論文の内容の要旨
Abstract of Dissertation

論文題目 Performance evaluation and microbial community analysis of an inclined-plate membrane bioreactor treating municipal wastewater at short hydraulic retention time (HRT) and complete sludge retention

（短い水理的滞留時間と汚泥完全貯留を実現させる傾斜板メンブレンバイオリアクターによる都市下水処理の性能評価と微生物叢解析）

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（本文）(Abstract)

Membrane bioreactor (MBR) is an innovative technology that combines the biological degradation capability of activated sludge with the direct solid–liquid separation provided by a membrane. This makes MBR a hybrid process in which a biological wastewater treatment process is combined directly with a membrane process. Ultra- or microfiltration membranes are often utilized for the separation of the treated water from the sludge. The main task of the membrane within this process is to separate the treated effluent from the biomass by retaining suspended solids and bacteria and allowing clean effluent to pass through. The membrane then replaces the traditional gravity sedimentation unit or clarifier in the activated sludge process since it acts as a barrier to retain biomass. This arrangement facilitates the independent control of sludge retention time (SRT) and hydraulic retention time (HRT). MBRs are usually operated at longer SRTs compared to conventional activated sludge systems. This allows slow growing microorganisms to establish themselves in the bioreactor and assist in improving treatment performance. In addition, at very long sludge retention times it is possible to attain almost zero excess sludge production.

However, one difficulty at very long SRTs is the elevated sludge concentration created in the reactor. High mixed liquor suspended solids (MLSS), if not controlled, can interfere with stable membrane filtration especially for long term operation. High MLSS hinders oxygen transfer to the sludge thus requiring extra air supply to maintain the appropriate aerobic environment. In addition, high MLSS also raises the sludge viscosity and increases the tendency for fiber clogging resulting in constant membrane fouling. It is therefore necessary

to address how stable operation with high sludge concentration can be achieved. An inclined plate membrane bioreactor (iPMBR) was introduced to meet this challenge. Since this system is a new design there is limited data demonstrating how it performs in the long run when operated at short HRT and without sludge wastage.

This study evaluated the performance of the iPMBR at the conditions of short HRT and complete sludge retention. The iPMBR is composed of two tanks in series, one operated under anoxic conditions and another one under aerobic conditions. The reactor received feed water from the primary sedimentation basin of the sewage treatment plant. One unique feature of the system is the presence of inclined plates inside the anoxic tank. The anoxic tank was constructed with seven inclined plates installed within it. These plates, which had an area of 750 cm^2 each, were to provide a settling area for the sludge. The aerobic tank contained a hollow-fiber, polyvinylidine fluoride (PVDF) membrane module manufactured by Mitsubishi Rayon. It had a surface area of 2.2m^2 and a nominal pore size of 0.4 μm.

The iPMBR was operated for over 400 days at different hydraulic retention times, which were changed several times throughout the period of study. The average hydraulic retention times for the entire system (anoxic and aerobic tanks) were relatively short ranging from approximately 1.0 hour to about 6.0 hours in total. The iPMBR was also operated at complete sludge retention. Small liquor volumes were taken for sampling but most of the sludge was kept inside the reactor. The performance of the system was evaluated in terms of the evolution of sludge concentration in the system over time and ability to remove pollutants from the wastewater.

With the use of inclined plates and intermittent blowing in the anoxic tank, a sludge concentration difference was created between the upstream anoxic and downstream aerobic tanks. MLSS in the anoxic tank was kept at a higher concentration (average of 11.1g/L) compared to the aerobic tank (average of 4.8 g/L). Biomass retention in the anoxic tank is desirable as it lowers the sludge concentration that flows to the aerobic tank. When operating at complete sludge retention where high MLSS is encountered, this ability of the iPMBR to concentrate the sludge in the anoxic tank is vital since it can extend membrane filtration by diverting most of the sludge from the aerobic tank. Additional energy requirements could also be potentially avoided by keeping the MLSS low in the aeration zone.

During the operation, the iPMBR was able to attain satisfactory removal of both carbonaceous and nitrogenous pollutants from the municipal wastewater even when operated without excess sludge discharge. The reactor was also able to achieve high clarity water by removing on average 99.8 percent of turbidity. At an increased recycle rate, the percentage nitrogen removal could be improved. The hydraulic retention time during the operation was relatively short compared to other systems, however, even at short HRTs and complete sludge retention, acceptable removal rates were obtained. Therefore, this system could be used in areas where the discharge criteria are not so strict and where space is limited and sludge disposal is problematic.

The use of molecular biology techniques in wastewater treatment systems has increased in use during the past years. This is because the identification and quantification of populations of microorganisms in their native habitat was made possible without the need to isolate them first. In the field of wastewater treatment, these techniques have been applied mainly to the study of flocs and biofilms that grow in aerobic treatment systems. The techniques mostly used include Denaturing gradient gel electrophoresis (DGGE), Fluorescent in situ hybridization (FISH) and PCR-Cloning/Sequencing of 16S rDNA.

Some researchers have investigated bacterial communities of MBRs but the information on structure, diversity, and stability of bacterial communities in MBRs treating domestic wastewater without sludge discharge is still largely limited. This study evaluated the microbial community in the iPMBR taking samples throughout various parts of the system including the sludge liquor and biofilm on the membrane surface.

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To identify the microbial community throughout the system, simultaneous sampling of the identified heterogeneous zones of the system had to be undertaken. Two experimental runs were conducted using mini-membrane modules. The first batch (Batch 1) used mini-membranes made of polyvinylidene fluoride (PVDF), which is the same material as the main membrane in the aerobic tank. The second batch (Batch 2) used two sets of mini-membranes, one set made of polyethylene (PE) and another set made of PVDF. The mini-membrane modules were immersed in an aerated tank using the same mixed liquor from the aerobic tank. These together with the liquor samples were used for the microbial community analysis. The sampling periods coincided with defined fouling phenomena occurring in the membrane.

Three fouling states were identified based on the transmembrane pressure (TMP), which is often used as an indicator for fouling. In this study the following criteria were used: low fouling state, TMP<10kPa; fouled state, TMP>20kPa and extremely fouled state, TMP>40kPa. The samples were taken at different fouling states to follow the development of the biofouling in terms of change in the microbial communities. This is to understand whether a shift or change in the microbial communities could shed light on the fouling phenomenon. The liquor and membrane biofilm samples from Day 30 of Batch 1 were processed by PCR-Cloning and Sequencing. The samples (mixed liquor and membrane biofilm) derived from the aerobic zone showed the same trend with regards to highest number of OTUs and clones present in the sample, *Betaproteobacteria*> *Bacteroidetes*> *Gammaproteobacteria*. On the other hand for both anoxic sludge samples (inclined plate sludge and bottom anoxic sludge), it was observed that the highest number of OTUs and clones followed the trend: *Bacteroidetes*> *Betaproteobacteria*> *Gammaproteobacteria*.

The liquor and membrane biofilm samples taken from Batch 1 and Batch 2 of the mini-membrane experiments were analyzed by FISH. According to the results, majority of the bacteria belonged to *Betaproteobacteria* in both aerobic and anoxic samples. In the aerobic *Betaproteobacteria* was followed by *Gammaproteobacteria* then *Bacteroidetes* while in the anoxic it was followed by *Bacteroidetes* then *Gammaproteobacteria*. *Chloroflexi* was identified in all liquor samples but not on the membrane samples.

DGGE analysis showed that the microbial communities were different between the liquor and the membrane biofilm samples. It was seen that several microbial species persist throughout the operation of the experiment. In the analysis of the band profiles from the PVDF biofilm samples, it was found that several bands persisted. This indicated the presence of a similar microbial species during the fouled state of the membrane. Physical cleaning of the membranes was done before they were returned back to the aeration tank. However, it seemed that the same microbial species grew back on the membrane after some time and they were present when the membranes reached a fouled state at TMP>20 kPa.

After day 407, two experiments were conducted to determine at what point the iPMBR will fail in terms of sludge retention. Failure was defined as the point when little difference between the sludge concentrations of the two tanks was observed. Two conditions were tested: high flux and high RAS ratio. Failure was realized at the high RAS condition. The iPMBR was also tested to determine whether it could recover and begin rezoning sludge at the anoxic tank again. It was seen that a recovery was possible albeit slowly. In terms of pollutant removal, COD removal rates remained the same but nitrogen removal declined due to low dissolved oxygen as a result of the high MLSS.
