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Recover energy from domestic wastewater using anaerobic membrane bioreactor: Operating parameters optimization and energy balance analysis

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A B S T R A C T

Anaerobic membrane bioreactor (AnMBR) is a promising process to recover energy and water resource from domestic wastewater; however, its energy-efficiency needs substantial improvement for real applications. In this study, based on the methanogenic activity batch tests and critical flux determination, an optimization protocol for AnMBRs is reported and a flux-centered energy balance analysis is conducted. The results demonstrate that organic loading rate by sludge (OLR_{sludge}) should be controlled within 0.43–0.90 kgCOD/(kgVSS·d), and the corresponding sludge retention time (SRT) should be in the range of 50 d to infinity. Energy balance analysis shows that the AnMBR systems at the temperature of 35 °C and 25 °C could achieve net energy recovery. For realizing energy-neutral operation, the corresponding fluxes should range from 8.3 to 9.5 L/(m^2·h) at 35 °C and 6.0 to 6.7 L/(m^2·h) at 25 °C, respectively. In the process design and operation, a relatively short hydraulic retention time (HRT) and an SRT close to 50 d should be considered in order to achieve an energy-efficient AnMBR performance.

1. Introduction

Water, food and energy shortages are three major challenges facing the world today [1,2]. To tackle these issues, recovering resources and energy from wastes and wastewater is a growing trend [3–6]. Domestic wastewater, traditionally considered as a waste, is now regarded as a resource, a resource for energy, fertilizer and water as well [6,7]. However, current municipal wastewater treatment plants (WWTPs) are mostly energy-intensive, produce large amount of residues and induce high carbon emissions [8,9]. Take US for example, the energy consumption for a WWTP using conventional activated sludge (CAS) treatment and anaerobic sludge digestion process is about 0.6 kWh/m^3 [7,10]. Thus, it is of great significance to develop new techniques to achieve resource recycling, energy recovery and low carbon emission.

In recent years, anaerobic treatment of domestic wastewater, being an energy-efficient alternative with low sludge production, has attracted much attention. Nevertheless, the major concerns with the conventional anaerobic bioreactors, such as completely stirred tank reactor (CSTR), upflow anaerobic sludge blanket (UASB) and expanded granular sludge bed (EGSB) reactors, are the slow growth rate of microorganisms and the unsatisfactory effluent quality [9]. Anaerobic membrane bioreactor (AnMBR) is a promising process as it can completely retain anaerobic microorganisms, produce a high-quality effluent and generate bioenergy to compensate the energy consumption of AnMBRs [7,11]. It is therefore thought to be a potential treatment process for domestic wastewater. However, in recent publications of AnMBRs, low organic loading rate (OLR), low membrane flux, severe membrane fouling and inefficient energy recovery are regarded as barriers hindering their applications to domestic wastewater treatment [11,12]. As for membrane fouling, biogas sparging is widely regarded as an effective strategy [13,14], whereas it also requires a large amount of energy input. According to a previous report [15], specific gas demands (SGD) ranging from 0.4 to 3.0 m^3/(m^2·h) are equivalent to energy demands of 0.69–3.41 kWh/m^3 through theoretical modeling in lab-scale AnMBRs. Temperature control and parameters optimization are also common approaches to alleviate membrane fouling and improve energy efficiency [12,16]. Martinez-Sosa et al. [17] reported that the membrane fouling rate was 2.61 mbar/d at 20 °C, which was much higher than that at 35 °C (0.14 mbar/d). Meanwhile, the methane yield was also higher under

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Abbreviations and symbols

A_m	membrane area
AnMBR	anaerobic bioreactor
b	decay rate
BMP	biochemical methane potential
CAS	conventional activated sludge
COD	chemical oxygen demand
C_0, C_e	influent COD, effluent COD
CSTR	completely stirred tank reactor
EGSB	expanded granular sludge bed
E_B	energy demand for blender
E_G	energy demand for membrane scouring
E_H	energy demand for heating devices
E_P	energy demand for influent, effluent and sludge circulation pumps
F/M	food-to-microorganisms ratio
HRT	hydraulic retention time
J	operating flux
J_c	critical flux
MLSS, X	mixed liquid suspended solid
MLVSS	mixed liquid volatile suspended solid
OLR	organic loading rate
$\text{OLR}_{\text{sludge}}$	organic loading rate by sludge
$\text{OLR}_{\text{volume}}$	organic loading rate by volume
PVDF	polyvinylidene fluoride
Q	treatment capacity per day
SGD, SGD_m	specific gas demands by membrane area
SMA	specific methanogenic activity
SRT, θ_c	sludge retention time
TMP	transmembrane pressure
UASB	upflow anaerobic sludge blanket
V	effective volume of the reactor
WWTPs	wastewater treatment plants
Y	net biomass yield coefficient

mesophilic conditions than that under psychrophilic conditions [14,17]. Although the above-mentioned research efforts are very helpful to improve AnMBR performance, a full understanding on how to optimize operating parameters for maximizing energy recovery is insufficient.

The objective of this study is, therefore, to optimize process parameters for AnMBR systems to maximize the energy recovery from methane production and minimize the energy consumption associated with the operation. Based on methanogenic activity and critical flux measurements, a flux-centered energy balance analysis was carried out to examine the energy recovery potential of AnMBRs. The obtained results are expected to facilitate the design and operation of AnMBRs, and to push forward AnMBR applications to domestic wastewater treatment.

2. Materials and methods

2.1. AnMBRs

The submerged AnMBR used in this study is shown in Fig. 1. The system consisted of a 15 L anaerobic reactor and a 16 L membrane tank, in which three flat-sheet membrane modules were installed. The membranes were made from polyvinylidene fluoride (PVDF) material with a mean pore size of 0.2 μm, provided by Shanghai Zizeng Environmental Technology Co. Ltd. (China). The total effective filtration area was 0.735 m^2. Three peristaltic pumps were used to feed influent into the anaerobic reactor, recycle mixed liquor from the anaerobic reactor to the membrane tank and to extract permeate from the membranes. A diaphragm gas pump (N810 FT.18, KNF, Germany) was used to recirculate biogas from the head space to the biogas diffuser located at the bottom for scouring membranes. A gas flow meter was used for regulating the gas intensities and a heating device installed for controlling temperature. The reactor was fed with domestic wastewater from a wastewater treatment plant in southern China. The AnMBR had been continuously operated for about 1 year prior to this study.

2.2. Specific methanogenic activity (SMA) batch tests

SMA (Specific methanogenic activity) tests were carried out to evaluate the influence of different food-to-microorganisms (F/M) ratios on anaerobic biomass activity. The sludge samples were taken from the submerged AnMBR as mentioned above. Prior to SMA tests, sludge samples were washed with deionized (DI) water 3 times, centrifuged at 1000 g for 10 min to remove the external substrate, and resuspended in DI water. Nutrients were added according to a previous publication [18]. A series of F/M ratios ranging from 0.20 to 1.30 kgCOD/kgVSS were tested and each was measured in triplicate. During the batch tests, temperature was controlled at 35 °C and agitating speed was set at 125 rpm. Biogas composition (CH_4 and CO_2) was measured using a gas chromatography (6890N, Agilent, U.S.) equipped with a thermal conductivity detector (TCD). The SMA (mL/(gVSS·d)) was calculated by dividing the volume of methane produced per unit time (maximum slope of cumulative methane as a function of time) by the initial weight of VSS (g) in the SMA bottles.

To obtain the methane production potential (also termed biochemical methane potential, BMP) under different F/M ratios, a modified Gompertz three-parameter model (Eq. (1)) [19,20] was used to simulate the experimentally observed cumulative methane production curves.

$$M(t) = P \times \exp\left\{ -\exp\left[\frac{R_{\max} \times e}{P} \times (\lambda - t) + 1\right]\right\} \tag{1}$$

where $M(t)$ is the cumulative methane production (mL/gVSS) at time t (d), P is the ultimate methane yield (mL/gVSS), $R_{\max}$ is the maximum methane production rate (mL/gVSS·d), and λ is the lag phase (d). P, $R_{\max}$ and λ were estimated by non-linear curve-fitting with minimum residual method using SigmaPlot 12.0 (Systat Software Inc.).

2.3. Critical flux determination

To determine critical fluxes (J_c) of the AnMBR under different operating conditions, the flux-step method [21–23] was used with a step length of 15 min and a flux-step height of 2 L/(m^2·h). J_c was calculated by averaging two permeate flux values: the flux at which the transmembrane pressure (TMP) began to increase perceptibly over one step length and the previous value at which TMP did not change.

The orthogonal experiment was designed to determine the critical flux under various operating conditions, considering temperature, biogas sparging intensity and MLSS as three main factors. The $L_8(4^1 \times 2^4)$ orthogonal array was chosen in this study according to the statistical theory [24], and the factors and their