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Feasibility of applying forward osmosis to the simultaneous thickening, digestion, and direct dewatering of waste activated sludge

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ABSTRACT

The feasibility of applying forward osmosis (FO) to the simultaneous thickening, digestion, and dewatering of waste activated sludge was investigated. After 19 days of operation, the total reduction efficiencies of the simultaneous sludge thickening and digestion system in terms of mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) were approximately 63.7% and 80%, respectively, and the MLVSS/MLSS ratio continuously decreased from 80.8% to 67.2%. The MLSS concentration reached 39 g/L from an initial amount of 7 g/L, indicating a good thickening efficiency. In using FO for sludge dewatering, two major factors were verified, namely, initial sludge depth and draw solution (DS) concentration. A sludge depth of 3 mm, where a dry sludge content of approximately 35% can be achieved in approximately 60 min, is recommended for future applications. In addition, the present study proved the feasibility of using seawater reverse osmosis concentrate as the DS.

1. Introduction

Large quantities of excess high water-content sludge are being produced in wastewater treatment plants (WWTPs) everyday. To minimize the costs of sludge transportation and handling, reduction in sludge volume through water separation is the most important issue that needs to be addressed prior to final disposal. Sludge thickening and dewatering are usually practiced for volume reduction. Normally, sludge thickening is performed first to reduce the sludge volume and increase the sludge solid content to attain a suitably concentrated sludge for the sludge dewatering processes. The commonly used sludge thickening processes include gravity thickening, dissolved air flotation thickening, and centrifugal thickening, among others. Although these traditional thickening technologies are already mature and are easy to perform, some problems limit their application. For example, the gravity thickening process has the disadvantages of a large footprint, low thickening efficiency, tendency of releasing phosphorus during long sludge retention time (SRT), and emission of unpleasant odors (Wang et al., 2008a; Kim et al., 2010). On the other hand, sludge digestion treatment is a standard practice, particularly for medium- and large-scale WWTPs, and is used as a stabilization step after the thickening process to achieve sludge stabilization, detoxification, and minimization, among others (Wang et al., 2008a). Aside from thickening and digestion, sludge dewatering is also necessary to reduce the water content in the sludge to about 70%. However, sludge dewatering currently remains the most expensive and most poorly understood wastewater treatment process (Pei et al., 2010; Yuan et al., 2011).

To solve the problems of conventional sludge thickening technologies and shorten the sludge treatment processes (i.e., to lessen the footprint and operational strength), a flat-sheet membrane was developed for simultaneous sludge thickening and digestion process (Wang et al., 2008a). This sludge reduction system is actually a membrane bioreactor (MBR), whose advantages include a small footprint, high pollutant removal efficiency, and low cost for the retreatment of the thickened supernate, among others (Judd, 2006). Nevertheless, the relatively high energy requirement, especially from membrane fouling due to high sludge concentration, is the main obstacle for the application of membrane sludge thickening process (Wang et al., 2008b, 2009).

In contrast to conventional MBR, several researchers proved that a forward osmotic MBR has better membrane fouling control performance (Cornelissen et al., 2008; Lay et al., 2011; Achilli et al., 2009b). In forward osmosis (FO), such as in the well-known reverse osmosis (RO), water is transported across a semipermeable membrane, which is impermeable to salt and is driven by the difference between the osmotic pressures across the membrane (Cath et al., 2006). Even though osmosis has been recognized and utilized for decades, FO remains a unique and emerging technology (Chung et al., 2010). For the last couple of years, increasing efforts on FO have been exerted due to the availability of more efficient FO membranes (Cornelissen et al., 2008). Present-day FO applications extend from water treatment and food processing to power generation and novel methods of controlling drug release (Wallace et al., 2008; Garcia-Castello and McCutcheon, 2011; Achilli et al., 2009a;

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Sotthivirat et al., 2007). However, in the past 30 years, no studies on the direct use of FO in sludge thickening, digestion, and dewatering were conducted. The only related creative study was performed by Pugsley and Cheng (1981) more than 30 years ago. Their study primarily proved the feasibility of applying FO to sludge dewatering. Nevertheless, because of limitations such as the lack of efficient FO membranes, many issues, including the exploration and optimization of the factors affecting FO performance, need further systematic investigation.

In FO, the reconcentration of the draw solution (DS), usually composed of dissolved salts, is a major part of the energy consumption. The current study proposes the utilization of RO concentrates in seawater desalination as the DS. In RO, typical seawater recoveries are between 30% and 50% (Ji et al., 2010; McCutcheon et al., 2005). Discharge of the concentrated brine back into the sea is proven to affect marine fauna and flora (Latorre, 2005) and damages benthic organisms due to the coagulants present in the brine (Lattemann and Höpner, 2008). This phenomenon is a critical environmental drawback to seawater desalination RO, which has been set up worldwide. If the concentrated brine from RO is used as the DS for FO sludge dewatering, the diluted brine could be directly discharged into the sea without causing any damage. For the FO sludge dewatering process without DS reconcentration, the energy requirements would be reduced to near zero.

In the current study, FO was innovatively applied to simultaneous thickening, digestion, and direct dewatering of raw waste activated sludge from WWTPs. The DS was synthesized to simulate the concentrated brine of seawater desalination RO (Ji et al., 2010) and was not reconcentrated to minimize the energy demand. The current work aims to conduct a preliminary study on the characteristics (including the digestion efficiency, the reversed salt transport, and the effects of DS concentration on the FO flux) of the simultaneous thickening and digestion system and on the sludge depth and DS concentration on FO dewatering performances. Other issues, such as the process modeling and membrane fouling mechanisms, will be discussed in subsequent studies.

2. Methods

2.1. Experimental setup and the FO membrane

The bench-scale FO experimental setups for simultaneous sludge thickening, digestion, and dewatering are shown in Fig. 1. In the sludge thickening and digestion system, the single FO membrane module unit consisted of two plexiglass cells that clipped the FO membrane sheet. The effective membrane surface area of a single unit was approximately 0.0133 m^2. Depending on the flux requirements, one to three membrane modules can be used for one reactor. The reactor had a cylindrical configuration and a total volume of 1.8 L. Air was supplied through a fine bubble diffuser to supply oxygen to the microorganisms. Two peristaltic pumps, produced by LanGe Company (China), were used for the circulation of the DS and the sludge. The weight change rates over time of the DS and the diluted DS tanks were recorded via a computer. Based on these data, the flow rates of the DS (i.e., the solution that went into the membrane module) and the diluted DS (i.e., the solution that went out of the membrane module) were calculated. The real-time membrane flux for a certain DS was calculated from the difference between the two measured flow rates.

The membrane module used in the sludge dewatering system was similar to a "sandwich". The circulation pump pushed the DS through the airtight channel, the bottom layer of the "sandwich". The middle layer was the FO membrane, and the top layer was a sludge container. Both the DS and the sludge were in direct contact with the FO membrane. The effective membrane area of this module was approximately 0.0035 m^2, and the sludge container had a length of 7 cm, a width of 5 cm, and a maximum depth of 1 cm. The calculated maximum sludge volume of the container was 35 mL, whereas the DS was normally more than 1000 mL. Therefore, the volume increment of the DS during the dewatering course was omitted (i.e., the DS concentration used for sludge dewatering was considered as constant).

The FO membrane used in the study was supplied by Hydration Technology (HTI, Albany, Oregon, US) and classified as cartridge type. The 50 μm-thick FO membrane was made of cellulose triacetate embedded in a polyester screen mesh (Cath et al., 2006). The HTI membranes, which have been used in a number of studies, are currently viewed as the best available membranes for FO applications (Achilli et al., 2009b; Lay et al., 2011; Holloway et al., 2007; Cornelissen et al., 2008; Xiao et al., 2011). The membrane orientation has a significant effect on the FO flux due to concentration polarization (CP) or membrane fouling. Compared with the rejection layer facing the DS, the configuration of the rejection layer facing the feed water showed a remarkable flux stability against both bulk DS dilution and membrane fouling, although its flux was relatively lower (Tang et al., 2010). In the current study, the configuration of the rejection layer facing the feed water was adopted to prevent a significant flux decline.

2.2. DS and activated sludge

As previously stated, synthetic DS #1 was prepared to simulate the concentrated brine from RO (30% recovery rate) by dissolving reagent grade NaCl (35,790 mg/L), $CaCl_2 \cdot 2H_2O$ (2297 mg/L), $MgCl_2$ (7996 mg/L), $NaHCO_3$ (274 mg/L), and Na_2SO_4 (4526 mg/L) in ultrapure water. For future applications, the RO concentrate can be discharged into the sea after dilution, similar to natural seawater. Synthetic DS #5 was also used in the tests and was prepared to simulate natural seawater by dissolving reagent grade NaCl (25,053 mg/L), $CaCl_2 \cdot 2H_2O$ (1608 mg/L), $MgCl_2$ (5597 mg/L), $NaHCO_3$ (192 mg/L), and Na_2SO_4 (3168 mg/L) in ultrapure water. Synthetic DSs #2, #3, and #4 were also prepared using the same salts but at proportional concentrations between those of solutions #1 and #5. The detailed information is shown in Table 1.

The activated sludge was obtained daily from a 60,000 m^3/d MBR facility in a WWTP located in the northern part of Beijing. The sludge samples had a MLSS of 7.3 g/L, a MLVSS of 5.9 g/L, a soluble COD in supernatant of 103 mg/L, and a conductivity of 310 μS/cm.

2.3. Analytical methods

Analyses of the mixed liquor suspended solids (MLSS), mixed liquor volatile suspended solids (MLVSS), chemical oxygen demand (COD), ammonia nitrogen, and total phosphate were performed based on the standard methods proposed by the State Environmental Protection Administration of China. The soluble COD (SCOD) samples were prepared using filter papers with a nominal pore size of 0.45 μm. The dissolved oxygen (DO) concentration was determined using a DO meter (Model YSI 58, YSI Research Incorporated, Ohio, US). The mixed liquor viscosity value was obtained using a viscometer (Brookfield, US). The specific oxygen uptake rate was determined based on the standard procedure provided by Zhang (1988). The conductivity of the sludge was monitored using a conductivity probe (Fisher Scientific, Hampton, NH, US) to calculate the reversed salt transport and the total accumulation of salt in the bioreactor. The equivalent salt (NaCl) concentration was calculated from the conductivity values using a calibration curve. The digestion efficiency was calculated as described in previous studies (Wang et al., 2008a,b, 2009) and is given by: