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Review

Recent developments in anaerobic membrane reactors

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HIGHLIGHTS

- ▶ Anaerobic membrane reactors (AnMBRs) can achieve high COD removal (98%) at 3 h HRTs.
- ▶ No understanding of the effect of reactor operation on SMP production and fouling.
- ▶ Addition of PAC and precipitants can reduce fouling in anaerobic membrane reactors.
- ▶ Membranes can enhance performance at extreme temperatures and toxins/shock loads.
- ▶ Robust pilot plant data on energy use and solids production is needed for AnMBRs.

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ABSTRACT

Anaerobic membrane reactors (AnMBRs) have recently evolved from aerobic MBRs, with the membrane either external or submerged within the reactor, and can achieve high COD removals (~98%) at hydraulic retention times (HRTs) as low as 3 h. Since membranes stop biomass being washed out, they can enhance performance with inhibitory substrates, at psychrophilic/thermophilic temperatures, and enable nitrogen removal via Anammox. Fouling is important, but addition of activated carbon or resins/precipitants can remove soluble microbial products (SMPs)/colloids and enhance flux. Due to their low energy use and solids production, and solids free effluent, they can enhance nutrient and water recycling. Nevertheless, more work is needed to: compare fouling between aerobic and anaerobic systems; determine how reactor operation influences fouling; evaluate the effect of different additives on membrane fouling; determine whether nitrogen removal can be incorporated into AnMBRs; recover methane solubility from low temperatures effluents; and, establish sound mass and energy balances.

1. Introduction

Anaerobic bacteria grow very slowly due to their low energy yields per gram of substrate, and hence efficient reactor design needs to separate hydraulic retention time (HRT) from the solids retention time (SRT). In recent years there has been increasing pressure on designing anaerobic reactors that not only have very short HRTs, but also reduce the footprint of the process by intensifying or combining unit operations-this has led to the development of the anaerobic membrane reactor (AnMBR) which incorporates solids removal and COD reduction in one reactor. This design has evolved from aerobic membrane bioreactors (AMBRs) which are more developed, but have obvious drawbacks such as; high energy use and solids yields, and emission of greenhouse gases (GHG) such as carbon dioxide and nitrous oxide (if nitrifying/denitrifying). Hence, there is increasing interest in AD due to these concerns, and also that AnMBRs enhance water and nutrient (nitrogen and phosphorus) recycling possibilities. The AnMBR can now be operated at very low HRTs 3 h- (Hu and Stuckey, 2006), and produces a solids free effluent with high COD removals due to the retention of slowly degradable organics within the reactor. In addition, it can retain slow growing bacteria which would be normally washed out of many reactors, and enable these bacteria to grow and persist under unfavourable conditions, e.g., under high salinity (Vyrides and Stuckey, 2009a).

This article will review recent progress in anaerobic membrane bioreactors, and build on the good and comprehensive reviews in the past on AnMBRs by Liao et al. (2006), and permeate flux and fouling in AnMBRs by Berube et al. (2006) and Liao et al. (2004). In addition, Meng et al. (2009) carried out a recent review of the literature on membrane fouling and materials in both AMBRs and AnMBRs. Given these recent and extensive reviews, especially in the area of fouling, this review will focus on recent advances in anaerobic membrane bioreactors, and on specific areas and

Abbreviations: AnMBR, anaerobic membrane reactor ; SRT, solids retention time; HRT, hydraulic retention time; SMPs, soluble microbial products; PAC, psychrophilic powdered activated carbon; ECPs, fouling, extracellular polysaccharides.

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questions such as the role of SMPs in membrane fouling, and fouling amelioration using additives such as powdered activated carbon (PAC) and polymers/metal salts/biopolymers, while drawing on work on both AMBRs and AnMBRs in these past reviews.

2. Membrane configuration

2.1. Pressure-driven external cross-flow membrane

Combining anaerobic reactors and membranes can be done primarily in three different ways. In the first way, the membrane is outside the reactor which makes membrane cleaning and replacement simple, but involves an external pump which circulates the biomass at quite high velocities (2–4 m s^{-1}), thereby scouring the membrane surface to reduce membrane fouling. This also provides high pressure to force the liquid through the membrane. While high fluxes result (60 L per square meter per hour- LMH), the energy costs are high, and it is clear that some pump types (e.g., rotary) lead to floc and cell shear with a decrease in overall particle size, and an increase in soluble organics (Kim et al., 2001), and this has also been shown to happen in aerobic systems (Wisniewski and Grasmick, 1998). The correlation between aerobic and anaerobic membrane behaviour is not clear at this point, but they seem to behave in similar ways, at least at the macroscale. This reduction in particle size and increase in soluble organics in turn leads to rapidly reducing fluxes. However, until recently there been disagreement in the literature about the effect of sidestream pumping and shear on methanogenic activity.

The initial work on the question of pump shear on methanogenic activity was by Brockman and Seyfried (1996). These authors showed that increasing recycle resulted in reducing substrate specific sludge activities assays (ml CH_4 g $MLSS^{-1}$ h^{-1}), and a 50% loss of activity was observed after only recirculating the biomass 20 times through the external membrane unit, while 100 cycles resulted in 90% loss of activity. They postulated that this loss in activity was due to a reduction in floc size which in turn impaired the syntrophic association between acidogenic and methanogenic bacteria. In terms of floc size distribution, Wisniewski and Grasmick (1998) showed with aerobic sludge that increasing velocities in the membrane unit resulted in substantial reductions in floc size, and this was confirmed by Choo and Lee (1998) who showed that after only 12 d of recirculation the average floc size dropped from 16 to 3 μm, and that there was an increase in the amount of colloidal particles; over this time there was also a 4fold decrease in flux to 10 LMH, although there was little decrease in performance. Hence, it appears that a reduction in floc size is not *a priori* evidence that the symbiotic association is still not functioning. Yang et al. (2011) found recently that even when floc sizes decreased to less than 5 μm during high shear, COD removals were still similar to the control. Kim et al. (2001) also found that the type of pump on the recycle of an aerobic reactor made a big difference-with a rotary pump resulting in a far higher shear on the flocs than a centrifugal one, and a reduction in the SOUR of 22% compared to none with the centrifugal pump. Whether these results can be extrapolated to anaerobic systems is not known, but clearly pump type could have a large impact on anaerobic systems.

Finally, Padmasiri et al. (2007) explored this question in some depth using swine manure with a crossflow external membrane module with velocities up to 2 m s^{-1}. The reactor started up successfully at an initial loading rate of 1 g VS L^{-1} d^{-1}. After doubling the loading rate and flow velocity on day 75, performance deteriorated. The dynamics of the methanogenic population in the reactor was monitored with terminal restriction fragment length polymorphism (T-RFLP). Relative changes in levels of *Methanosarcinaceae* and *Methanosaetaceae* correlated well with changes in VFA concentrations, i.e., high and low levels of acetate correlated with a high abundance of *Methanosarcinaceae* and *Methanosaetaceae*, respectively. The concentrations of hydrogenotrophic methanogens (*Methanomicrobiales*) increased during reduced reactor performance suggesting that syntrophic interactions involving hydrogenotrophic methanogens were still maintained regardless of the shear rate in the AnMBR. They concluded that decreasing reactor performance was due to an increase in the rate of hydrolysis caused by increased shear and mixing, and that this lead to an increase in VFAs overwhelming the methanogens. While this seems plausible, it is not clear whether the presence of insoluble and non-biodegradable fibres in the pig slurry may ameliorate the effect of shear, and preserve the microbial consortia. It appears that shear itself may inhibit methanogens by increasing cell lysis and enhance both extracellular polysaccharide (ECP) and soluble microbial products (SMPs) release. However, it is clear that external membrane modules have some drawbacks despite their high fluxes and convenience in terms of cleaning and replacement (Jeison et al., 2009). Nevertheless, this issue would become clearer if definitive measurements of shear were made on both small and large scale reactors-the latter often having lower shear rates due to their size and geometry.

2.2. Vacuum-driven submerged membrane immersed directly into the reactor

The second way of operating these reactors is to use a vacuum (or even hydrostatic head) to draw the effluent through the membrane. Despite this being a common method in aerobic treatment, e.g., Kubota plant, there have not been many examples of this type of setup in use. In addition, the membrane can either be immersed in the reactor tank itself (submerged anaerobic membrane bioreactor-SAMBR), or in a separate reactor, which requires a pump, but the flow is not through a module. This type of setup is used in many aerobic plants, e.g., GE-Zenon, since it is easier to clean the module.

The advantages of having the membrane submerged in the reactor is that the energy required for pumping is eliminated, although biogas needs to be recycled from the headspace to underneath the membranes to provide gas bubble shear to keep the membranes relatively clear from fouling (Vyrides and Stuckey, 2009a). In addition, the biomass in the reactor is subjected to less severe shear than in a sidestream membrane unit, and hence based on the previous discussion the biomass should be less stressed. However, in most designs this would lead to lower shear rates, and hence lower fluxes. This in turn would lead to greater installed membrane areas, although lower operating expenses. Finally, the capital cost would probably be lower since external modules and pumps are not required, although the installed membrane area would probably increase. A little work was done in the 80s and 90s, however, it is only recently that more literature on the submerged configuration has been published, and this will be discussed in more detail later (Hu and Stuckey, 2006; Van Zyl et al., 2008; Akram and Stuckey, 2008a; Jeison and van Lier, 2008; Walker et al., 2009).

Kim et al. (2011) controlled fouling by placing membranes directly in contact with GAC in a novel anaerobic fluidized bed bioreactor (AFMBR-2.2 h HRT) treating effluent from another AFBR-GAC reactor treating dilute wastewater (513 mgCOD/L) at 2.0–2.8 h HRT. Membrane flux was set at 10 LMH, and the TMP only increased from 0.075 to 0.1 bar over 40 d of operation. COD removals were 88% and 87% in the respective reactors, and 99% overall, with a permeate COD of 7 ± 4 mg/L. Total energy required for fluidization for both reactors was 0.058 kWh/m^3, which could be met by using only 30% of the methane produced. The AFMBR alone only required 0.028 kWh/m^3, which is significantly less than