学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

Fouling mitigation in membrane bioreactors by nanobubble-assisted backwashing
(ナノバブルを用いた逆洗による膜分離活性汚泥法のファウリング抑制)

Membrane bioreactors (MBRs) are a relatively new wastewater treatment technology that applies efficient solid-liquid separation via membrane filtration, integrated with a biological process. Since their first introduction in a 1989 paper by Japanese and Thai engineers, the use of submerged membrane bioreactors (SMBRs) has been increasing. MBR technology has significant advantages over conventional activated sludge (CAS) processes including higher quality effluent, smaller footprint, complete removal of bacteria, and ease of operation. Nevertheless, the widespread application of MBRs still faces a major obstacle: membrane fouling. The accumulation of foulants on the membrane surface and inside its pores requires periodic cleaning, which increases operational and maintenance costs and reduces the membrane's lifetime and initial permeability. Several measures have been presented to mitigate membrane fouling, including intensive aeration, granular material scouring, antifouling membranes, optimization of operating conditions, coagulation, and diverse cleaning protocols. The application of ceramic membranes is also increasing. Ceramic membranes are compact, can withstand heat and high pressures, have a long life, and are resistant to chemical/physical damage. It has been shown that granular scouring is effective in controlling membrane fouling. Intensive physical cleaning with granular materials was possible due to the high resistance of ceramic membranes. An increasingly prevalent measure for the mitigation of membrane fouling in MBRs by enhancing the efficiency of membrane cleaning is chemically enhanced backwashing (CEB). The combination of mechanical scouring using granular material and CEB with sodium hypochlorite (NaClO) has been demonstrated to efficiently control fouling in MBRs. Although these countermeasures are effective to some extent, it was observed that a dense gel layer was still formed on the surface of membranes used in MBRs even with such intensive cleaning. In addition, the environmental impact of the use of chemicals is a concern. Therefore, further improvements in cleaning efficiency are still necessary to promote the widespread installation of MBRs and bring impactful changes to wastewater treatment systems. On the other hand, Nanobubbles (NBs), also called ultrafine bubbles (UFB), are environmentally friendly and have been shown to possess cleaning properties. Therefore, a novel approach to mitigate fouling in MBRs, nanobubble-assisted backwashing (NBB), is presented in this study. NBs generated in this study had an average diameter of about 150 nm, and some of the nanobubbles could pass through microfiltration (MF) membranes used for MBRs. Therefore, nanobubbles introduced from the permeate side during backwashing might exhibit cleaning effects for membranes since applications of nanobubbles for cleaning various materials such as protein-coated gold electrodes and stainless steel have been reported. The effectiveness of NBB was compared with that of tap water backwashing (TWB) and CEB using 50 ppm NaClO. Experiments were carried out by using three bench-scale MBRs installed

at a local wastewater treatment plant. The three MBRs were operated in parallel with identical operating conditions except for backwashing conditions. Polyethylene glycol (PEG) granular materials were inserted in each membrane tank to scour the membrane surface. Regardless of the variation of the feed, NBB always exhibited better cleaning performance than TWB, and the cleaning efficiency of NBB was sometimes comparable to that of CEB. The degree of reversible fouling observed with TWB was 424% higher than that with NBB, indicating that NBB is much more effective than TWB for the control of reversible fouling. It was also found that NBB could mitigate irreversible fouling even in the absence of a thick protective layer on the surface of the membrane. It was attempted to reveal the mechanism by which NBB enhances the cleaning effect by carrying out a comprehensive analysis of the distribution of filtration resistance, mixed liquor suspension, and the fouling layer. Significant changes in the microbial activity of the mixed liquor suspension and sludge properties in the MBRs were not observed when NBB was carried out. The results of the analysis suggested that NBB made the structure of the fouling layer more porous, possibly facilitating the removal of the fouling layer from the membrane. The use of high-concentration nanobubble (HC-NB) water can be beneficial for the cleaning efficiency of NBB. However, further studies are needed to elucidate the optimal concentration of NBs. Further improvements in the cleaning efficiency of NBB can be achieved. It was attempted to improve the cleaning efficiency of NBB by adding a small amount of NaClO to NB water used for backwashing. The cleaning efficiency of NBB was improved by the synergetic effect of NaClO and NBs working in different ways when they were co-present in the backwash solution. It was suggested that NBs made the structures of the fouling layer looser and more porous, whereas NaClO chemically degraded the components of the fouling layer. The importance of pH (4, 8.5, and 12) in NBB combined with NaClO was shown in this study. The cleaning efficiency was found to be high at pH 4, followed by 8.5 and 12. This difference was mainly attributed to differences in the sizes of NBs under different pH. Thus, the synergetic effects of NBB combined with NaClO were mostly enhanced under acidic conditions. An assessment of the costs of backwashing showed that the NB water is the cheapest among all the backwashing solutions used in this study, while HC-NB water is the most expensive. Although the mixture of NBs and NaClO is more expensive than each solution separately, the synergy of NBs and NaClO at acidic conditions (pH 4) is so positive that it becomes significantly more cost-effective, due to considerable improvements in the degree of fouling mitigation. The synergy of NBs and other chemicals can be further investigated in future studies. The application of NBB has still been rarely investigated and this study showed for the first time that NBs can be used for fouling mitigation in MBRs. In addition, the efficiency of NBB could be further improved by mixing NB with chemical reagents. This can lead to a new method for alleviating membrane fouling in MBRs.