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Fouling control of a pilot scale self-forming dynamic membrane bioreactor for municipal wastewater treatment

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ABSTRACT

A pilot scale self-forming dynamic membrane bioreactor (SFDMBR) was used for municipal wastewater treatment and its fouling control was investigated. Two methods, on-line bottom aeration flushing and off-line high-pressure water flushing, were applied to control the self-forming dynamic membrane (SFDM) fouling. Aeration intensity of 22 $m^3/(m^2 \cdot h)$ and aeration time of 2 min were the optimized operational conditions. Fouling of SFDM could be on-line controlled by bottom aeration flushing to keep the bioreactor continuously working for about 50 days. However, the intervals of bottom aeration flushing were gradually shortened which suggested that fouling could be controlled to some extent but gel layer could not be removed effectively. High-pressure water flushing could remove cake layer and most gel layer, and the membrane flux could be almost 100% recovered. Through the convenient fouling control by combination of bottom aeration and high-pressure water flushing, the present SFDMBR has been normally operated for more than one year and the effluent was suitable for urban miscellaneous water consumption if disinfection was added.

Keywords: Membrane fouling; Pilot scale experiment; Self-forming dynamic membrane; Municipal wastewater

1. Introduction

Membrane bioreactor (MBR) technology, an activated sludge process coupled a membrane separation process, has been regarded as a promising wastewater treatment technology due to its high quality effluent, small footprint, and less sludge production. However, expensive membrane modules and reduction of permeate flux caused by membrane fouling are major hurdles to its practical application [1,2].

Membrane fouling is generally caused by precipitation of inorganic particulates, adsorption of organic matters, and microbial adhesion and growth [3]. It is known that the fouling cake formed on the membrane surface

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enables the separation membranes to reject smaller objects, such as virus, inorganic ions and so on [4]. Based on positive application of the separation feature of fouling cake, a new kind of membrane has been developed, which is called as dynamic membrane (DM) or secondary membrane [5,6]. DM is created on the surface and in the pores of the membranes or other porous supports when filtering feed solutions containing membrane-forming materials such as inorganic hydrous oxides and macromolecular materials. The common supports include Dacron mesh [7], nonwoven fabric [8], nylon mesh [9,10], stainless steel mesh [11,12], and so on. Dynamic membrane bioreactor (DMBR) was developed to separate solid and liquid of mixed liquor in a bioreactor by using such DM [13]. There are two types of DM, self-forming dynamic membrane (SFDM) and precoated DM [7]. Correspondingly, there are two types of DMBR, self-forming dynamic membrane bioreactor (SFDMBR) and precoated DMBR.

SFDMBR features a low module cost, less energy consumption, and a high flux compared with MBRs using micro-/ultra-filtration membrane [14,15]. As a potential wastewater treatment technology, it has been of growing interest in recent years. Nevertheless, technical challenges for its practical application still remain particularly for the membrane fouling [16]. In course of filtration, there are physico—chemical interaction or mechanical actions between excess suspended solid, colloidal particles, soluble macromolecule and DM. As a result, they deposit on the DM surface or in the membrane pores so that membrane pores are blocked.

It plays an important role in practical application of SFDMBR to develop effective on-/off-line membrane fouling control methods. Membrane cleaning, including physical, chemical, and physical—chemical methods, is an essential step in maintaining the permeability and selectivity of a membrane process [17]. Without any chemical reagents, physical cleaning could be a preferable alternative in many occasions. There are several physical cleaning methods have been used including bottom aeration flushing [7,18], brushing and water flushing [19], off-line high-pressure water flushing [12].

At present, most of the studies on fouling control of SFDM still focused on lab-scale. There is a little information in detail about the fouling control on pilot scale experiment [12]. The aim of this study was to test two methods, on-line aeration from bottom of SFDM and off-line high-pressure water flushing to control fouling of SFDM for municipal wastewater treatment at a pilot scale and to forward beneficial references for long-term stable operation and practical application of SFDMBR.

2. Experiment

2.1. Experimental apparatus

A sketch of a SFDMBR is presented in Fig. 1. The SFDM modules resembled flat membrane ones. Steel wire mesh was served as the coarse pore-sized material of membrane modules. The size of each module was 0.5×1.0 m^2.

Filtrate, driven by a liquor level difference ΔH between bioreactor and water outlet, permeated through SFDM and flowed out from bioreactor. The effective volume of bioreactor was 2.8 m^3 and was divided into two parts with a baffle plate in bioreactor.

The apparatus was equipped with two aeration systems, lateral rubber micropore aerator and bottom perforated aerator. The two aeration systems, supplied with air by a blower, were controlled by a computer through several common ball valves and two electromagnetic valves. Each air branch was equipped with rotor flow meter and air amount could be manually adjusted. Micropore aerator was set in the left bottom of bioreactor, and the aeration was called lateral aeration. Perforated aerator was set under the membrane modules in the right bottom of bioreactor, and the aeration was called bottom aeration. During the normal running of the bioreactor, the lateral aeration supplied the mixed liquor with oxygen, drove mixed liquor to circulate from top to bottom in the bioreactor and to create a cross-flow on the membrane surface. Hydraulic sensor conveyed liquor level of the bioreactor to the computer that recorded all the data.

During filtration, SFDM could be gradually fouled and filtration resistance grew. When liquor level in the bioreactor rose to the given high level, which could be set

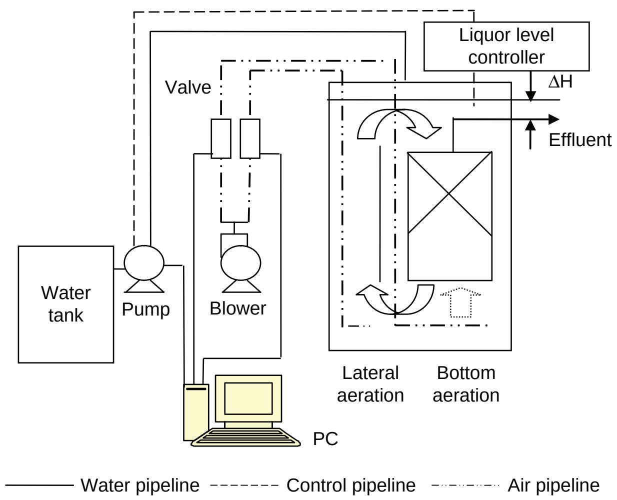

Fig. 1. Sketch of a SFDMBR.

Table 1
Span of each high-pressure water flush period.

High-pressure water flushing period	Starting and ending time (d)
1	1~25
2	25~46
3	46~107
4	107~138

up in the computer, computer automatically shut down the pump, opened the electromagnetic valve at bottom aeration pipe and turned off the electromagnetic valve at lateral aeration pipe. Air—water multiphase flow, produced by air from bottom aeration, flushed the cake layer on the SFDM surface. After several minutes, computer automatically shutdown the electromagnetic valve at bottom aeration pipe and opened the electromagnetic valve at lateral aeration pipe. Effluent, driven by liquor level difference, flewed out from the bioreactor. When liquor level of the bioreactor dropped to the given low level, computer automatically turned on the pump and bioreactor repeated another bottom aeration flushing period.

After running for a span of time, bottom aeration was becoming more and more frequent. When membrane flux decreased to about 10 L/(m^2·h), DM blocking was so serious that the fouling could not be fully removed by bottom aeration. The modules were lifted out of the bioreactor by an electronic windlass. A reducing pipe was connected to a water pipe. Water flowed out of the reducing pipe at a high speed to flush module surface to clean cake layer and most gel layer. The modules were then put back to the bioreactor and the SFDM could be re-formed by a new deposited layer. This cycle between two adjacent high-pressure water flushings is called high-pressure water flushing period. There were four high-pressure water periods in this research and the details are presented in the Table 1.

2.2. Operation of pilot scale apparatus

The pilot scale apparatus was located in Qinghe Municipal Wastewater Treatment Plant, Beijing. The influent was mainly municipal wastewater, including a small amount of industrial wastewater. The apparatus was controlled by computer. It could be either automatically or manually operated. The influent flux was adjusted by time relay to open and shut down pump.

Activated sludge was cultured in the bioreactor. At the first day, sludge concentration reached 2 g/L with sludge volume index (SVI) of 13.1%. The new modules were put into bioreactor. At day 19, sludge concentration reached 4 g/L with SVI of 19.7%. At day 20, the fouling removal by different bottom aeration intensity and aeration time, and high-pressure water flushing were investigated.

During each high-pressure water flushing period, the flux of newly-flushed modules was fairly high. The liquor level in bioreactor was constant in the initial days. The first bottom aeration occurred at day 2~5. Thereafter, aeration flushing periods was becoming shorter and shorter, and flux decreased. When flux reduced to about 10 L/(m^2·h), high-pressure water would be used to flush modules.

3. Results and discussion

3.1. Occurrence of membrane fouling

3.1.1. Changes of trans-membrane pressure

A crossflow filter that uses SFDM formed from suspended solids has many potential advantages including inexpensive membrane regeneration and low trans-membrane pressure (TMP) [20]. Thus, a pump to suck effluent is not necessary and effluent could flow out from bioreactor naturally. Two water level testing tubes were set up and connected to the bioreactor and effluent tank, respectively. The water level difference between the two tubes was TMP of SFDM shown in Fig. 2.

The TMP of the newly-flushed module was only 0.5 kPa. It increased to around 3 kPa at day 10~25, and by then SFDM was fully formed. At day 25~50, SFDM grew and distributed more evenly on the surface of steel wire mesh, with thickness of 1~2 mm. It was fairly fixed and not subject to detach from the surfaces of steel wire mesh. TMP was lower than that of at day 10~25 and SFDM was at the best running period. At day 51~62, thickness of SFDM was compacted with thickness of 2–4 mm.

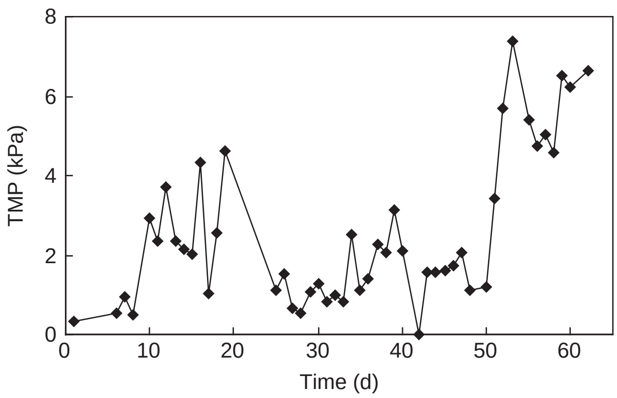

Fig. 2. Changes of trans-membrane pressure of SFDM during a high-pressure water flush period.

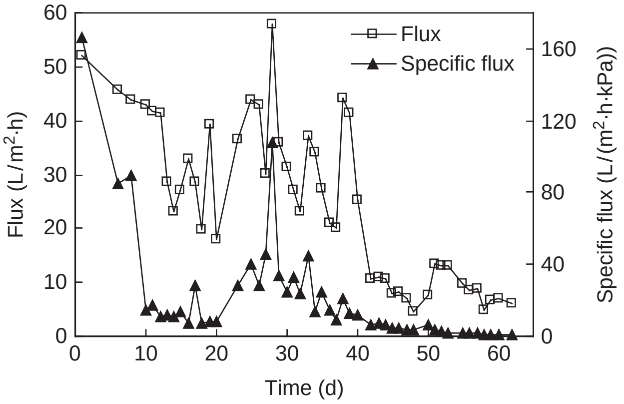

Fig. 3. Changes of membrane flux and specific permeability during a high-pressure water flushing period.

3.1.2. Changes of membrane flux and specific permeability

Figure 3 shows changes of membrane flux and specific permeability during a high-pressure water flushing period.

Flushed by high-pressure water, the flux was initially about 50 L/(m^2·h), and then decreased to 40 L/(m^2·h) within 12 days. Henceforth, it fluctuated sharply within 40 days at an average flux of 32 L/(m^2·h). At day 42~62, it decreased notably at an average flux of 9 L/(m^2·h). Fluctuation of specific flux resembled that of flux, from initial 166 L/(m^2·h·kPa) to final 1 L/(m^2·h·kPa). The specific flux of SFDM was higher than that of a microporous membrane under similar TMP, so SFDM exhibited the same permeate flux as micro-porous membrane with lower energy consumption [8,21].

There are two scenarios about SFDM fouling. In the first one, the fouling is mostly caused by soluble microbial product [22,23]. Such product could gradually adhere to the membrane surface and void to form gel layer even at high shear force. This kind of fouling, formed by gel layer, is difficult to be removed which is called irreversible fouling. In the second scenario, the fouling is caused by particles, mainly sludge flocs. They deposit to the membrane surface to form cake layer [24]. This kind of fouling, formed by cake layer, is called reversible fouling and can be removed by changing hydraulic conditions. The macro characterization of membrane fouling is that TMP increases.

3.2. Methods for membrane fouling control

Stability of the SFDM is an important criterion for potential application [25]. Alleviation and control of membrane fouling are principal methods for stability improvement.

3.2.1. Bottom aeration flushing

Bottom aeration flushing could automatically online perform so that it is practical for retaining stable running of SFDMBR.

Step 1: Determination of aeration intensity

With the bottom aeration flushing time of 2 min, the effect of different bottom aeration intensities on effluent turbidity was investigated. At the aeration intensities of 15 m^3/(m^2·h), 22 m^3/(m^2·h), and 30 m^3/(m^2·h), all the initial effluent turbidity was more than 16 NTU. However, the subsequent turbidity of effluent, was less than 5 NTU after 10 min, 15 min, and 21 min, respectively. Therefore, SFDM was considered to be recovered within a short period of time. Very strong aeration intensity could fully remove the fouling but extend the recovery time of SFDM; weak intensity could not remove the fouling effectively. According to energy consumption and membrane fouling removal, aeration intensity of 22 m^3/(m^2·h) was chosen as best one.

Step 2: Determination of aeration time

Under of the aeration intensity of 22 m^3/(m^2·h), effect of three aeration flushing times on effluent turbidity was investigated. When the bottom aeration flushing times were 1 min, 2 min, and 5 min, all initial effluent turbidity was more than 19 NTU. However, turbidity was less than 5 NTU after 16 min, 20 min, and 24 min, respectively. Results revealed that if the aeration time was too long, the recovery time of SFDM would be extended, even though fouling could be removed effectively. Therefore aeration time of 2 min was chosen as best one with considering overall factors.

SFDM evenly distributed on the surface of supporting material during normal operation of SFDMBR. Bottom aeration changed the hydrodynamic conditions around the modules, which resulted in different deposit layer properties: thickness, structure and particle size distribution [26]. The modules were flushed by bottom aeration and then lifted out of the bioreactor. It was observed that most SFDM, mainly cake layer, was flushed off.

Step 3: Changes of bottom aeration flushing period during a high-pressure water flushing period

The 2nd high-pressure water flushing period was selected to investigate the changes of bottom aeration flushing period. As illuminated in Fig. 4, membrane modules were flushed by high-pressure water with the flux of 52.1 L/(m^2·h) at day 46, which was close to flux of new modules. After 74 h, liquor level in bioreactor rose to some extent because of membrane fouling, and the first aeration flushing was started under control of the computer. Namely, the first aeration flushing period was

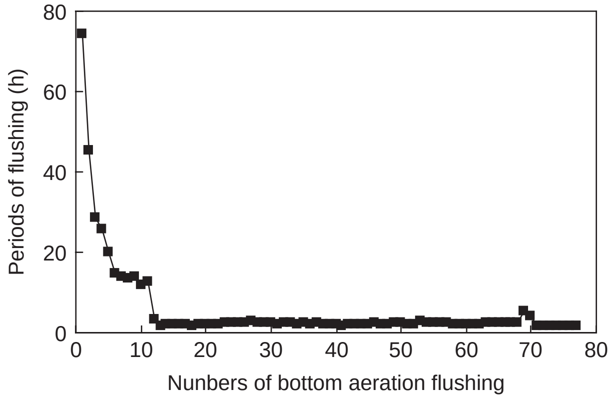

Fig. 4. Changes of bottom aeration flushing periods during a high-pressure water flushing period.

74 h. The second aeration flushing was performed at the 119 h which meant the second aeration flushing period was 45 h. Similarly, the 11th aeration flushing was performed at day 13 with aeration period of 12 h. At day 14~56, aeration flushing periods remained about 2 h. At day 57~62, it was about 1.5 h with flux of less than 10 L/(m^2·h) which meant that membrane fouling was fairly serious. High-pressure water would be used to flush modules. The 100th aeration flushing was performed at day 19. Thereafter, aeration flushing periods had little fluctuation and were not shown in Fig. 4.

Therefore, SFDM fouling could be on-line controlled by bottom aeration flushing to keep the bioreactor continuously working for about 50 days. However, the intervals of bottom aeration flushing were gradually shortened which suggested that fouling could be controlled to some extent and gel layer could not be removed effectively.

3.2.2. High-pressure water flushing

When bottom aeration flushing was more and more frequent and flux decreased to about 10 L/(m^2·h), membrane fouling was so serious that high-pressure water could be used to flush off cake layer and most gel layer. A thin SFDM was formed on the surface of the modules at 5 min after the flushed modules were put back to the bioreactor. Table 2 shows the recovery of permeability flux after modules being flushed by high-pressure water at different operational times.

Flux of new modules was 56.8 L/(m^2·h) at the first day. The first high-pressure water flushing was performed at day 25 and the flux was lower because bioreactor had been running for only a short time and activated sludge had not achieved good property. Subsequently, flux exceeded 50 L/(m^2·h) when the 2nd, 3rd and 4th high-pressure water flushing were performed. In ultra-filtration, the thickness of gel layer depends on operational parameters such as TMP, temperature, and the properties of the feed solution, especially crossflow velocity [27]. The complete flux recovery meant that high-pressure water flushing could effectively remove fouling caused by cake layer and gel layer.

Table 2
Recovery of permeability flux after modules being flushed by high-pressure water at different operational date.

No. of high-pressure water flushing	Operational time/d	Flux/(L/(m^2·h))
1	25	30.3
2	46	52.1
3	107	51.3
4	138	58.1

Changes of effluent turbidity within 50 min after modules being flushed by high-pressure water is shown in Fig. 5. The initial effluent turbidity, when modules were flushed by high-pressure water, was much higher than turbidity when flushed by bottom aeration. However, turbidity decreased quickly to 10 NTU at 10 min, and decreased to 5 NTU at 25 min. This indicated that cake layer and most gel layer could be removed by high-pressure water and new SFDM could be rapidly re-formed by new deposited layers.

According to the national standard "The reuse of urban recycling water—water quality standard for urban miscellaneous water consumption (GB/T 18920-2002)", turbidity of municipal miscellaneous water used for toilet flushing, the street sweeping, fire fighting, municipal greening, vehicle flushing, building construction should be less than or equal to 5, 10, 10, 5, 20 NTU, respectively.

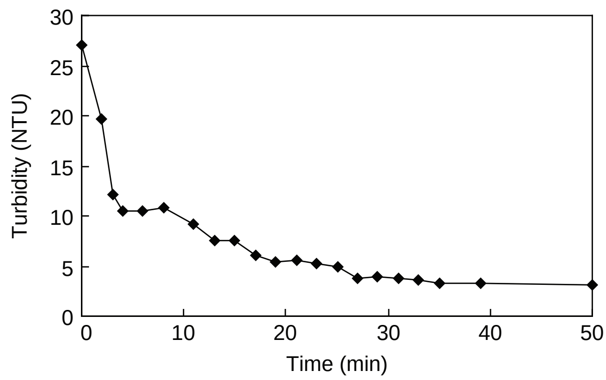

Fig. 5. Changes of effluent turbidity after modules being flushed by high-pressure water.

During stable running of SFDMBR, the effluent turbidity was less than 5 NTU, generally 2 NTU. If the effluent was disinfected, it could meet the standard of all urban miscellaneous water consumption. For the effluent within an initial short time period after bottom aeration or high-pressure water flushing perhaps did not meet the standard and should be recycled to the bioreactor for further treatment.

As for ultra-filtration membranes, chemical cleaning alone is not enough to control fouling because foulants are insufficiently removed while both hydraulic and chemical cleanings can be used [28]. However, it was convenient to control fouling of SFDMBR by bottom aeration and high-pressure water flushing. The present SFDMBR has been normally operated for more than one year and the effluent was suitable for urban miscellaneous water consumption if disinfection was added. This research lays a good foundation for the optimal design, operation, and practical application of SFDMBR.

4. Conclusions

Based on investigation on effects of the bottom aeration intensity and aeration flushing time on control of SFDM fouling, aeration intensity of 22 $m^3/(m^2{\cdot}h)$ and aeration time of 2 min were chosen as optimal conditions. Fouling of SFDM could be on-line controlled by bottom aeration flushing to keep the bioreactor continuously working for about 50 days. However, the intervals of bottom aeration flushing were gradually shortened which suggested that fouling could be controlled to some extent but gel layer could not be removed effectively. When high-pressure water flushing was performed, the membrane flux could be almost 100% recovered. Therefore, high-pressure water flushing could removed cake layer and most gel layer and new SFDM could be rapidly re-formed by new deposited layers. Through the convenient fouling control by combination of bottom aeration and high-pressure water flushing, the present SFDMBR has been normally operated for more than one year and the effluent was suitable for urban miscellaneous water consumption if disinfection was added. This research lays a good foundation for the optimal design, operation, and practical application of SFDMBR.

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