: initial → middle → final

(±) Stable performance: One standard deviation to show the spread of the data from the average value under stable performance

(*) Daily average

(**) Normalised to total biogas content in sample (neglecting air introduced dissolved through feed)

(***) Takes into account the methane lost dissolved in the effluent

Figure Captions

Fig. 1. Experimental set up diagram

Fig. 2. Effect of MCRT on daily average membrane flux, MLSS and MLVSS concentration, COD removal efficiency, SMP, and SMP_{MLSS} during experimental period.

Fig. 3. COD balance

Fig. 4. (a) Observed biomass growth COD fraction; (b) observed biomass yield

Fig. 5. Membrane fouling at the end of experimental run: (i) membrane front – before rinse, (ii) membrane back – before rinse, (iii) membrane front – after rinse, (iv) membrane back – after rinse.

Fig. 6. Mixed liquor filterability: (a) CST; (b) CST_{MLSS}