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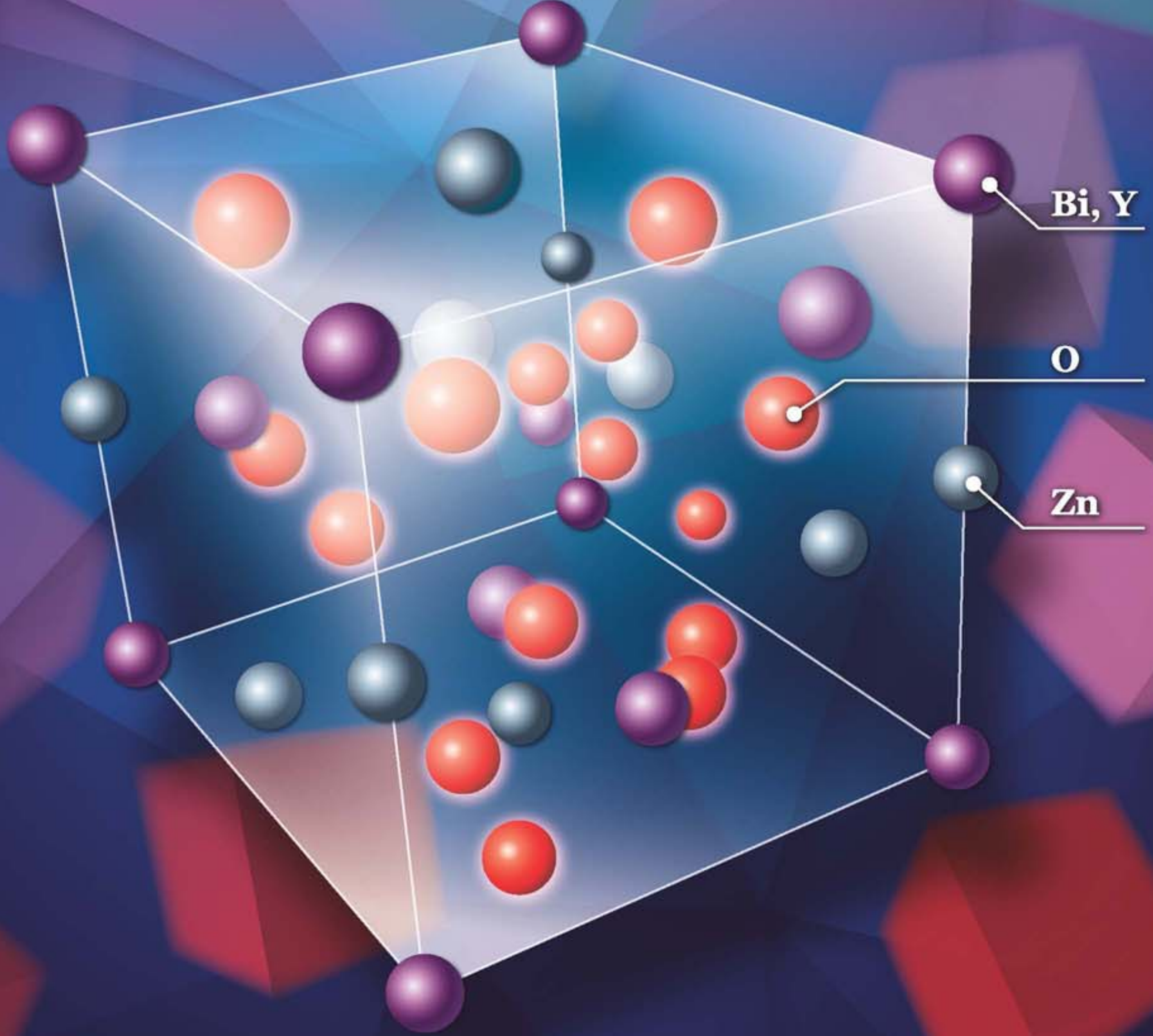

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A fouling suppression system in submerged membrane bioreactors using dielectrophoretic forces

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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):

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

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:

$$\widetilde{K} = \frac{\widetilde{\varepsilon}_P - \widetilde{\varepsilon}_M}{\widetilde{\varepsilon}_P + 2\widetilde{\varepsilon}_M} \tag{2}$$

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

where $\widetilde{\varepsilon}$ is the complex permittivity of the particle $(\widetilde{\varepsilon}_P)$ and the medium $(\widetilde{\varepsilon}_M)$, 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).

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

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

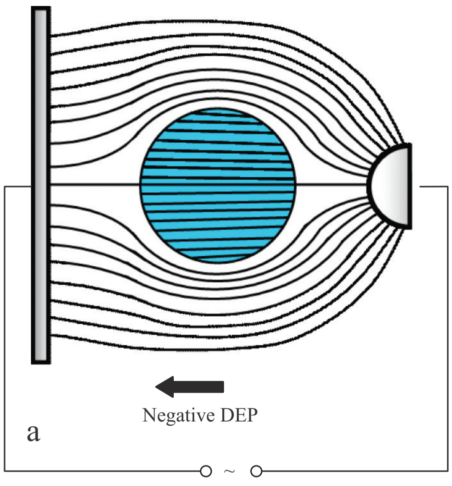

Fig. 1 – Particle motion direction dependent on the relative effective polarization of particle. Particle with lower permittivity compared with that of medium is repelled from higher electric field regions, presenting negative dielectrophoretic (DEP) effect (a), while more polarizable particle than medium is attached to higher electric field region, presenting positive dielectrophoretic (DEP) effect (b) (Baune et al., 2008).

itself. The particle concentration in the suspension tank was uniformly maintained by a magnetic stirrer (IKA Labortechnik, Staufen, Baden-Wurttemberg, Germany) with a stable stirring speed of 500 r/min.

The membrane–electrode assembly is shown in Fig. 4. The membrane filtration cell was made of acrylic glass (5 cm in length, 5 cm in width, and 2 cm thick) with an effective membrane area for filtration of 5.0 cm^2. A chlorinated polyethylene membrane, manufactured by Kubota Co. in Japan, was used as the filter medium. The membrane had a nominal (maximum) pore size of 0.4 μm and an average pore size of 0.2 μm. The membrane and the plastic mesh membrane support were mounted on an array of parallel interdigitated electrodes made of titanium (2 mm in diameter covered with a 2 μm TiO_2 insulation layer). The spacing between the electrodes was 2 mm. The sets of electrodes were connected to a power amplifier (FM 1290, FM Elektronik, Berlin, Germany) integrated with a function generator (VOLTCRAFT® 7202, Conrad Electronic AG, Wollerau, Switzerland), which can provide ac effective voltage ranging from 0 to 280 V, and frequency from 0 to 106 Hz.

2. Results and discussion

2.1. Impact of voltage on the permeate flux

The change in the permeate flux with time at different electrical field strengths is shown in Fig. 5. The initial permeate flux of tab water was 0.6 mL/(cm^2·min). In order to demonstrate the DEP effect in suppressing fouling, the membrane module used in the experimental setup was designed to get an extremely severe fouling problem, differently from the real industrial application. Therefore, when the biomass was filtered through the system without applying electric field the permeate flux was zero because of the severe fouling caused by the biomass particles. This condition was unfavorable because there was no force moving the biomass particles away from the membrane and thus the particles rapidly accumulated on the membrane's surface. When applying an electrical field with only 60 V the permeate flux increased from zero to 0.16 mL/(cm^2·min) in the first 5 min

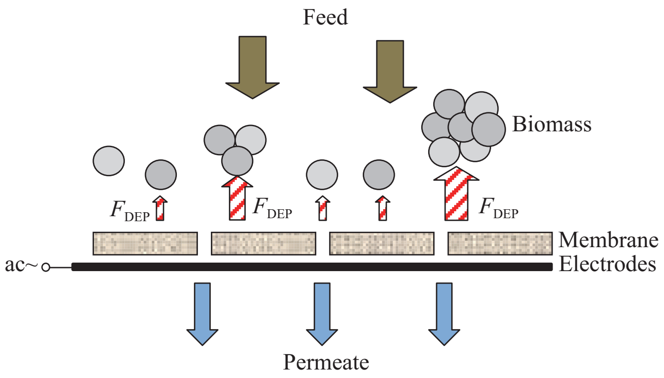

Fig. 2 – Schematic description of suppression function using dielectrophoretic force F_{DEP} in alternative current (ac) inhomogeneous electric field generated by interdigitated cylindrical electrodes mounted under the membrane.

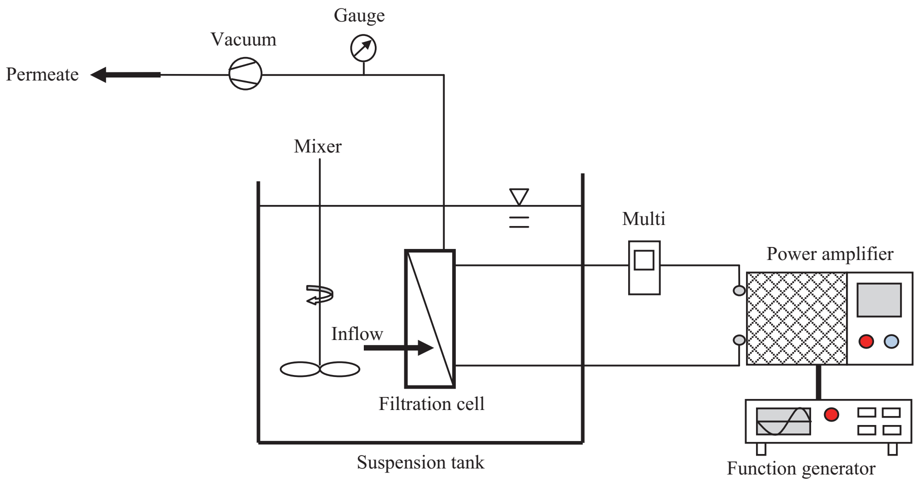

Fig. 3 – A schematic illustration of the experimental setup for the submerged membrane filtration system.

then dropped to 0.04 mL/(cm^2·min) after 60 min. With increasing the voltage the permeate flux increased, where at 160 V the permeate flux increased to 0.24 mL/(cm^2·min) in the first 5 min then dropped to 0.1 mL/(cm^2·min) after 60 min. For all three electrical field strength values applied, the drop of permeate flux after several minutes was due to the accumulation of biomass particles on the membrane which resulted in pore blockage and/or fouling of the membrane. Nevertheless, in all cases the permeate flux was still higher than when no electrical field was applied.

The ac electrokinetic process used in this system involves the generation of repulsive dielectrophoretic (DEP) force on the suspended biomass particles, which will repel them away from the membrane. A higher DEP force will cause particles to be further repelled away from the membrane which will result in less fouling and therefore a higher permeate flux. On the other hand, high electrical field strength will be associated with a large temperature increment caused by the Joule heating [20]. The increased temperature on the membrane caused by the underlying electrodes will reduce the porosity of the membrane (Bansod et al., 2011), thereby requiring higher transmembrane pressure and decreasing the permeate flow. Since power P (W) depends bilinearly on voltage U and current I (A) ($P = U \times I$), and since the current was almost constant as measured during the experiments, the increase of voltage would increase the power. The increase of power will increase the heat in the system which will negatively affect the DEP force. The effect of Joule heating can be seen in Fig. 5: At 130 V the permeate flux was higher than the permeate flux at 60 V at the beginning of the experiment but after 50 min the permeate flux was lower than the permeate flux at 60 V. In the case of 160 V although a heat increase has occurred the DEP force was high enough to be less affected by the Joule heating effect.

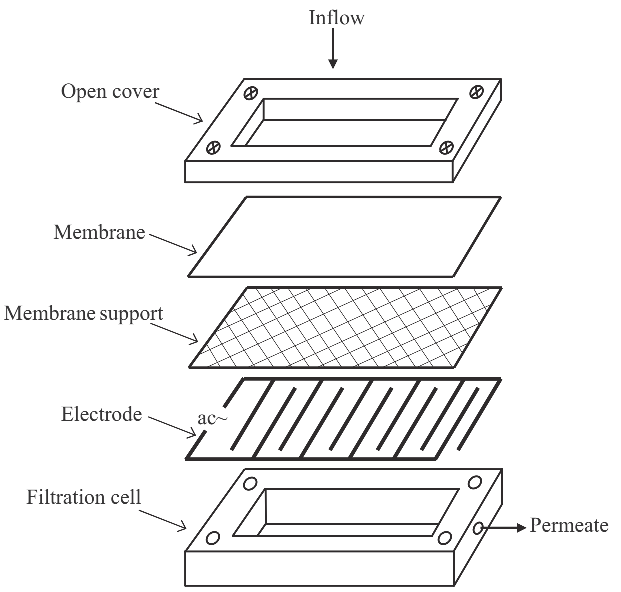

Fig. 4 – Schematic representation of the membrane–electrode filtration cell assembly.

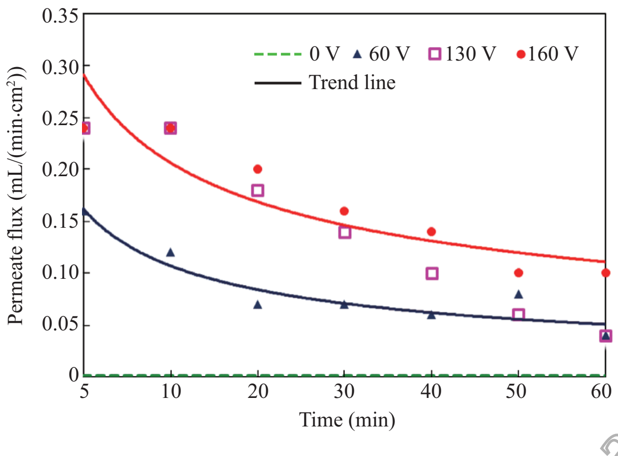

Fig. 5 – Permeate flux with different voltages at 50 Hz frequency.

2.2. Impact of frequency on the permeate flux

The change in the permeate flux with time at different electrical frequencies at 90 V (Fig. 6) shows that at a frequency of 200 Hz the permeate flux was lower than the permeate flux at 500 Hz. Also at a high frequency of 1000 Hz the permeate flux for the first 20 min was higher than the permeate flux at lower frequencies. The fact that a higher permeate flux was attained with higher frequencies could be due to a high-pass-filter effect (Du et al., 2008). According to Du et al. (2008) the insulated electrodes applied in a DEP system together with the surrounding medium could be represented by a high-pass-filter circuit. The high pass filter effect is due to the insulation on the electrodes. In order to avoid any human electric shock, side chemical reactions and problems of short circuit effect, electrodes should be insulated. This insulation will reduce the efficiency of DEP in low frequencies and will increase the amount of consumed energy in the system (Baune et al., 2008). Therefore, a special design of electrodes is required. Baune et al. (2008) simulated the influence of properties of insulation film on the high-pass-filter effect, and demonstrated that a properly thin insulation film with high permittivity will reduce the influence of high-pass filter effect. In a low frequency region such a high-pass-filter circuit will require much higher voltage to satisfy the high electrical field required in a DEP system. Therefore, it is deducted that at low frequency the electrical field strength in the medium will be low, meaning that the dielectrophoretic force on the biomass particles will be low and therefore, less repulsion will occur resulting in a lower permeate flux (Fig. 6). However, it was observed that a drastic drop in permeate flux at 1000 Hz after 30 min occurred. This could be caused by the Joule heating effect. The AJoule heating caused by the high electrical field strength in a DEP system is called the electrothermal effect (ETE). Due to Joule heating a temperature gradient will be formed which will cause the liquid in the system to flow, which in return will affect the movement of the particles in the system (Du et al., 2007). In a negative DEP system, the direction of fluid flow is identical to the particle motion, and thereby increasing motion velocity of particle (Du et al., 2007). In addition, the induced fluid flow due to the electrothermal effect will generate turbulence over the membrane's surface, thereby enhancing suppression of fouling. However, the temperature increase of membrane due to the electrothermal effect could cause changes in the membrane's structure, properties such as porosity and pore size, which might influence the permeate. As a result the heat produced increases with the applied frequency. Above a certain threshold the heat cannot be transferred completely out of the system by permeate flow and heat conduction therefore, the heat will accumulate inside the system which would result in reducing the permeate flow as shown in Fig. 6 at a frequency value of 100 Hz.

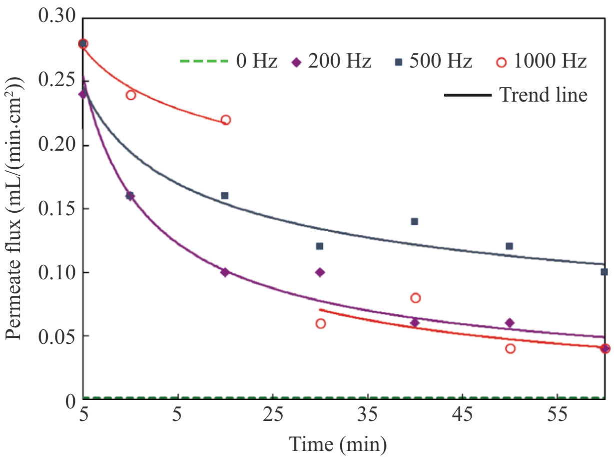

Fig. 6 – Permeate flux with different frequencies at 90 V.

2.3. Energy requirements

A normalized permeate flux as a function of voltage and frequency is shown in Fig. 7. The normalized permeate flux was calculated by dividing the average permeate flux by the permeate flux of tab water (0.6 mL/(cm^2·min)). It can be seen from Fig. 7 that as the frequency and voltage increase the normalized permeate flux increases. Except for the case of 1000 Hz the normalized permeate flux was 0.23 compared to 0.26 at 500 Hz. However, it was found that the normalized permeate flux for the first 20 min at 1000 Hz was 0.41 which is higher than the normalized permeate flux at 500 Hz. This reduction in the normalized permeate flux at 1000 Hz after the first 20 min could be due to the Joule heating effect as explained previously. Energy consumptions were calculated as described before. In Fig. 7, the increase of energy consumption presents an increase of normalized permeate flux. However, the normalized permeate flux in the process with a voltage input of 160 V at 50 Hz was the highest with a relatively lower energy consumption compared to processes with higher frequencies (500 and 1000 Hz). The higher voltage input will generate sufficiently high DEP force for suppressing fouling, while the lower current due to the applied lower frequency will not consume as much energy. The use of high energy in the process with a frequency value of 1000 Hz will generate more Joule heating, and thereby decrease the permeate flux. Although the increase of frequency could reduce the influence of high-pass-filter effect due to the generation of a higher electrical field across the surrounding medium, the much more generated Joule heating will result in lowering the permeate flux due to the lower fouling suppression effect. In conclusion the DEP intensified MBR process could be optimized by applying a properly high voltage value at a low frequency value for a better fouling suppression effect and a lower consumption of energy.

3. Conclusions

In this study, a novel membrane–electrode assembly for submerged MBRs that applies dielectrophoretic force to suppress fouling was proposed and developed. Using a real sample of biomass as feed, the fouling-suppression performance using DEP at different electrical field intensities (6–160 V) and different frequencies (50–1000 Hz) was investigated. It was

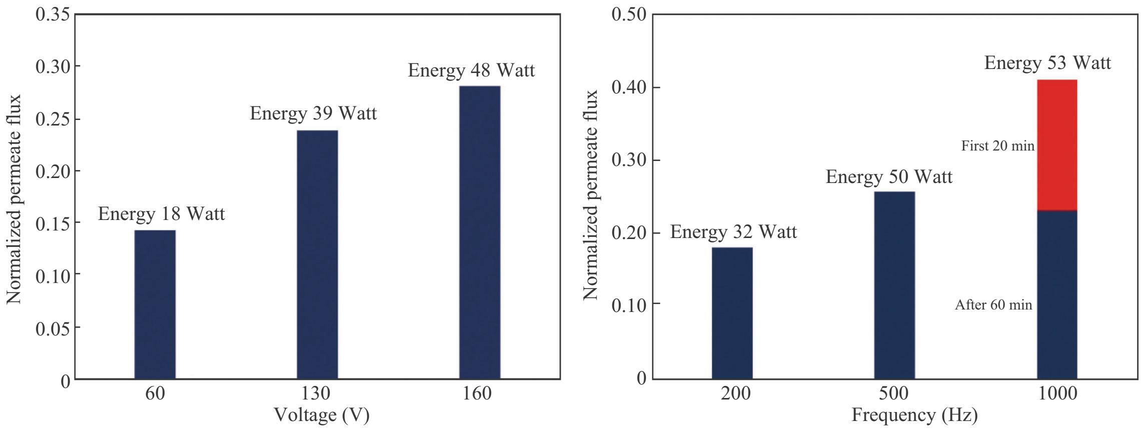

Fig. 7 – Normalized permeate flux with different voltages and frequencies.

found that it was possible to repel the biomass particles away from the membrane in the submerged MBR process owing that to the applied DEP force. This resulted in less fouling and therefore an enhanced permeate flux. It was demonstrated that a stronger electrical field suppressed the fouling effectively due to a stronger DEP force acting on the biomass particles. On the other hand, a stronger electrical field was associated with Joule heating which decreased the permeate flux. It was also demonstrated that at higher frequencies a higher permeate flux was produced. On the other hand, higher frequencies were associated with an increased current, which in return generated more heat and thereby reduced the permeate flux drastically. Applying higher frequencies will result in higher energy consumption without a better fouling suppression effect. In order to reduce fouling with low energy consumption it is recommended to apply an electrical field with high voltage at a low frequency value. An optimization of the DEP MBR system can be accomplished after a better understanding of the DEP effect on the membrane's surface and the impact of other parameters that would influence the DEP MBR system. Although the tested lab-scaled DEP MBR system presented a great potential in suppressing fouling in MBRs, further studies for such a technique are still required which will be presented in future publications.

Acknowledgments

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