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Fouling suppression in submerged membrane bioreactors by obstacle dielectrophoresis

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ABSTRACT

Submerged membrane bioreactor (MBR) is currently believed to be an efficient biological treatment for reusing and recovering wastewater to extenuate the ever increasing water scarcity crisis. To mitigate the main problem, membrane fouling, in MBR systems, we propose a solution that avoids usage of chemicals, and allows uninterrupted operation using a novel concept of obstacle dielectrophoresis (oDEP). The utilization of obstacles, insulator or metal (floating) electrodes, between electrically excited electrodes, can extend the DEP force field to move suspended particles away from membranes without having to increase voltage, for suppressing fouling with low energy consumption. Experimental investigation verified our theoretical simulation prediction and demonstrated that insulator membrane modules provide longer membrane service time for maintaining normalized permeate flux of 55% than those by floating electrode membrane modules, with a maximum intensification factor of 7.8 when applied 220 V voltage and 50 Hz as well as the transmembrane pressure of 0.1 bar. Although stronger DEP force and hence better performance of fouling suppression can be generated by higher voltage, 50 V insulator membrane module demonstrated to be the most energy efficient process with a specific energy consumption of 0.295 kWh/m^3 product and 13 times higher efficient factor than the 220 V.

1. Introduction

The increasing water scarcity and population growth are posing more and more challenges for water supply. By 2025, half of world's population will be living in water-stressed areas. Therefore, the reuse and recovery of wastewater with low energy consumption is becoming more important. Membrane bioreactors (MBRs), a compact technology combining an activated sludge process and membrane filtration for wastewater treatment, are recently widely used for reusing and recovering wastewater [1]. Although MBRs have many advantages such as compact design, low production of excess sludge, high COD (chemical oxygen demand) removal efficiency and high concentration of suspension, they suffer from membrane fouling and short durability [2]. The induced permeate reduction and hence shortened membrane lifespan by fouling increase operational costs due to reduced effluent and enlarged transmembrane pressure [3]. Many efforts have been made for suppressing fouling problems in MBRs that can be represented by ever increasing research publications (1800 publications in 2015) [1,2].

Fouling in MBRs can be suppressed by mechanical aeration scouring and backwashing [4], chemical cleaning [5], electrically assisted fouling mitigation [6], and application of ultrasound [7,8]. However, all above mentioned methods suffer drawbacks, such as high energy consumption from aeration scouring and stopped process during backwashing [1], membrane damage and secondary contaminants in chemical cleaning [1,9], bulky instrument and difficulty in integration into MBR [3]. Electrically assisted fouling mitigation is considered to be a convenient and energy-saving method [1], mainly based on electrophoresis (EP) [9–11] or dielectrophoresis (DEP) [3,12–14]. In EP assisted membrane anti-fouling process homogeneous dc (direct current) electric field is applied to move charged biomass particles from membranes. It is assumed that all suspended particles in MBRs are negatively charged, however, the ion complexity of the feed suspension prevents such an assumption [8]. In addition, the application of dc field and bare electrodes induces electrochemical reaction on electrodes, and consumes high energy [3].

Different from EP, the DEP induced particle motion is due to the dielectric polarization in inhomogeneous electric field [15]. The DEP force, F_{DEP}, given as,

$$F_{DEP}=2\pi a^3\varepsilon_0\varepsilon_m \mathrm{Re}(\widetilde{K})\,\nabla|E|^2 \quad (1)$$

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is dependent on ε_o, the permittivity of free space with the value 8.854 × 10^{-12} F/m, particle size (a), permittivity of medium (ε_m), Clausius-Mossotti factor ($\widetilde{K}$), a factor representing effective polarization of the particle in the medium, and the gradient of the square of the electric field ($\nabla|E|^2$) [15].

In a certain DEP system with given particles and medium (constant particle size and properties of particle and medium) the magnitude of DEP force is solely dependent on the $\nabla|E|^2$. In contrast, the motion direction of particle is dependent on the Clausius-Mossotti factor, that is, the permittivities difference between particle and medium, which therefore will not be limited by ion complexity of feed suspension. Due to the lower permittivity of particles compared to that of water, particles are repelled from membrane, where stronger electric field is generated by electrodes, and thereby suppressing fouling [3,12–14]. With the application of ac (alternating current) electric field, the insulated electrodes can be used in DEP system and hence prevent the electrochemical reaction on electrodes [3]. The DEP fouling suppression was experimentally demonstrated to be feasible in a lab-scaled cross flow membrane filtration [3]. It was further enhanced by applying a new electrode configuration design, cylindrical interdigitated electrodes (IDE), with a 68% permeate flux for 9 times longer lifespan of active membrane [12]. The same electrode configuration was utilized in a lab-scale MBR system for studying parameters influence on the anti-fouling by DEP [13]. Hawari et al. demonstrated that the fouling suppression performance is dependent on the applied voltage, i.e. the higher induced DEP motion of biomass particles in stronger electric field by higher applied voltage, due to the quadratic dependence of DEP velocity on voltage [13–15]. Although the enhancement of permeate flux and membrane effective working time was obvious using DEP, the Joule heating induced by applied high electric field and hence electrothermal effect due to temperature gradient intervene particles motion, possibly damage membrane and increase energy consumption [13,16–18]. In addition, the increased temperature might severely affect the biomass in wastewater and lead to reduced biodegradation process [19,20]. Larbi et al. experimentally studied the influence of high electric field on the sludge characteristics using a DEP submerged MBR installed with interdigitated electrodes [21]. Their experimental results demonstrated that the increased temperature by Joule heating and high current density in a DEP system with high voltage applied (over 100 V) would induce a significant decline in the bacterial activity and pollutant removal efficiency as a result of bacterial lysis [21]. The only solution to mitigate influence of Joule heating is to reduce the system energy input (voltage and current). However, the reduction of voltage for a certain DEP system (constant impedance) will decrease the quadratic voltage dependent DEP force, and hence the performance of fouling suppression. Therefore, a new electrode configuration design, which can extend DEP force without having to increase the amplitude of voltage, is demanded.

In this study, we present an obstacle DEP (oDEP) concept, in which an obstacle (non-electrically-excited) is arrayed between two electrically excited electrodes to extend DEP force (Fig. 1). When obstacles are superimposed by electric field, the generated dipole moment and hence electric potential on the obstacles due to polarization can intensify local electric field on/around obstacles [22,23]. The obstacle can be conductive (floating electrodes) or dielectric (insulator). Floating electrodes (metallic obstacle) have been used and demonstrated many advantages in microsystems for manipulating nanoparticles, carbon nanotubes and DNA molecules [22–26]. The device dimensions and the number of connecting wires can be reduced without having to increase voltage, because the floating electrodes do not need to be connected to external electric source. A DEP system with an array of many insulators (posts) under the presence of electric field excited by two metallic electrodes at both inlet and outlet of the process, termed as insulator-based (electrodeless) DEP (iDEP), is utilized for trapping particles [27]. The material of posts in all of iDEP devices is insulator [28]. Our recent researches thoroughly studied the influence of obstacle

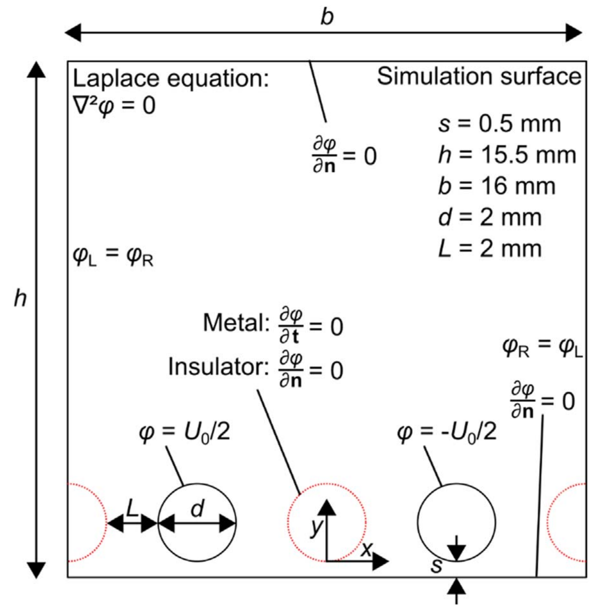

Fig. 1. Sketch of the simulation surface and the geometrical parameters involved, of an oDEP electrode configuration with obstacles (red circles) arrayed between excited electrodes (black circles). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

material and geometry on DEP force, and demonstrated that the permittivity ratio between obstacle and medium plays an important role in determining the generated electric field [28,29]. We take advantage of the research results in suppressing fouling in MBR processes in this study for reducing excited electrodes numbers with no increase of applied voltage, so as to remain the good performance of DEP force on fouling mitigation with less energy input and hence alleviate the Joule heating problems.

Therefore, we employed two oDEP electrode configurations with two different obstacle materials, metal (floating electrode) and dielectric (insulator), integrated into two lab-scale MBR systems in this work. Finite element simulations were performed for theoretically studying the magnitude of DEP force. Experimental work was followed to demonstrate and compare the performance of two types of membrane modules in terms of fouling suppression, the influence of Joule heating, and energy consumption.

2. Materials and method

2.1. Simulation

An oDEP system used in membrane module can be represented with obstacles (floating or insulator) mounted between two excited electrodes as shown in Fig. 1. To determine the efficiency of the fouling suppression system the gradient of the square of the electric field ($\nabla|E|^2$) for a set of electrodes with insulating or conducting metal rods (floating electrodes) in between is calculated (cf. Fig. 1). The field is calculated for an arbitrary liquid in the absence of particles and without considering any plastic spacers or the membrane. The membrane itself will shield the electric field but this effect exists for all electrode configurations and can therefore be ignored for a comparison. We solve the problem in two dimensions, i.e. we assume that the electrodes and rods are infinitely long, which is an appropriate assumption for the underlying geometry.

To determine the electric field and the dielectrophoretic forces on the particles, the electric potential is solved for a simulation volume and a set of boundary conditions which represent the electrode array and the insulators or floating electrodes between them. For the currents and frequencies applied in this study the problem can be solved in the quasi-