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A fouling suppression system in submerged membrane bioreactors using dielectrophoretic forces

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ABSTRACT

A novel method was developed to suppress membrane fouling in submerged membrane bioreactors. The method is based on the dielectrophoretic (DEP) motion of particles in an inhomogeneous electrical field. Using a real sample of biomass as feed, the fouling-suppression performance using DEP with different electrical field intensities (60–160 V) and different frequencies (50–1000 Hz) was investigated. The fouling-suppression performance was found to relate closely with the intensity and frequency of the electrical field. A stronger electrical field was found to better recover the filtrate flux. This is because of a stronger DEP force acting on the biomass particles close to the membrane's surface. Above an intensity and frequency value of 130 V and 1 kHz, respectively the permeate flux was reduced due to an electrothermal effect.

Introduction

Limitations of conventional biological processes in treating domestic and industrial wastewater to meet the discharge standards became more evident in recent years. This led to a large number of research aimed at alternative technologies and/or improvement of existing technologies (Le-Clech et al., 2006). Membrane bioreactor (MBR) is one of the improved existing technologies, which combines both biological and membrane separation processes. Because of their unique advantages such as good effluent quality, compact structure, higher volumetric loading, good disinfection capability and less sludge production, MBRs have been widely used for municipal and industrial wastewater treatment (Judd, 2006; Hwang et al., 2009). Nevertheless, the decline of permeate flux due to membrane fouling is addressed as a major problem during the operation of membrane bioreactors (Judd, 2006; Huyskens et al., 2012). Membrane fouling refers to the particle deposition on the surface and/or internal structure of the membrane (Huyskens et al., 2012). Such accumulation would influence the operational performance, stability and cost (Mishima and Nakajima, 2009).

Several methods were proposed to limit fouling in MBRs such as low flux operation, increased aeration, relaxation of membranes and backwash (Mishima and Nakajima, 2009). An alternative method includes the addition of chemical coagulants such as alum and iron salts (Song et al., 2008; Wu and Huang, 2008; Lee et al., 2001; Ngo and Guo, 2009), or natural organic coagulants (Guo et al., 2008). In addition adsorptive materials such as a high concentration of powdered activated carbon and zeolite could be utilized (Ngo and Guo, 2009; Bani-Melhem and Electorowicz, 2010). Although these techniques may somewhat reduce fouling, they have drawbacks: potential issues of membrane breakage, stopped process, additional equipment cost, additional energy and usage of chemicals. It is also expected that the effectiveness of these processes tends to decrease with operation time as more irreversible fouling accumulates on the membrane surface (Judd, 2006).

Instead of using the chemical coagulants, electrocoagulation was used to reduce fouling in MBRs (Bani-Melhem and Electorowicz, 2010). Electrocoagulation and electrosedimentation are conducted prior to filtration, which reduces the deposition of foulants on the membrane and accordingly maintains high filtration performance. The application of additional force for anti-fouling in MBRs was

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studied by different researchers. Akamatsu et al. (2010, 2012) and Chen et al. (2007) applied an electric field directly to the membrane surface to reduce membrane fouling. With the assumption that most potential foulants such as activated sludge and secreted polymers are negatively charged, an electric repulsive force was utilized to move the sludge away from the membrane. Akamatsu et al. (2012) used carbon cloth as electrodes. The carbon cloth inside their assembly was used as the anode, and the assembly was placed between two additional carbon cloths, which were used as the cathode. However, negatively charged silica particles with a zeta potential of −47 mV should be attracted to the anode in their assembly instead of being repelled from the membrane. Akamatsu et al. (2010) used a flat-sheet membrane placed between two platinum meshes, and only aimed to develop MBRs with membrane modules placed externally to the bioreactor. Chen et al. (2007) used hollow-fiber membranes that were placed between two electrodes made of stainless steel with many evenly distributed tiny holes. The mechanism of these electrical cross-flow filtration systems is based on the assumption that most particles in suspension are negatively charged. The high complexity of suspensions in MBRs may prevent the use of this process in many cases. Also the application of bare electrodes required by these processes will result in an electrochemical reaction, leading *e.g.*, to pH shifts or even worse to toxic by-products, and increase the risks of short circuit and human electric shock (Du et al., 2007).

In this work, a preliminary assessment of a new method to reduce membrane fouling in MBRs is presented. The method is based on dielectrophoretic motion of particles in an inhomogeneous electrical field. A lab-scaled dielectrophoretic submerged membrane filtration process was designed and experimentally examined for the first time with a membrane average pore size of 0.2 μm.

Dielectrophoresis, which has been employed in separating particles mainly in biological industries (Morgan and Green, 2002; Pethig and Markx, 1997), was firstly defined by Pohl, 1978 as a translational motion of neutral particles caused by dielectric polarization in an inhomogeneous electrical field. This must be distinguished from electrophoresis, which is a motion induced by free charges carried by the particle in a homogeneous electrical field (Pohl, 1978).

A particle will be polarized when it is superimposed in an electric field. The induced dipole moment due to polarization can be represented by equal but opposite charges distributed on the particle's boundary. In an inhomogeneous electrical field, the local electrical field and the resulting forces on both sides of the particle will be different, thereby generating a net force, termed as dielectrophoretic force (F_{DEP}). The dielectrophoretic force, F_{DEP} (N), acting on a spherical particle was introduced by Pohl (1978):

$$F_{\mathrm{DEP}} = 4\pi a^3 \varepsilon_0 \varepsilon_{\mathrm{M}} re\left[\widetilde{K}\right](E \bullet \nabla)E. \tag{1}$$

where a (m) is the radius of a spherical particle, ε_{M} is the relative dielectric constant (permittivity) of the medium, ε_0 (F/m) is the permittivity of free space with the value of 8.854×10^{-12} F/m, and $re\left[\widetilde{K}\right]$ is the real part of Clausius–Mossotti factor $\widetilde{K}$. This parameter describes the effective dielectric polarizability of the particle as a function of frequency of the electric field, and is given as:

$$\widetilde{K} = \frac{\widetilde{\varepsilon}_{\mathrm{P}} - \widetilde{\varepsilon}_{\mathrm{M}}}{\widetilde{\varepsilon}_{\mathrm{P}} + 2\widetilde{\varepsilon}_{\mathrm{M}}} \tag{2}$$

$$\widetilde{\varepsilon} = \varepsilon - \frac{j\sigma}{\omega} \tag{3}$$

where $\widetilde{\varepsilon}$ is the complex permittivity of the particle $(\widetilde{\varepsilon}_{\mathrm{P}})$ and the medium $(\widetilde{\varepsilon}_{\mathrm{M}})$, σ (S/m) is the conductivity, ω (rad/s) is the angular frequency of the applied electric field ($\omega = 2\pi f$) in which f (Hz) is frequency, and $j = \sqrt{-1}$. $(E \bullet \nabla)E = \frac{1}{2}\nabla|E|^2$ is the (geometric) gradient of the square of the field intensity E (V/m), as an example of cylindrical electrode configuration can be given (Pohl, 1978).

$$\nabla|E|^2 = \frac{-2U_{\mathrm{M}}^2}{r^3\left(\ln\left(\frac{r_1}{r_2}\right)\right)^2} \tag{4}$$

where U_{M} (V) is the voltage across medium, r (m) is the distance between particle and electrode, r_1 (m) is the radius of central electrode, and r_2 (m) is the characteristic length of electrode configuration.

Depending on the difference of permittivities between particles and the surrounding medium, particles will present different dielectrophoretic (DEP) effects and accordingly will move in different directions. With a higher permittivity of particles compared to that of the surrounding medium, particles will move toward the strong electrical field, presenting positive DEP (pDEP) (Fig. 1b), while particles with lower permittivities compared to that of the surrounding medium will be repelled to the side of the weak electrical field, presenting negative DEP (nDEP) (Fig. 1a) (Du et al., 2008). Negative DEP would be the expected case in a biological wastewater reactor, where the permittivities of particles (*e.g.*, microorganisms, colloids, solutes, and cell debris), are expected to be lower than the permittivity of the surrounding medium (*i.e.*, wastewater). In addition, it would be expected that if the surrounding medium is highly conductive (*i.e.*, wastewater with a conductivity value of around 1 S/m), both living and dead particles would create an identical negative DEP effect throughout any frequency value. Thus, the electrodes should be designed in a proper way in order for these particles to move in the direction away from the membrane, thereby increasing the permeate flux by reducing the fouling. As mentioned before the main advantage of the DEP force is that it would influence all particles in suspension regardless of their charge (Du et al., 2009). In addition, an agglomeration of particles in the biological wastewater reactor often occurs. This will result in a larger particle size with the same electrical properties, thereby still presenting a nDEP effect pushing the agglomerates away from the membrane, but with a higher DEP force as illustrated in Fig. 2.

The main objective of this study is to demonstrate that fouling caused by biomass particles in MBRs can be suppressed by the use of dielectrophoretic forces. The dielectrophoretic forces in this study were created by a new electrode configuration which consists of an array of interdigitated circular cross-sectioned electrodes deposited underneath the membrane, through which an alternative current (ac) potential was applied.

1. Materials and setup

A schematic illustration of the MBR experimental setup is shown in Fig. 3. The aqueous suspension of biomass was pumped to the membrane using a vacuum pump (KNFLABOPORT® N86KN.8, KNF Neuberger GmbH, Freiburg, Baden-Wurttemberg, Germany). The suction pressure was kept constant at 0.8 bar. The permeate flux was collected and volumetrically measured in a certain process time. The biomass was supplied from an industrial wastewater treatment plant in Bremen, Germany. The initial concentration of the biomass in the feed suspension was 10 g/L. Before use the biomass was autoclaved at 121°C/103 kPa for 24 hr (30 L Top Load Vertical Lab Autoclave). Autoclaving treatment is supposed to kill the active microbial biomass. In this study it is intended to study the impact of DEP on only the particle's movement. Therefore, the biomass was killed and the system was designed to have severe fouling in order to examine the impact of DEP. Future publications will study the impact of the different characteristics of the biomass