Direct sewage filtration for concentration of organic matters by dynamic membrane
Hui Gong, Xian Wang, Mingxia Zheng, Zhengyu Jin and Kaijun Wang

ABSTRACT
Sewage treatment is experiencing a paradigm shift whereby sewage should be treated as a resource with maximum reuse of water, nutrients and energy. Concentration of sewage for organic matter enrichment is essential for improved energy recovery. In this study, the concentrating performance of direct sewage filtration by a dynamic membrane was investigated. A novel double-layer cloth-media membrane module was developed. A 50 μm Daron cloth was selected as inner layer and a 1 μm propene polymer cloth as outer layer. Quick formation of the dynamic membrane was observed and it agreed with the complete blocking model. The results of continuous-flow experiments showed that chemical oxygen demand (COD) was concentrated to about 4500 mg/L within nine operation cycles in 70 hours. Trans-membrane pressure increased quickly to 80 kPa at the end of each cycle. Theoretical concentrating efficiency (η) was 77% and the carbon balance calculation showed 70.7% COD was retained in the reactor during the concentrating process. Scanning electron microscopy analysis showed that the cake layer was almost completely removed after physical cleaning and the gel layer was not remarkable. A sequencing sewage concentrating process was proposed for long-term operation.

Key words | sewage concentrating, energy recovery, dynamic membrane, double-layer cloth filter

INTRODUCTION
Sewage treatment is experiencing a paradigm shift in that sewage should not be treated as a waste but as a resource (McCarty et al. 2011; Wang et al. 2012). Future objectives of sewage treatment will be achieving the sustainable reuse of energy, water and nutrients, and the reduction of greenhouse gas release. With these objectives in mind, novel concepts have been discussed and proposed in recent years. McCarty et al. discussed the potential of using the sewage plant as a net energy producer (McCarty et al. 2011). Sutton et al. evaluated a new treatment flow-sheet which shunted a large fraction of organic carbon in sewage to sludge and ultimately treated the sludge via anaerobic digestion (Sutton et al. 2011). Verstraete et al. discussed the potential of using the sewage plant as a net energy producer (McCarty et al. 2011). Sutton et al. evaluated a new treatment flow-sheet which shunted a large fraction of organic carbon in sewage to sludge and ultimately treated the sludge via anaerobic digestion (Sutton et al. 2011). Verstraete et al. proposed the ZeroWasteWater concept as a sustainable centralized technology and the ‘up-concentration’ process was proposed to be followed by anaerobic digestion of organics to achieve maximum use of resources present in domestic ‘used water’ (Verstraete et al. 2009; Verstraete & Vlaeminck 2011).

Among the above-mentioned concepts, anaerobic treatment is regarded as the core technology for energy recovery. However, low organic concentration is the main barrier for direct sewage anaerobic treatment. Thus, organic matter enrichment in the sewage concentration process becomes the key step to improve energy recovery (Akanyeti et al. 2010; Hernández Leal et al. 2010; Mezohegyi et al. 2012). To provide concentrated sewage with high chemical oxygen demand (COD) which meets economic requirement for subsequent anaerobic treatment, cost-effective sewage concentrating technologies needed. Conventional physical–chemical technologies including pre-precipitation and flotation have been employed to concentrate organic matters in sewage, especially the suspended and colloidal parts. Nevertheless, high chemical use and increased salinity in the effluent were identified as main drawbacks (Mels et al. 1999; Van Nieuwenhuijzen et al. 2001). Recently, membrane technologies have been tested for sewage concentrating and have achieved high COD removal from sewage. A high-load membrane biological reactor (MBR) was evaluated to concentrate organics in grey water by bio-flocculation (Akanyeti et al. 2010; Hernández Leal et al. 2010).

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Submerged aerated and vibrated membranes were tested and compared for sewage up-concentration (Mezöhegyi et al. 2012). However, these sewage concentrating processes suffered comparatively high investment on membrane materials and in situ COD losses caused by biodegradation in aerated process.

A dynamic membrane, also called secondary membrane, could self-form on the surface of coarse media during filtration of solutions containing membrane-forming materials (Kuberkar & Davis 2000). Similar separation efficiency could be achieved by dynamic membranes as compared to microfiltration or even reverse osmosis membranes (Kiso et al. 2000; Fan & Huang 2002; Fuchs et al. 2005). There have been many previous studies focusing on the feasibility of using dynamic membranes to replace microfiltration membranes (Yu et al. 2012). However, few studies have been conducted to make use of dynamic membranes for sewage concentrating. When raw domestic sewage was directly filtered, particles in sewage deposited as a cake layer and formed a dynamic membrane. Thus, the dynamic membrane process could avoid aeration for fouling control, making it promising for sewage concentrating with low expenditure, low energy consumption and low fouling. In addition, different kinds of mesh materials (e.g. stainless steel non-woven fabric and industrial filter-cloth) have been tested and employed as filter media in previous studies (Zhang et al. 2010). However, little attention has been paid to the structure of the filter media and membrane module.

In this study, the dynamic membrane process was tested and a novel double-layer filter-cloth media was designed as a membrane module. The effects of cloth pore diameter on the dynamic membrane formation were investigated. Sewage concentrating performance was examined and factors influencing concentration efficiency are discussed. Also, membrane fouling characteristics were studied and a sequencing sewage concentrating process for long-term operation is proposed.

**MATERIALS AND METHODS**

**Wastewater source**

Raw sewage was taken from Xiao Jiahe municipal wastewater treatment plant in Beijing, P. R. China. The plant treated 20,000 ton of sewage every day, which was continuously collected from nearby communities, and no industrial wastewater was mixed. The major physicochemical characteristics are shown in Table 1.

**Double-layer cloth-media membrane module**

A schematic diagram of the double-layer cloth-media dynamic membrane module is shown in Figure 1(left). The manually prepared module was quite similar with rectangular flat sheet membranes (20 cm × 11.5 cm), made of a stainless steel grid and covered by a double-layer cloth. The inner cloth was Dacron while the outer cloth was propene polymer (PP). In this study, PP cloth with equivalent pore sizes of 1, 10, 50 and 100 μm was tested.

**Table 1** | Characteristics of the domestic sewage

<table>
<thead>
<tr>
<th>Items</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.98</td>
<td>7.95</td>
<td>7.64</td>
</tr>
<tr>
<td>COD (mg/L)</td>
<td>367</td>
<td>595</td>
<td>472</td>
</tr>
<tr>
<td>SS (g/L)</td>
<td>0.2</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>16.1</td>
<td>21.5</td>
<td>19.4</td>
</tr>
</tbody>
</table>

**Figure 1** | (Left) Schematic diagram of membrane module (inner cloth (a); outer cloth (b); cake layer (c)). (Right) Experimental setup.
Experimental setup

As shown in Figure 1(right), the laboratory-scale experimental setup consisted of a 10-L reactor tank with an automatically controlled peristaltic pump maintaining the liquid level. The effluent was sucked out by peristaltic pump. A high-precision vacuum pressure gauge was installed on the effluent pipe to measure the suction pressure which was used to calculate the trans-membrane pressure (TMP). At the start of the experiment, 10 g diatomite was added as coagulant to enhance formation of the dynamic membrane.

Experimental procedures had two operation modes: cyclic-flow mode and continuous-flow mode. The cyclic-flow mode was used only for dynamic membrane formation. In this mode, the effluent was returned to the reactor tank until most particles in the reactor were attached on the surface of the support media. The total process lasted for about 2 hours until the TMP reached stability. The continuous-flow mode was used for the sewage concentrating process. In this mode, domestic sewage was directly filtered by the double-layer cloth module with the dynamic membrane formed on the surface. The reactor was continuously operated by withdrawing the filtrate and feeding the same amount of raw sewage with a liquid level controlled peristaltic pump. The membrane was mechanically cleaned every 8 hours. One cycle was defined as from one mechanical cleaning to another. The experiment lasted nine cycles. This study focused on the feasibility of making use of the self-forming dynamic membrane to concentrate sewage so that no concentrated sewage was discharged during the sewage concentrating process.

Blocking filtration laws

Dynamic membrane formation is a complex process including many physicochemical and microbiological mechanisms which can be expressed by classic filtration laws. Four classic filtration laws (Table 2) for dead-end filtration (Hlavacek & Bouchet 1995) could be used to explain the relationship between flux behaviors and the filtration pressure.

<table>
<thead>
<tr>
<th>Filtration law</th>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cake filtration</td>
<td>( t/V = aV + b )</td>
<td>Particles larger than the membrane pore size</td>
</tr>
<tr>
<td>Complete blocking</td>
<td>(-\ln (J/J_0) = at + b)</td>
<td>Occlusion of pores by particles with no particle superimposition</td>
</tr>
<tr>
<td>Intermediate blocking</td>
<td>( J_0/J = at + b )</td>
<td>Occlusion of pores by particles with particle superimposition</td>
</tr>
<tr>
<td>Standard blocking</td>
<td>( t/V = at + b )</td>
<td>Particles smaller than membrane pore size</td>
</tr>
</tbody>
</table>

\( V \) is the cumulative volume of permeate at time \( t \); \( J \) is the flux; \( J_0 \) is the initial flux; \( a \) and \( b \) are model parameters.

Evaluation of concentrating efficiency

To evaluate the sewage concentrating process, COD concentrating efficiency (\( \eta \)) was defined as Equation (1):

\[
\eta = \frac{(C_i - C_e)}{C_i}
\]  

where \( C_i \) and \( C_e \) are the COD concentration in influent and effluent, respectively. COD concentrating efficiency (\( \eta \)) implies the ratio of achieved concentrated COD amount to the theoretical maximum COD amount which could be concentrated.

Analytic methods

Suspended solids (SS) were determined according to the Chinese National Environmental Protection Agency standard methods (NEPA 2002). Total COD and soluble CODs were determined by colorimetric techniques using a Hach spectrophotometer (DR 5000, Hach, USA). Turbidity and pH were measured using a photoelectric turbidity instrument (Model 2100Q, Hach, USA) and pH meter (Sension1, Hach, USA) respectively. Morphologies of the dynamic membrane and cloth media were observed by using a scanning electron microscope (Hitachi S-4500, Japan).

RESULTS AND DISCUSSION

Selection of cloth-media and dynamic membrane formation

Formation of the dynamic membrane was influenced by the characteristics of the supporting materials and sewage. Dacron cloth with high strength functioned as inner materials to provide mechanical support, while PP cloth constituted the outer supporting materials on which the dynamic membrane was formed. To identify the most suitable cloth pore diameter, PP cloth with equivalent pore sizes of 1, 10,
50 and 100 μm was tested in cyclic-flow mode in the study. The stable operation pressure of different cloth media is shown in Figure 2(a). The results indicated that decreasing of the cloth pore diameter was associated with an increase of stable operation pressure except for the 50 μm cloth whose pressure was much higher than the others. It was probably because most particles in the sewage mixture were between 20 and 50 μm. Thus, when sewage was filtered by the 50 μm cloth, the filtration pattern was in accordance with the complete blocking model, in which each particle blocked a certain pore and no more fluid was allowed to pass through this pore. Consequently, the pressure of the 50 μm cloth was highest among the four cloth types. For the 1 and 10 μm cloth media, particles in sewage were larger than cloth pore size and the cake filtration model applied, in which each particle was stacked onto early arrivals on the cloth surface and a formed cake layer. Thus, the 1 and 10 μm cloths were more suitable for dynamic membrane formation. COD removal efficiency of 1 and 10 μm cloth was also compared. As shown in Figure 2(a), 1 μm cloth achieved higher COD removal efficiency than 10 μm cloth, indicating that 1 μm cloth was the most suitable media for dynamic membrane formation in this study.

**Sewage concentrating performance**

**COD concentrating**

Continuous-flow mode was used for the sewage concentrating process in this study. The concentrating process lasted for 70 hours with nine cycles and the COD concentration in the reactor is shown in Figure 2(b). COD in influent was between 490 and 760 mg/L with an average value of 615 mg/L while effluent COD was between 60 and...
250 mg/L averaging 139 mg/L. COD in the reactor increased from 700 mg/L to about 4500 mg/L. SS in concentrated sewage increased as COD increased and reached about 4 g/L at the end of the experiment.

**TMP profiles**

During sewage filtration, rapid dynamic membrane formation was observed. The variations of TMP and flux with operation time are demonstrated in Figure 2(c). Membrane fouling occurred quickly during all experiment cycles. TMP increased quickly to about 80 kPa at the end of each cycle while the flux decreased from 10 L/(m²·h) to lower than 2 L/(m²·h). The flux was higher than 5 L/(m²·h) in the first half of the cycle and an average flux of 2.4 L/(m²·h) was achieved based on integration calculation of fluctuant flux. The profiles of TMP and flux were similar to a previous study (Hernández Leal et al. 2010). It should be noted that although TMP developed quickly, the flux recovered completely after just physical cleaning and there was no need for chemical cleaning. It also indicated that frequent physical cleaning is helpful for flux recovery. The development of a cleaning strategy, therefore, is probably crucial for better performance of the concentrating process. Different from controlling fouling by coarse bubble aeration, which consumes as much energy as in MBRs, the energy cost of physical cleaning is lower. Thus, to some extent frequent physical cleaning is acceptable. Furthermore, shortening the cycle and increasing cleaning frequency could obtain higher average flux. As mentioned, the development of cleaning strategy is one key step for good performance of the dynamic-membrane sewage concentrating process and the energy consumption of the concentrating process should be considered in the total energy balance.

**Mass balance and concentrating efficiency**

The total COD concentrating performance was evaluated by calculating mass balance and concentrating efficiency. The fraction of COD in effluent was 29.3%, which indicated 70.7% COD was retained in the sewage concentrating process. Mass balance calculation showed that 44.7% of total COD was collected in the concentrated sewage. Meanwhile, 26.0% COD was retained in the reactor but not in the concentrated part. Because of their incapability for entering energy recovery process, this amount of COD included organic matters retained in cake layers, deposited in the reactor and perhaps COD involved in mineralization process. It should be noted that, without aeration in the dynamic-membrane concentrating process, mineralization of organic matters might be much lower than other membrane concentrating technologies. Considering potential negative effects caused by biomass formation on energy recovery during anaerobic treatment, better energy recovery performance for energy recovery could be achieved by a dynamic membrane. In addition, better mixing in the reactor and frequent membrane cleaning could be employed to improve concentrated COD in further research.

**Fouling and filtration performance of dynamic membrane**

The scanning electron microscopy (SEM) pictures of the inner cloth, outer cloth, cake layer and outer cloth after cleaning are shown in Figure 3. The inner cloth showed a tight coupling web-like structure which provided mechanical strength while the outer cloth showed a hair-like structure which helped maintain filtration flux. After dynamic membrane formation, a developed cake layer was observed. As shown in Figure 3(c), the deposits on the surface of the cake layer were tiny and homogeneous. The cake layer surface was a little rough and diatomite particles were observed. Once the dynamic membrane was formed, the support cloth contributed little to the filtration capacity, and it only played the role of supporting material and improved the membrane strength. The dynamic membrane formed during sewage filtration could be divided into two parts: cake and gel layer (Fan & Huang 2002). The cake layer attached to the outer cloth loosely but performed the main separation function by rejecting particle COD and colloid COD. After physical cleaning, the cake layer was almost completely removed and the gel layer turned out to be unremarkable, which could help the regeneration of the dynamic membrane (Figure 3(d)).

**Sequencing batch mode for long-term operation**

Because of no concentrated sewage discharged, the continuous-flow operation mode in this study should only be considered as the first step for continuous concentration of sewage. To obtain concentrated sewage continuously, two possible post-steps were further designed. The first was sewage filtration with constant concentrated sewage production. However, satisfactory continuous concentrating performance could only be achieved and maintained by appropriate control of process parameters such as influent COD, effluent COD and effluent flux (Mezöhegyi et al. 2012).

The second possible post-step, which was proposed in this research, was based on the fill-batch process. As shown in Figure 4, the proposed process sequencing
sewage concentrating process), which performed like the sequencing batch reactor process for activated sludge treatment, repeated the ‘fill–concentrating–draw–idle’ cycle. When COD reached the expected concentration, for example 4500 mg/L in this study, the total sewage in the reactor would be discharged as concentrated sewage and the whole concentrating process was repeated as a batch process. The sewage concentrating process under this situation could be evaluated by the final sewage concentration at the end of each batch.

Implications of dynamic membrane filtration for sewage concentrating

Pollutant removal is always the basic requirement of sewage treatment, and resource recovery from sewage will also be an attractive option for future sewage plant. The process of sewage concentrating serves as a pretreatment designed to improve energy recovery from sewage through producing biogas by the anaerobic process, which also provides benefits for subsequent pollutant removal since much of the organics have been removed during this pre-treatment step. However, there are still some issues for dynamic membrane filtration, which should be carefully considered. First, the removal performance of the dynamic membrane for toxic compounds contained in the sewage, including hormones, pharmaceuticals, personal care products and pathogens, is still unclear. Further investigation is needed to guarantee security of resource reuse from sewage. Also, the stability of cloth media for DM should be evaluated under long-term operation to achieve lifecycle assessment.

Figure 3 | SEM view of cloth media and dynamic membrane (150): (a) inner layer of cloth media; (b) outer layer of cloth media; (c) surface of dynamic membrane; (d) surface of outer cloth media after cleaning.

Figure 4 | Procedure of sequencing sewage concentrating process.
CONCLUSIONS

Direct sewage filtration by a dynamic membrane was feasible for COD concentrating, especially for the non-soluble fraction. A novel double-layer cloth-media module was designed and showed high efficiency. Rapid formation of a dynamic membrane was observed and was in accordance with the complete blocking model. One-micron PP cloth was chosen as most suitable outer supporting materials. In the laboratory-scale continuous-flow experiment, COD was concentrated from 615 mg/L to 4500 mg/L in 70 hours. TMP increased quickly to about 80 kPa at the end of each cycle, and a high-frequency physical cleaning strategy could solve the fouling problem and increase concentrating performance. SEM analysis showed the gel layer was unremarkable after physical cleaning. COD loss caused by biodegradation and biomass conversion was limited by avoiding the aeration process and 70.7% COD was retained in reactor.

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