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Fouling mitigation in Anaerobic Membrane Bioreactor using fluidized glass beads: Evaluation fitness for purpose of ceramic membranes

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ABSTRACT

The use of fluidized glass beads to mitigate fouling in a novel Anaerobic Membrane Bioreactor (AMBR) with external crossflow membrane was investigated in lab scale. Two ceramic ultrafiltration (UF) membranes with a molecular weight cut-off/pore size of 100 kDa (ZrO_2) and 0.05 µm (Al_2O_3) and a 0.4 µm pore-sized ceramic microfiltration (MF) membrane (TiO_2) were tested for fouling behavior, mechanical resistance and solute rejection at an operating time of 46 days. For all tested membranes, at crossflow velocities between 0.073 and 0.074 m/s, the fouling rate was reduced by more than 95% in the presence of fluidized glass beads. The fouling rates of the UF membranes were between 0.01 and 0.02 Pa/min in the presence of fluidized glass beads. In contrast, the MF membrane showed a higher fouling rate of 0.73 Pa/min. The fluidized glass beads damaged all the membranes by abrasion. The TiO_2 MF membrane showed the highest and the ZrO_2 UF membrane the lowest resistance against abrasion. The solute rejection of the MF membrane was lower than of the UF membranes but increased with increasing membrane fouling. Presumably, internal deposits diminished the pore size of the MF membrane and increased its solute rejection. The required electrical energy for filtration was predicted to be about 0.3 kWh/m^3. A ceramic Al_2O_3 MF membrane (pore size 0.1 µm), which was additionally tested in a clean water abrasion test, showed no membrane damage and might represent a promising option for use in the novel AMBR configuration.

1. Introduction

In contrast to aerobic wastewater treatment, anaerobic treatment offers several substantive advantages, e.g.: low production of waste biological solids, generation of a useful end product in the form of methane gas and lack of energy-intensive aeration [1]. However, the anaerobic treatment of municipal wastewater, characterized by low substrate concentrations and a high particulate fraction, is still challenging wastewater engineers, particularly at low temperatures (≤ 20 °C) [2]. The Upflow Anaerobic Sludge Bed (UASB) reactor, the most common reactor applied in anaerobic municipal wastewater treatment [3], does not generally generate high-quality effluents at low temperatures [4,5]. Recently, the Anaerobic Membrane Bioreactor (AMBR), a combination of an anaerobic bioreactor and membrane filtration, was suggested to be a promising option for the intensification of the anaerobic treatment of municipal wastewater [6–8]. Several studies, e.g. [9–12], showed that by means of AMBRs high chemical oxygen demand (COD) removal ($70-90\%$) can be achieved in the treatment of municipal wastewater, even at temperatures below 20 °C.

A crucial obstacle in launching AMBRs to commercial application is fouling control, as it is associated with a high energy demand [7,13–15]. The most widespread methods for fouling control are biogas sparging (in case of submerged membranes) and the generation of high crossflow velocities (in case of external crossflow membranes) [6,7]. Recently, solid-liquid fluidization was introduced as effective method for fouling control in AMBRs. This approach was first described by Kim et al. [16] and was implemented by submerging a hollow-fiber membrane in a fluidized bed of granular activated carbon (GAC). Due to the positive results of this initial work, several subsequent studies focused on the use of fluidized GAC for fouling mitigation in AMBRs [11,16–23]. The use of solid-liquid fluidization in membrane processes to reduce concentration polarization and fouling had already been described before. For instance, fluidized glass and stainless steel beads increased the steady-state flux (at constant pressure filtration) in tubular membranes during the filtration of macromolecular solutions [24–29]. Comparable results during the filtration of alumina suspensions [30] and cheese whey [31] using fluidized glass beads were reported in the past.

Based on these findings, in a previous study, we introduced a novel AMBR configuration using fluidized glass beads as turbulence promo-

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ters in an external crossflow ultrafiltration (UF) membrane [32]. That study showed that fluidized glass beads enabled the operation at extraordinary low crossflow velocities between 0.053 and 0.073 m/s. The novel AMBR was run for about 150 days using glass beads with a diameter of 0.8 − 1.2 and 1.5 mm and applying a bed voidage of 74% and 80%. The results showed that glass beads with a diameter of 1.5 mm and a bed voidage of 74% showed the strongest efficacy in terms of fouling mitigation. The required electrical energy for filtration was about 0.3 kWh/m^3 [32]. However, a major drawback of using solid-liquid fluidization for fouling mitigation became evident in that study as well: the fluidized glass beads damaged the used ceramic UF membrane (150 kDa, ZrO_2, atech innovations, Germany) severely. The membrane was exposed to the 0.8 − 1.2 mm fluidized glass beads for 76 days and to the 1.5 mm ones for 75 days. Dissolved organic carbon (DOC) rejection indicated that 1.5 mm glass beads presumably caused membrane damage.

Against this background, the objective of the present study was to test the fitness of commercially available ceramic membranes at comparable operating parameters (glass beads diameter, bed voidage, duration of exposition) regarding their application in the novel AMBR. Two ceramic UF membranes with an active layer of ZrO_2 and Al_2O_3, respectively and a microfiltration (MF) membrane with an active layer of TiO_2 were tested. The ZrO_2 UF membrane (100 kDa) was similar to the one used in the previous study [32]. Although membrane damage had to be expected for this membrane, it was tested because, based on the results of the previous study [32], no conclusion about the rate of mechanical degradation at given operating parameters (bead diameter, bed voidage, superficial veloctiy) could be drawn. However, this result might be useful in terms of ranking the mechanical resistance of the other tested membranes. The tested MF membrane is a commercially available membrane with a high mechanical resistance. Unfortunately, this type of membrane is only available with a pore size of 0.4 µm. A pore size in this range might be disadvantageous because internal pore blockage might lead to irremovable fouling [33]. Therefore, an Al_2O_3 membrane with a pore size of 0.05 µm was tested as well. The mechanical resistance of this membrane was expected to be higher than of the ZrO_2 UF membrane but lower than that of the TiO_2 MF membrane.

Fouling behavior in the presence of fluidized glass beads, mechanical resistance against abrasion and solute rejection were evaluated for each membrane at 46 days of operation. Operation with intermittent fluidization as measure for reducing the required energy for fluidization was examined as well. Moreover, the overall COD removal and the COD balance were assessed for each membrane. Furthermore, the relationship between bed voidage (of the fluidized bed) and the required pumping energy for fluidization and fouling mitigation efficacy, respectively, was analyzed. Since membrane damage was the critical point in the case of all tested membranes described above, a further commercially available ceramic MF membrane (Al_2O_3, pore size 0.2 µm) was tested in terms of its mechanical resistance during a clean water filtration test in the presence of fluidized glass beads.

2. Materials and methods

2.1. Anaerobic Membrane Bioreactor operation

2.1.1. Experimental setup

Fig. 1 shows a schematic diagram of the laboratory setup. An anaerobic fluidized bed bioreactor (FB) was connected to a tubular ceramic membrane. The FB reactor consisted of an acrylic tube (height = 700 mm, diameter = 24 mm, volume = 317 ml) and was described in detail in a previous study [34]. The membrane was mounted vertically in a PVC housing and operated in inside-out mode.

The transmembrane pressure (TMP) was generated by suction on the permeate side. Glass beads (soda-lime glass, density = 2500 kg/m^3, Worf Glaskugeln, Germany) with a diameter of 1.5 mm were added as turbulence promoters and were fluidized by the upflow to the top of the membrane module. To enable fluidization, a wire cloth was fixed at the bottom of the membrane module and glass beads (4 mm) were added as support layer. The volume of the fluidized bed reactor (317 ml) was defined as reaction zone for calculating the organic loading rate (OLR) and the hydraulic retention time (HRT). A cylindrical settler was attached above the reactor (height = 150 mm, diameter = 72 mm) to catch carry-over GAC. A second cylindrical settler was placed between bioreactor and membrane module (height = 180 mm, diameter = 72 mm) to distribute the volume flows and catch carry-over glass beads, respectively. The total volume of the AMBR (excluding membrane module and recirculation lines) was about 1600 ml. Granular activated carbon (GAC) (Epibon A, 0.595 − 1.00 mm, Donau Carbon, Germany) was chosen as carrier material for the bioreactor.

Peristaltic pumps were used for recirculating (ProMinent, Germany) and introducing feed or drawing permeate (IDEX, USA). The recirculation rates were adjusted using flow meters (GEMÜ, Germany). Pressure was monitored at the top and the bottom of the membrane module and at the permeate line using pressure transmitters (PAA-33X, Keller). The permeate flow rate was monitored gravimetrically using a balance (Entris, Sartorius, Germany). The biogas flow rate was measured volumetrically (MilliGascounter, Ritter, Germany). ORP and pH (Sensolyt, WTW, Germany) electrodes were installed in the settler and connected to a pH meter (pH 191, WTW, Germany).

Three different commercially available ceramic membranes were tested. The characteristics of the membranes are shown in Table 1. All membranes were manufactured by atech innovations (Germany) and all had the same dimensions: ID (inner diameter) = 16 mm, L (length) = 500 mm, A_M (membrane surface area) = 0.025 m^2. The UF100 membrane was similar to the one used in a previous study [32] and membrane damage was expected for this membrane. The MF0.4 membrane is a commercially available membrane with high resistance to mechanical abrasion. The mechanical resistance of the UF0.05 membrane was expected to be higher than that of the UF100 membrane but lower than that of the MF0.4 membrane.

2.1.2. Operating conditions

The reactor was fed with raw municipal wastewater (160 µm pre-

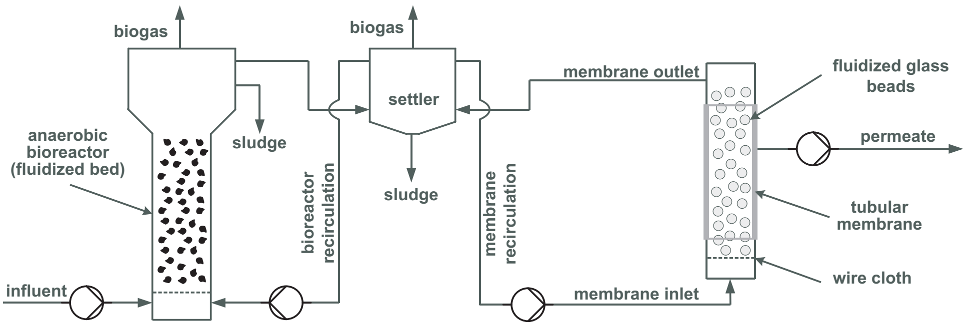

Fig. 1. Schematic diagram of the laboratory AMBR.