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Identification of gas sparging regimes for granular anaerobic membrane bioreactor to enable energy neutral municipal wastewater treatment

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ABSTRACT

In this study, conventional and novel gas sparging regimes have been evaluated for a municipal wastewater granular anaerobic MBR to identify how best to achieve high sustainable fluxes whilst simultaneously conserving energy demand. Using continuous gas sparging in combination with continuous filtration, flux was strongly dependent upon shear rate, which imposed a considerable energy demand. Intermittent gas sparging was subsequently evaluated to reduce energy demand whilst delivering an analogous shear rate. For a flux of 5 $L\,m^{-2}\,h^{-1}$, a fouling rate below 1 $mbar\,h^{-1}$ was sustained with low gas sparging frequency and gas sparging rates. However, to sustain low fouling rates for fluxes above 10 $L\,m^{-2}\,h^{-1}$, a gas sparging frequency of 50% (i.e. 10 s on/10 s off) and an increase in gas sparging rate is needed, indicating the importance of shear rate and gas sparging frequency. An alternative gas sparging regime was subsequently tested in which filtration was conducted without gas sparging, followed by membrane relaxation for a short period coupled with gas sparging, to create a *pseudo* dead-end filtration cycle. Fouling characterisation evidenced considerable cake fouling rates of 200–250 $mbar\,h^{-1}$ within each filtration cycle. However, long term fouling transient analysis demonstrated low residual fouling resistance, suggesting the cake formed during filtration was almost completely reversible, despite operating at a flux of 15 $L\,m^{-2}\,h^{-1}$, which was equivalent or higher than the critical flux of the suspension. It is therefore asserted that by operating filtration in the absence of shear, fouling is less dependent upon the preferential migration of the sub-micron particle fraction and is instead governed by the compressibility of the heterogeneous cake formed, which enables higher operational fluxes to be achieved. Comparison of energy demand for the three gas sparging regimes to the energy recovered from municipal wastewater AnMBR demonstrated that only by using dead-end filtration can energy neutral wastewater treatment be realised which is the ultimate ambition for the technology.

1. Introduction

Electricity demand in the water industry accounts for 2–3% of national power production [1]. More than half of this demand is for aeration in activated sludge [2,3]. Anaerobic processes therefore present an attractive alternative to conventional aerobic domestic wastewater treatment since there is no aeration, less sludge production and energy can be recovered from the biogas formed [4,5]. The energy saved through aeration coupled with the potential for energy production, offers the prospect of energy neutral sewage treatment, which is the ultimate ambition for many advocates of this technology [6].

For municipal application, the main challenge for conventional anaerobic technology is preventing biomass washout [4]; an effect which is exacerbated at low temperature [7]. In anaerobic membrane bioreactors (AnMBRs), the membrane enables complete biomass retention, thereby facilitating the separation of hydraulic retention time (HRT) from solids retention time (SRT) [8–10]. Furthermore, membrane integration can deliver permeate compliant for chemical oxygen demand (COD) and suspended solids [10] in addition to a reduced biological oxygen demand (BOD_5). Whilst the membrane enables process intensification, the AnMBR matrix is concentrated, and considerably more heterogeneous than conventional aerobic MBR which increases fouling propensity and reduces the attainable flux [11]. As such fouling mitigation contributes over two-thirds of the overall energy demand for immersed AnMBR [12], which emphasises the need for fouling control strategies that limit AnMBR membrane fouling whilst conserving energy [5,13]. Our previous anaerobic research on municipal wastewater with an average temperature of 18 °C [14], demonstrated that 0.28 $kWh\,m^{-3}$ energy is recoverable from biogas and dissolved methane, which is comparable to the average energy production

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Nomenclature

A	membrane surface area [dimensionless]
AnMBR	anaerobic membrane bioreactor [dimensionless]
BOD_5	five-day biological oxygen demand [$mg\,L^{-1}$]
BSA	bovine serum albumin [dimensionless]
C_b	MLSS concentrations [dimensionless]
CGS	continuous gas sparging [dimensionless]
COD	chemical oxygen demand [$mg\,L^{-1}$]
COD_t	total chemical oxygen demand [$mg\,L^{-1}$]
CSTR	completely stirred tank reactor [dimensionless]
d_{50}	equivalent diameter corresponding to 50% of cumulative volume undersize [μm]
e	compressor efficiency, 0.70–0.90 [dimensionless]
DE	dead-end [dimensionless]
dP/dt	fouling rate [$mbar\,h^{-1}$]
G-UASB	granular upflow anaerobic sludge blanket [dimensionless]
HPLC	high performance liquid chromatography [dimensionless]
HRT	hydraulic retention time [dimensionless]
IGS	intermittent gas sparging [dimensionless]
J	permeate flux [$L\,m^{-2}\,h^{-1}$]
J_{20}	flux normalised to 20 °C
$J_{20\ net}$	net flux normalised to 20 °C
J_c	critical flux [$L\,m^{-2}\,h^{-1}$]
J_T	flux at T °C [dimensionless]
k	constant, k = 1.4 for nitrogen [dimensionless]
MBR	membrane bioreactor [dimensionless]
$M_{critical}$	critical mass [dimensionless]
MLSS	mixed liquor suspended solids [dimensionless]
n	constant [dimensionless]
P_1	inlet pressure [Pa]
P_2	outlet pressure [Pa]
P_a	the pressure required to obtain a specific cake resistance twice as high as α_0 [mbar]
P_{power}	power requirement [kW]
PVDF	polyvinylidene fluoride [dimensionless]
Q_w	wastewater flow [$m^3\,h^{-1}$]
r_f	cake fouling rate [$mbar\,h^{-1}$]
R	gas constant, 8.314 [$J\,K^{-1}\,mol^{-1}$]
R_{if}	internal residual fouling resistance [m^{-1}]
R_m	clean membrane resistance [m^{-1}]
R_{rvf}	reversible fouling resistance [m^{-1}]
R_t	total resistance [m^{-1}]
SCOD	Soluble chemical oxygen demand [dimensionless]
SGD_m	specific gas demand per unit membrane area [$m^3\,m^{-2}\,h^{-1}$]
$SGD_{m,\ net}$	net specific gas demand per unit membrane area [$m^3\,m^{-2}\,h^{-1}$]
SGD_p	specific gas demand per unit permeate [$m^3\,m^{-3}$]
SMP	soluble microbial production [$mg\,L^{-1}$]
SMP_p	protein concentration [$mg\,L^{-1}$]
SMP_c	carbohydrate concentration [$mg\,L^{-1}$]
SMP P/C	protein to carbohydrate ratio [dimensionless]
SRT	solids retention time [dimensionless]
t	filtered time [min]
T_1	temperature [K]
TMP	transmembrane pressure [mbar]
TMP_{ave}	average transmembrane pressure [mbar]
TMP_i	initial transmembrane pressure for each filtration cycle [mbar]
TMP_{max}	maximum transmembrane pressure [mbar]
TMP_t	transmembrane pressure at the end of dead-end filtration cycle [mbar]
UASB	upflow anaerobic sludge blanket [dimensionless]
VFA	volatile fatty acid [dimensionless]
V_{crit}	critical filtered volume [L]
W	specific energy demand [$kWh\,m^{-3}$]
w	weight of flow of gas [$kg\,s^{-1}$]

Greek letters

α	specific cake resistance [$m\,kg^{-1}$]
α_0	specific cake resistance at zero pressure [$m\,kg^{-1}$]
ΔTMP_c	pressure drop of cake layer [mbar]
$\Theta_{gs,f}$	gas sparging frequency [dimensionless]
$\theta_{gs,on}$	gas sparging on time [s]
$\theta_{gs,off}$	gas sparging off time [s]
μ	permeate viscosity [Pa s]
ρ_G	gas density [$kg\,m^{-3}$]
ω	solids concentration in the cake per unit filtrate volume [$kg\,m^{-3}$]

of 0.34 $kWh\,m^{-3}$ cited for AnMBR treating settled municipal wastewater in the literature [8,14–16]. For comparison, the specific energy demand for membrane operation of full-scale aerobic MBR is typically between 0.19 and 0.70 $kWh\,m^{-3}$ [17]. Consequently, the specific energy demand for AnMBR membrane operation must be towards the lower end of the energy demand range for conventional aerobic MBR to achieve energy self-sufficiency, despite operating in a more challenging matrix [11] (Fig. 1).

Immersed membranes are predominantly studied for inclusion within AnMBR due to their lower specific energy demand, with gas sparging employed for fouling mitigation [9,13,18]. Analogous gas sparging regimes to those of aerobic MBR are commonly employed in AnMBR studies, comprising of either continuous gas sparging (CGS) or intermittent gas sparging (IGS, 10 s on/10 s off) in which cycling enables analogous shear stress at the membrane wall, whilst enabling a 50% reduction in energy demand [4,5,8,15,19,20]. Several AnMBR studies have now evidenced that integrating immersed membranes within Upflow Anaerobic Sludge Blanket (UASB) configured AnMBR [5,11,21,22] develop less tenacious fouling than within Completely Stirred Tank Reactor (CSTR) configured AnMBR. The authors accounted for this by the considerably lower solids concentration developed within the membrane tank, which evidently limited cake layer growth at the membrane surface [9,22,23]. Using a UASB configured AnMBR, Martin Garcia et al. [5] undertook a preliminary investigation of an alternative gas sparging regime which comprised sequential filtration cycles without gas sparging, followed by a combination of

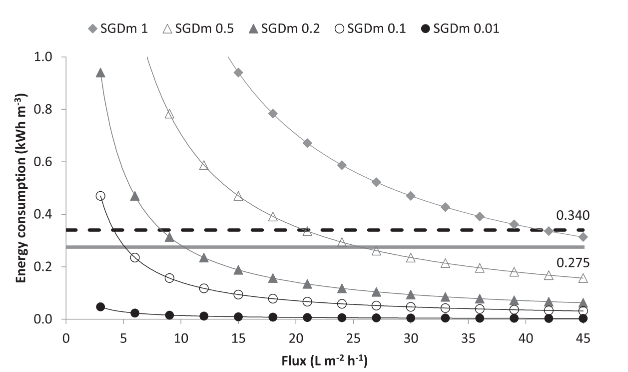

Fig. 1. Energy consumption of AnMBR for different fluxes and specific gas demand per unit membrane area (SGD_m). Data compared to energy recovered from this sewage using AnMBR (0.275 $kWh\,m^{-3}$, biogas from UASB and dissolved CH_4) [14]. Black break line illustrates average energy recovery from municipal AnMBR literature (0.34 $kWh\,m^{-3}$) [8,14–16].