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The Impact of Intermittent Aeration on the Operation of Air-Lift Tubular Membrane Bioreactors under Sub-Critical Conditions

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Abstract: An air-lift sidestream polymeric multi-tube membrane module has been investigated to compare the hydraulic performance of an MBR challenged with municipal wastewater and landfill leachate. In both cases the MBRs were operated under the same conditions of membrane aeration rate and sludge retention time, but with hydraulic retention time for the leachate set by scoping trials based on porous pots to 48 hours. Operation under conventional continuous aeration conditions yielded critical flux values, based on classical flux step experiments, of $36–42\,l\,m^{-2}\,hr^{-1}$ for the sewage-fed trial compared with $\sim 24\,l\,m^{-2}\,hr^{-1}$ for the leachate-fed trial. Substantial improvements in operating flux, between 20 and 100%, were obtained when operating with air pulsing (1s on/s off). Intermittent operation under more conventional conditions (5s on/5s off) yielded no improvement.

Keywords: Membrane bioreactor, tubular membrane, air-lift, leachate, intermittent aeration

INTRODUCTION

Whilst membrane bioreactors (MBRs) offer an attractive alternative to conventional biological processes for reasons generally well-known (1), their performance, as with conventional processes, depends critically on the quality of the feedwater being treated. Performance is reflected both in the level of purification attained, i.e. the % removal, and the specific energy demand in

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kWh m^{-3}. The latter relates mainly to the system hydrodynamics and the manner in which the technology is configured to overcome membrane fouling.

Landfill leachate, effluent arising from municipal solid waste management operations, represents one of the most recalcitrant effluents for biological treatment due to the generally low level of biodegradability as reflected in the BOD:COD ratio, i.e. the ratio of biochemical to chemical oxygen demand. For old landfill leachate, water which has undergone anaerobic decomposition for >5 years, this factor generally lies between 0 and 0.3 (2), as opposed to values of generally between 0.35–45 for municipal sewage (3). This means that MBRs can rarely achieve more than 80% COD removal for such effluents, compared with values generally exceeding 95% for sewage treatment (1). In addition, landfill leachate presents a significant challenge hydraulically; the fouling propensity of the biomass developed from landfill leachate feeds is such that the permeate flux can be as little as half that for sewage treatment (4).

Fouling in submerged MBRs can be meliorated by, amongst other things, increased aeration of the membrane (5, 6). However, this impacts directly upon specific energy demand. To counter this the aeration can be applied intermittently. Whilst this has been applied commercially on a 10s on-10s off cycle to an existing hollow fiber membrane, there are few examples of where the impact of aeration frequency has been examined for the better hydrodynamically-defined tubular membrane configuration. Vertically-aligned membrane multitubular modules permit air-lift operation under slug flow conditions, which has been shown to provide enhanced mass transfer compared to single-phase pumped flow (7–9).

This paper presents results of trials conducted using a polymeric multitube membrane module in an MBR challenged with both a sewage and a leachate feed. The membrane was operated as an air-lift sidestream with both continuous and intermittent aeration, the latter being applied over a range of frequencies (0.1, 0.5 and 1 Hz). The aim of the study was to establish the impact of intermittent aeration, and the frequency thereof, on hydraulic performance, and also assess the influence of feedwater quality on any changes noted.

EXPERIMENTAL

All studies were conducted on an 8 mm diameter tubular membrane of hydrophilicized PVDF (Norit, Enschede, the Netherlands) having the specification given in Table 1. This was mounted vertically external to a bioreactor (Fig. 1) comprising a *Perspex* cylindrical tank of 0.2 m internal diameter and 2 m total height, yielding a total volume of 45 L (Model products, Wootton). It was fed with either settled sewage from the Cranfield University sewage treatment works or "old" leachate collected from a local landfill site (Table 2), with similar bioreactor operating conditions being applied for each feedwater type (Table 3). The MBR was fitted with a submerged

Table 1. Membrane and module specification

Membrane material	Hydrophilicised polyvinylidene difluoride
Tube internal diameter, mm	8
Module length, mm	1000
No tubes	7
Total cross-sectional area, mm^2	352
Total membrane area, m^2	0.176

hollow fiber membrane for control of hydraulic retention time. Fine and coarse aeration were introduced from an oil-free supply at a constant rate of $5\,L \cdot min^{-1}$ and $15\,L \cdot min^{-1}$ respectively, the fine bubble aerator being placed at the base of the bioreactor and the coarse bubble aeration below the submerged module. Permeate was removed under suction using a peristaltic pump (Watson-Marlow Ltd, model *505 S*, Falmouth) connected to a module outlet. The submerged module was operated at a very low flux ($<7\,l\,m^{-2}\,hr^{-1}$, or LMH) with relaxation (i.e. cessation of permeation) for 2

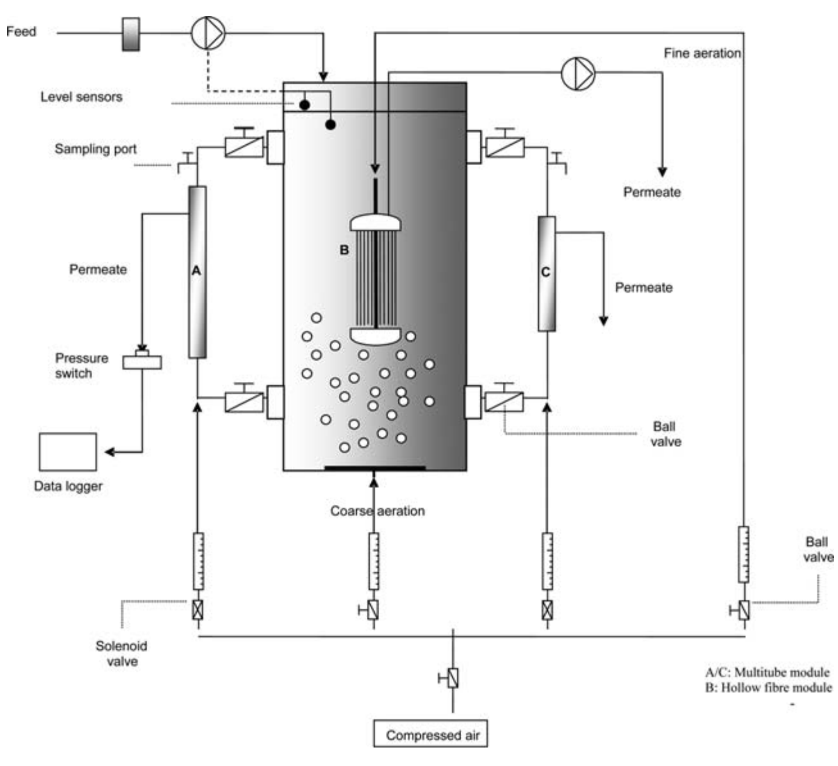

Figure 1. Experimental rig, schematic.

Table 2. Feedwater quality

	Mean		Minimum		Maximum	
Determinant	Sewage	Leachate	Sewage	Leachate	Sewage	Leachate
COD_{total} ($mg \cdot L^{-1}$)	250	2701	82	1560	478	4760
$COD_{soluble}$ ($mg \cdot L^{-1}$)	82	2225	13	1250	>150	3455
$BOD_{soluble}$ ($mg \cdot L^{-1}$)	78	125	4	106	178	134
Ammonia as NH_4 ($mg \cdot L^{-1}$)	28	756	0	505	>50	955
Conductivity ($\mu S.cm^{-2}$)	NA	25610	NA	21550	NA	29850
Carbohydrate ($mg \cdot L^{-1}$)	65	131	8	18	160	613
Protein ($mg \cdot L^{-1}$)	572	571	26	104	1300	1580

Table 3. Bioreactor operating conditions

	Sewage	Leachate
HRT, hr	8	120
SRT, d	30	30
MLSS, $g\,L^{-1}$	7–8.3	6.3–8.7
MLVSS, $g\,L^{-1}$	5.9–7.5	3.8–6
SMP, $mg\,L^{-1}$	118 ± 43	2,330 ± 500
EPS, $mg\,L^{-1}$	1.436 ± 75	923 ± 90

minutes every 7 minutes of filtration to ensure minimal fouling of the submerged module.

The HRT for the leachate feed was selected following scoping trials conducted using porous pots (biotreatment based on 4-litre permeable-barrier reactors). The latter indicated that nitrifiers were adversely affected by higher loading rates, such that the proportion of heterotrophs increased, possibly enhanced by increased levels of readily biodegradable carbon. The result was that COD removal remained roughly constant whilst ammonia removal decreases with decreasing HRT, from 99% and 10 days to 73% at 2 days (Table 4).

Continuous aeration of the tubular sidestream module was conducted at the same air flow rate throughout (Table 5). Intermittent aeration was via a solenoid valve fitted to the compressed air supply directly upstream of the module. The solenoid valve was used to adjust the intermittency of the aeration between 0.5 on/0.5 off (1 Hz) and 5s on/5s off (0.1 Hz), and permeability data compared with that obtained for continuous aeration. Permeate was again extracted via a peristaltic pump. Approach air velocity was measured with a rotameter tube; liquid air-lifted flow rate was recorded by temporarily diverting the retentate outlet to a measuring cylinder and recording the liquid volume carried over a set time period. The permeate pressure and flowrate were measured using a pressure transducer (RS, Corby) and liquid flowmeter (Patterson Scientific Ltd., Luton) respectively, and recorded on a personal computer via a data logger (*Pico System*, Pico technology Ltd., Cambridge).

Table 4. COD and ammonia removal, porous pot trials

HRT days	% COD removal	% NH_4^+ removal
10	58 ± 2	99 ± 1
5	69 ± 1	99.9 ± 0.1
3	45 ± 21	94 ± 3
2	52 ± 5	73 ± 22

Table 5. Operational condition parameters continuous aeration

Feed type	Q_G $m^3 \cdot h^{-1}$	Q_L $m^3 \cdot h^{-1}$	U_G $m \cdot s^{-1}$	U_L $m \cdot s^{-1}$	ε $U_G/(U_G + U_L)$
Sewage	0.2	0.11	0.28	0.15	0.7
Leachate	0.2	0.13	0.28	0.18	0.6

Tests were conducted using the standard flux step technique to study fouling rate (dP/dt) and permeability (K) as a function of flux (10). Fluxes were increased incrementally in units of either 3 or 6 LMH ($l\,m^{-2}\,bar^{-1}$) at 30 minute filtration periods. Data from continuous operation were used to identify the critical, or perhaps more accurately the sustainable, flux; all subsequent trials employing intermittent aeration were conducted under largely sub-sustainable flux conditions, as would be the case in practice. Modules were chemically cleaned between duplicate runs soaking for 24 hrs with a solution of 0.1 M NaOH at 50°C followed by another 24 hour soak in 0.1M HCl.

RESULTS

Averaged data from duplicate trials for fouling rate (dP/dt) and mean permeability ($(P_{init} + P_{end})/2J$) are respectively given for a continuous aeration in Figs. 2 and 3. As expected, the leachate biomass has a lower sustainable flux than the sewage biomass, and also a lower sustainable permeability of 180 vs. 280 LMH/bar (Fig. 3). The threshold flux appears to be around 36-42 LMH, the threshold value based on permeability being somewhat lower than that based on fouling rate, for sewage and ~24 LMH for leachate. All subsequent trials were conducted at fluxes between 6 and 33 LMH.

The impact of intermittent aeration is depicted in Figs. 4 and 5 for a sewage and leachate feed respectively. According to these trends, for both feedwaters the impact of a aeration low frequency (5s on/5s off, or 0.1 Hz) is to reduce K, whereas at higher frequencies (0.5 and 1 Hz), higher permeabilities than those recorded for continuous aeration are obtained. For both a sewage and leachate feed the highest permeability values were recorded at 0.5 Hz (1s on/1s off), with the highest frequency of 0.5 Hz yielding slightly lower permeabilities. This is almost certainly due to the downtime opening and closing the valve.

Data taken from Figs. 4 and 5 to provide the ratio of the permeability obtained for intermittent aeration to that for continuous aeration (Fig. 6) indicates that, below the threshold flux value (36 LMH for sewage and 24 LMH for leachate), the improvement if permeability is between 20 and 95%. The mean value for enhancement is 54% (±23%) for sewage and 49% (±14%) for leachate. It also appears that, in the case of leachate, the stabilised permeability region is extended to at least 33 LMH.

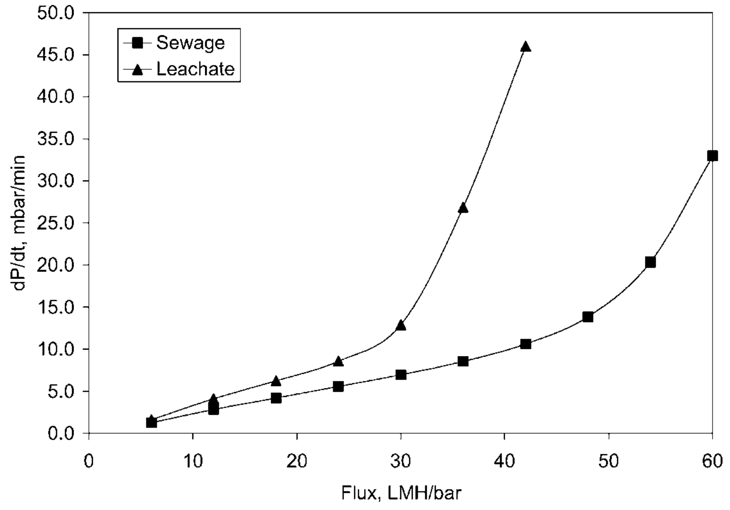

Figure 2. Fouling rate vs. flux for leachate and sewage biomass.

CONCLUSIONS

Over the range between 6 and 24 LMH, representing sub-critical operation for both feedwaters, the improvement in flux produced by intermittent operation at 0.5 Hz over that obtained from continuous operation is around 50% for both a leachate and sewage feed. Data suggests that intermittent operation extends

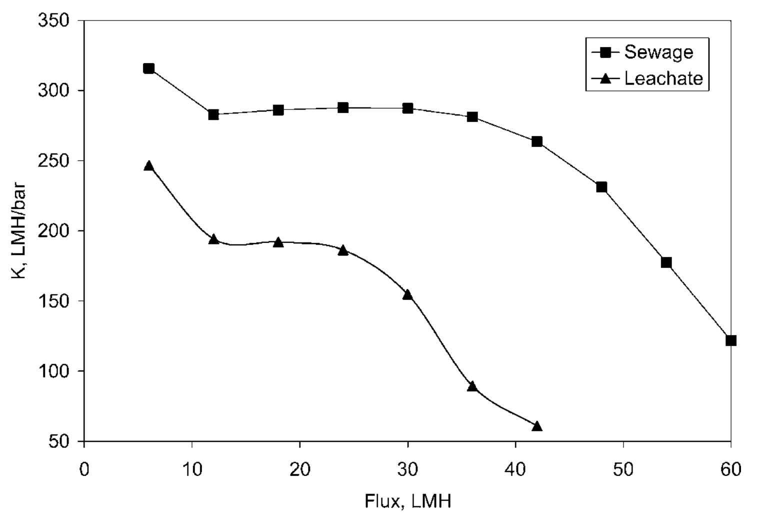

Figure 3. Permeability vs. flux for leachate and sewage biomass.

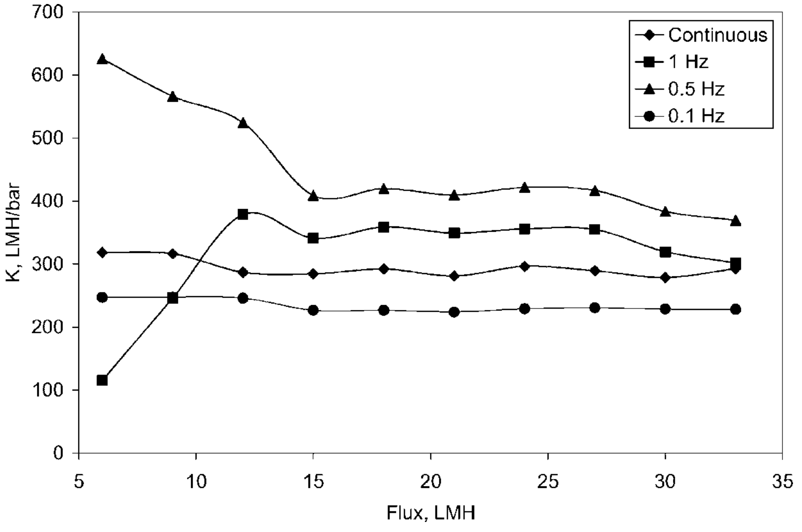

Figure 4. Impact of aeration frequency on permeability, sewage feed.

the range of sustainable flux operation of the MBR challenged with leachate from 24 LMH to at least 33 LMH in this case. Operation at very low frequencies, on the other hand, appears to be slightly detrimental to permeability; at a frequency of 0.1 Hz, or 5s on/5s off, resulted in a reduction of around 20% on the sub-critical permeability for both feedwater types.

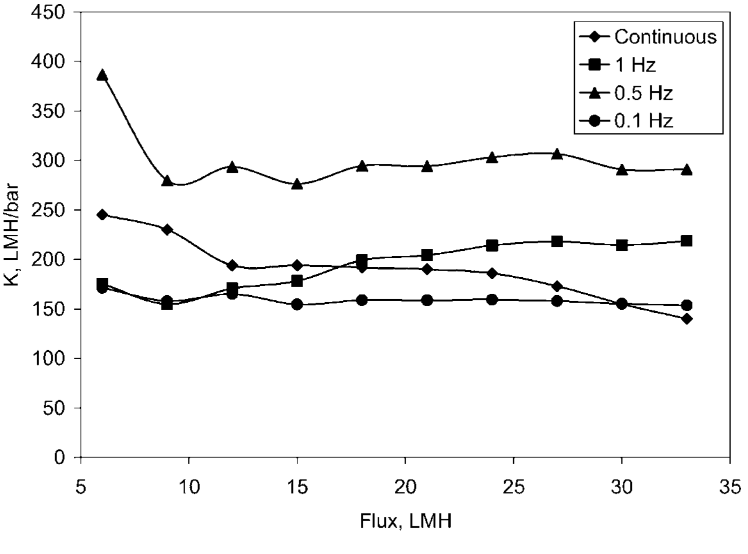

Figure 5. Impact of aeration frequency on permeability, sewage feed.

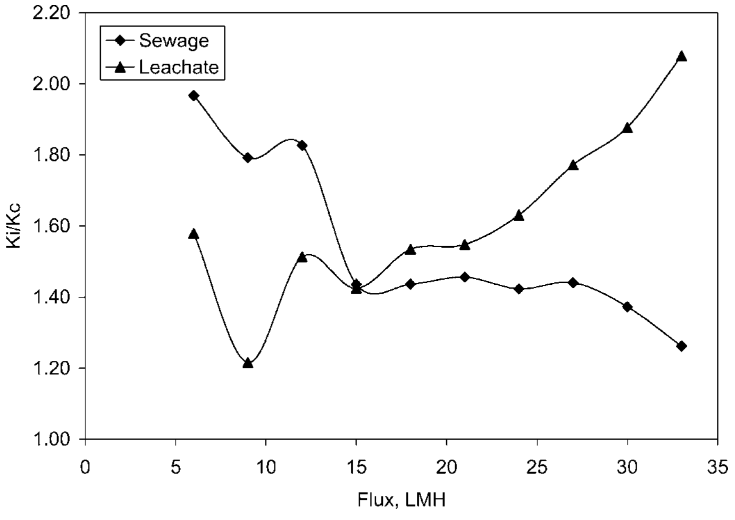

Figure 6. Ratio of permeability values for intermittent (K_i) and continuous (K_c) aeration at 0.5 Hz aeration frequency.

Results are of some practical significance. Intermittent aeration is currently conducted commercially on a leading submerged HF MBR product at a frequency of 0.05 Hz (i.e. 10s on/10 s off). The study indicates that operation at frequencies an order of magnitude higher yield significantly enhanced fluxes, regardless of the feedwater type. However, it should be noted that

a. the data refer to a multitube module, and
b. cost savings generated by reduced aeration demand may be offset by the considerably increased cost of installation and robust operation of the actuators and valves at these high frequencies.

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