Submerged anaerobic membrane bioreactor for wastewater treatment and energy generation

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ABSTRACT

Compared with conventional wastewater treatment processes, membrane bioreactors (MBRs) offer several advantages including high biodegradation efficiency, excellent effluent quality and smaller footprint. However, it has some limitations on account of its energy intensive operation. In recent years, there has been growing interest in use of anaerobic membrane bioreactors (AnMBRs) due to their potential advantages over aerobic systems, which include low sludge production and energy generation in terms of biogas. The aim of this study was to evaluate the performance of a submerged AnMBR for the treatment of synthetic wastewater having 4,759 mg/l chemical oxygen demand (COD). The COD removal efficiency was over 95% during the performance evaluation study. Treated effluent with COD concentration of 231 mg/l was obtained for 25.5 hours hydraulic retention time. The obtained total organic carbon concentrations in feed and permeate were 1,812 mg/l and 89 mg/l, respectively. An average biogas generation and yield were 25.77 l/d and 0.36 m³/kg COD, respectively. Evolution of trans-membrane pressure (TMP) as a function of time was studied and an average TMP of 15 kPa was found suitable to achieve membrane flux of 12.17 l/(m² h). Almost weekly back-flow chemical cleaning of the membrane was found necessary to control TMP within the permissible limit of 20 kPa.

INTRODUCTION

Over the years, availability of water has been declining and a need for wastewater treatment with a recycling option is gaining importance. There are a number of newer treatment technologies that have come into practice in recent times. The membrane bioreactor (MBR) is one such technology, which combines biological activated sludge process with membrane filtration, eliminating the operational issues associated with gravity separation (Melin et al. 2006; Judd 2008; Gao et al. 2010a). The MBR is now a proven and popular technological solution for the efficient treatment of industrial and municipal wastewater (Kang et al. 2002; Meng et al. 2009; Kanai et al. 2010). However, membrane fouling, an intrinsic phenomenon linked to MBR operation, requires chemical cleaning and operational downtime periods, one of the major drawbacks of this technology (Herrera-Robledo et al. 2011). Generally, air scouring is used to control the fouling; however it increases the operating cost of the system. Compared to the aerobic counterparts, the costs of aeration and sludge handling in anaerobic treatment are dramatically lower as no oxygen is needed and sludge yield is lower (Lin et al. 2011). However, the effluent quality in anaerobic treatment is poorer compared to aerobic treatment.

An anaerobic bioreactor coupled with a membrane unit is phrased as anaerobic membrane bioreactor (AnMBR) and could be an effective solution to address challenges faced in conventional anaerobic systems. Unlike the conventional single-stage anaerobic reactor, a membrane-coupled system facilitates independent control of hydraulic and solid retention within the reactor. Such a system can withstand higher organic loading rate (OLR) and operating biomass concentration (Bornare et al. 2014). The AnMBRs are also expected to provide more efficient digestion, higher methane production and better effluent quality, and can be smaller in size than conventional anaerobic digesters (Padmasiri et al. 2007). Most of the AnMBRs in wastewater treatments have
used the external configuration although over the last few years, there has been increased research into submerged AnMBRs (Hu & Stuckey 2006; Jeison & van Lier 2008).

The objective of this study was to evaluate the performance of a submerged AnMBR for medium-strength synthetic wastewater treatment. A laboratory-scale 19 l AnMBR was used for this purpose. The performance was evaluated in terms of organic removal efficiency, biogas generation, biogas yield and membrane filtration.

MATERIALS AND METHODS

Wastewater characteristics

A synthetic wastewater representing medium-strength industrial effluent consisting of dextrose monohydrate and other nutrients was used for this study. The synthetic wastewater comprised dextrose monohydrate (5,000 mg/l), urea (210 mg/l), di-ammonium phosphate (106 mg/l), NaCl (1,200 mg/l), MgCl₂ (600 mg/l), CaCl₂ (160 mg/l), MnSO₄ (20 mg/l), FeSO₄ (20 mg/l) and NaHCO₃ (300 mg/l).

Experimental setup

The laboratory scale setup used for this study comprises a bioreactor with related accessories and a membrane filtration system. A schematic diagram of the submerged AnMBR is shown in Figure 1.

Bioreactor with related accessories

The total and effective volumes of the bioreactor were 19 l and 17 l, respectively. A fraction of space from the total volume of the bioreactor was dedicated for biogas collection, reducing the effective volume. The bioreactor was made up of an acrylic cylindrical shell. The vertical height and internal diameter of the shell were 420 mm and 240 mm, respectively.

The bioreactor was equipped with a pH probe (Hanna Instruments), a resistance temperature detector series temperature sensor, a level switch (model: FGSI-P11CO1WWW, make – Pune Techtril, Bhosari, India) and a rod-type 1.5 kW electrical heater. A drain port and a sampling port were provided to the bioreactor as shown in Figure 1. A part of the head space biogas was purged in the bioreactor using a KNF vacuum diaphragm pump (model: N838 KNE) for membrane scouring. A rotameter supplied by Eureka Industrial Equipments Pvt., Limited, Bhosari, India (model: CIVF-PG-4) was used for measuring the flow rate of biogas purged for membrane scouring. A varying volume gas dome arrangement (inverted acrylic cylinder) was used for biogas storage.

Membrane filtration system

A microfiltration membrane element (model: SADFM0790A, material of construction – polyvinylidene difluoride, pore size – 0.4 μm, fiber outside diameter – 2.8 mm, area of the element – 0.073 m²) supplied by Mitsubishi Rayon Corp.
Japan was used in this study. A KNF make liquid vacuum pump (model: NF 10 KPDC) was used as the permeate pump. A pressure gauge was installed on the permeate line to indicate the negative pressure applied by the pump. A rotameter (model: SSRS-MGS-5) supplied by Eureka Industrial Equipments Pvt., Limited, Bhosari, India, was installed in the discharge line of the permeate pump to measure the flow rate of the permeate. The provision for recycling the excess permeate back to the reactor was available in the setup.

AnMBR operation and operating conditions

The AnMBR was in operation for the treatment of a similar wastewater before starting this study. A hollow-fiber membrane module was removed from the bioreactor and washed chemically (immersion for 12 hours in sodium hypochlorite solution having 3,000 mg/l effective chlorine) before starting the experiment.

Synthetic feed solution with targeted chemical oxygen demand (COD) concentration of 5,000 mg/l was prepared in the feed tank on a daily basis. Hydraulic retention time (HRT) of 25.5 hours was maintained constant throughout the study. The permeate flux was set at 12.17 l/(m² h) (LMH) and kept constant throughout the study. The solenoid valve fitted on the feed line was operated as per the signals received from the level switch fixed in the bioreactor, and feed flow was controlled. The AnMBR was allowed to stabilize to the new organic load before starting the performance evaluation study. The trans-membrane pressure (TMP) was monitored regularly and adjusted periodically within allowable limits in order to regulate the required permeate from the membrane. The permeate pump was programed to switch ON and OFF for 3 minutes and 1 minute, respectively. The biogas recycle flow for membrane scouring was set at 1,000 l/h. The operation of the biogas recycle pump was intermittent and ON-OFF timings were similar to permeate pump. The sludge was withdrawn from the bioreactor on a daily basis to keep the mixed liquor suspended solids (MLSS) concentration in the range from 12,000 to 12,500 mg/l and mixed liquor volatile suspended solids (MLVSS) concentration in the range from 686 mg/l and 231 mg/l, respectively. Even though targeted concentrations in feed, bioreactor and permeate were 4,759 mg/l, 686 mg/l and 231 mg/l, respectively. Even though targeted COD for the feed was 5,000 mg/l, measured COD for the feed solution was always less than targeted. This could be

flow chemical cleaning of the membrane. Normal filtration operation was stopped during back-flow chemical cleaning of the membrane.

Analysis

The samples from the feed tank, bioreactor and permeate flow were collected for the measurement of pH and COD on a daily basis; however, total organic carbon (TOC) analysis was carried out periodically. The bioreactor content was analyzed periodically for MLSS and MLVSS.

COD, MLSS and MLVSS were measured according to Standard Methods (APHA et al. 2005). TOC analysis was carried out with a Shimadzu TOC analyzer (model: TOC VCPH). TMP was recorded from the pressure gauge fixed on the permeate line of the membrane. Analysis of the generated biogas for methane composition was carried out periodically using a Thermo Fisher Scientific gas chromatography (Chemito, Ceres 800 plus) fitted with a TG-WAXMS column (30 m × 0.25 mm × 0.25 μm) and a flame ionization detector. Nitrogen gas was used as a carrier gas, while the temperatures of the oven, injector port and the detector were 50 °C, 100 °C and 100 °C, respectively. Biogas generation was measured through rise in the height of the floating dome used for gas storage.

RESULTS AND DISCUSSION

The performance evaluation of the submerged AnMBR was started after stabilization of the biological activity in the bioreactor. Fairly constant output was achieved during stable biological operation of the bioreactor. The biological stability was assumed to be reached when fairly constant pH and COD for bioreactor content as well as permeate were attained. The average pH of the feed, bioreactor content and permeate were 7.35, 7.1 and 7.05, respectively. Lower pH of the bioreactor and permeate sample was expected than the feed because of acids formed during anaerobic treatment in the bioreactor.

Organic removal performance

Figure 2 shows evolution of concentrations of COD in the bioreactor effluent and permeate. The average COD concentrations in feed, bioreactor and permeate were 4,759 mg/l, 686 mg/l and 231 mg/l, respectively. Even though targeted COD for the feed was 5,000 mg/l, measured COD for the feed solution was always less than targeted. This could be
on account of natural slow degradation of the organics available in the feed. The feed flow rate was 16 l/d corresponding to an OLR of 4.5 kg COD/(m³ d), kept constant for throughout the study.

Since there was considerable difference in concentrations of COD for reactor content and permeate, the used microfiltration membrane might be rejecting a considerable amount of organics available in the reactor during filtration. High concentration of organics in the reactor content may have an adverse impact on membrane fouling and can be rectified by improving the organic degradation rate in the bioreactor. Hu & Stuckey (2006) reported bioreactor COD to be more than three times higher than the permeate obtained during treatment of dilute wastewater using a submerged AnMBR with 0.4 μm pore size membrane.

COD removal performance of the AnMBR varied from 94.8 to 95.5% as shown in Figure 2 and average COD removal was 95.14%. No shock loading and optimum process parameters could be the main reasons for stable organic removal performance of the AnMBR. The obtained organic removal performance of the submerged AnMBR was comparable with the reported literature of Lin et al. (2013). Bohdziewicz et al. (2008) reported 90% COD removal in AnMBR treating leachate diluted with synthetic wastewater at HRT of 2 days and OLR of 2.5 kg COD/(m³ d). Xie et al. (2010) operated a submerged AnMBR at 37 ± 1 °C to treat kraft evaporator condensate and reported a COD removal efficiency of 93–99% for the OLR of 1–24 kg COD/(m³ d). Gao et al. (2010b) investigated thermo-mechanical pulp whitewater treatment with a submerged AnMBR at an average OLR of 2.4 kg COD/(m³ d) and achieved steady-state COD removal efficiency of about 90%, yielding an effluent with COD less than 300 mg/l.

The organic strength of the feed and permeate was represented by an average TOC concentration of 1,812 mg/l and 89 mg/l, respectively. Figure 3 shows evolution of concentrations of TOC in feed and permeate collected during the study. The average TOC removal efficiency of the AnMBR was 95% and overall TOC removal performance was very similar to COD removal performance of the AnMBR.

**Biogas generation and yield in AnMBR**

After stabilization of biological performance, the biogas generation and yield were as indicated in Figure 4. Biogas generation varied from 24.8 to 26.6 l/d with average biogas generation of 25.77 l/d. The biogas generation was very consistent after stabilization of the bioreactor and it shows the robustness of the anaerobic process at optimum, constant operating parameters.

The average biogas yield for AnMBR during the complete study was estimated to be 0.36 m³/kg COD removed. The biogas yield for anaerobic treatment depends upon the nature of influent and generally ranges from 0.2 to 0.4 m³/kg COD removed for upflow anaerobic sludge blanket systems. Bohdziewicz et al. (2008) observed the biogas yield to be in the range 0.45 to 0.5 m³/kg COD removed.
for the treatment of leachate diluted with synthetic wastewater using anaerobic MBR. Methane content in generated biogas was found to vary from 57% to 72%.

**Biomass concentration in AnMBR**

The solid retention time (SRT) in the bioreactor was maintained at 220 days. SRTs in the range from 30 to 300 days are very common in AnMBR systems (Dereli et al. 2012). In fact, high SRT is always preferable to minimize the sludge generation. However, long SRT may have an adverse effect on methanogenic sludge activity, reducing viable micro-organism concentration. Jeison & van Lier (2006) reported the impact of sludge concentration on critical flux in an AnMBR and lower flux rates were obtained at increasing sludge concentration. The ratio of average MLVSS to average MLSS in the bioreactor was 0.66 and it was almost the same for throughout the study.

**Membrane filtration performance of AnMBR**

The TMP was daily monitored and adjusted within allowable limits to regulate the required permeate flow from the system. As per operating guidelines from the membrane supplier, the maximum allowable TMP was 20 kPa for the membrane used in the study. Figure 5 shows evolution of TMP throughout the study.

Almost weekly back-flow chemical cleaning was found useful in reducing fouling of the membrane and reducing TMP to the lowest level. Figure 5 shows the reduction in
TMP immediately after weekly chemical cleaning of the membrane. In the initial phase of the study, the TMP build-up after back-flush chemical cleaning was at slower rate whereas in the later phase of the study, the TMP build-up was faster and therefore chemical cleaning frequency was higher in this phase. As shown in Figure 5, the TMP varied from 8 to 20 kPa during the study and the average TMP maintained across the membrane was 15 kPa. Generally, the flux and operating TMP for a submerged MBR are much lower than for an external MBR. The obtained data for flux and TMP closely matches that reported by Hu & Stuckey (2006). Lin et al. (2011) obtained a filtration flux of 15 LMH for a flat sheet microfiltration membrane used in a submerged AnMBR treating municipal wastewater at 30 °C. Xie et al. (2010) observed a flux in the range from 5.6 to 12.5 LMH for a flat sheet microfiltration membrane used in a submerged AnMBR treating kraft evaporator condensate with less than 0.3 bar TMP. The present study indicated that such type of membrane can satisfactorily perform the filtration operation without in-line chemical cleaning for 2 months. Outside immersion cleaning was provided to the membrane module at the end of the study.

CONCLUSIONS

During long-term performance evaluation of a submerged AnMBR at fixed HRT of 25.5 hours and 37 °C temperature, treated effluent with 231 mg/l COD was obtained for the feed COD of 4,759 mg/l. A residual concentration of TOC in permeate was 89 mg/l for feed TOC of 1,812 mg/l. An average biogas generation of 25.77 l/d and biogas yield of 0.36 m³/kg COD removed were obtained during the study. The maintained 220 days SRT in the bioreactor resulted in MLVSS to MLSS ratio of 0.66 and achieved more than 95% organic removal efficiency in the submerged AnMBR. An average TMP of 15 kPa was maintained during the performance evaluation study. Almost weekly back-flush chemical cleaning of the membrane was found necessary to control the TMP within the permissible limit of 20 kPa. It has been observed that the membrane can satisfactorily perform the filtration operation without in-line chemical cleaning for 2 months.

REFERENCES


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