Operational Factors in Membrane Bioreactors Using a Simple Ceramic Filter

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ABSTRACT
To explore the cost reduction of water reclamation and reuse facilities in developing countries, a simple ceramic filter made of local materials, such as clay and rice bran, was used in a membrane bioreactor (MBR) process. The feasibility of applying suction filtration to an MBR with a simple ceramic filter was examined by a laboratory-scale experiment; successful results using gravity filtration were reported in a previous paper. The BOD removal performance was satisfactory and demonstrated the feasibility of reusing effluent water for many purposes. The MBR operation with a flux less than 0.2 m/d showed a lower risk of fouling; increasing the flux caused an increase in fouling risk. The suction filtration and gravity filtration results were compared using the total resistance of the filter ($R$) and the resistance change rate ($dR/dt$). The $R$ and $dR/dt$ values were estimated higher in the suction filtration compared to those in the gravity filtration. The high $dR/dt$ seemed to cause the necessity of the filter cleaning. The gravity filtration was suggested to be a more advantageous operation than the suction filtration in MBR using the simple ceramic filter.

Keywords: low-cost technology, MBR, simple ceramic filter, suction and gravity filtration, water reuse

INTRODUCTION
The world is facing a global water shortage and a water quality crisis due to continuing population growth and urbanisation, rapid industrialisation, climate change and the unregulated or illegal discharge of wastewater within and beyond national borders (Ujang and Buckley, 2002). Therefore, the concept of wastewater reclamation and reuse has been recognised widely, even in developing countries, where the development of water supply and sanitation are still major concerns.

Advanced wastewater treatment technologies have been designed and proposed so that the treated effluent can meet the highly restrictive guidelines for disposal and/or reuse. However, these technologies are still limited to developed countries only. Advanced treatment technologies have not expanded to developing countries due to the high cost and the difficulties of installation, operation and maintenance (Mara, 2004). To overcome these challenges, interest in the development of simple, innovative, inexpensive and effective techniques for wastewater reclamation and reuse is increasing (Al-Malack, 2007; Bani-Melhem and Elektorowicz, 2011).

Membrane bioreactor (MBR) processes are regarded as a key element of advanced wastewater reclamation and reuse schemes (Howell et al., 2004) and have gained popularity, especially for decentralised applications (Stephenson et al., 2000; Abegglen and Siegrist, 2006; Yang et al., 2006). In MBR processes, the bioreactor is a biological treatment processor and the membrane is used as a filter for solid-liquid separation. MBR technologies with microfiltration (MF) or ultrafiltration (UF) membranes have the merits...
of very high effluent quality, low footprint, quick startup, low sludge production and the capability to resist high organic loading (Holler and Trosch, 2001; Masse et al., 2006; Kraume and Drews, 2010; Mutamim et al., 2012). However, the high cost of membranes and the likelihood of membrane fouling are considered the main barriers to widespread application of MBR technologies (Gander et al., 2000; Le-Clech et al., 2006; Hasan et al., 2011). MBR technologies can only compete with activated sludge systems by substituting a low-cost filter for the traditional membrane and tackling the fouling problem using a low-cost technology (Meng et al., 2009; Bilad et al., 2011). Consequently, in recent years, there has been rapid development of modified MBRs to make them cost-effective and practical for use in developing countries.

MBR membranes and filters are usually made of organic polymer or inorganic ceramics; however, alternative materials such as clay, fly ash, coarse meshes and fabrics have also been considered for use in MBRs to reduce the membrane cost and the fouling phenomena associated with conventional membranes (Tewari et al., 2010; Jedidi et al., 2011; Zahid and El-Shafai, 2011; Wang et al., 2012). A simple ceramic filter made with locally available and cheap materials (clay soil and rice bran) was developed for arsenic removal from groundwater (Shafiquzzaman et al., 2011). The ceramic filter was manufactured in rural areas in Bangladesh, and its arsenic removal performance was examined on both the laboratory and field scales. Iron oxide floc with adsorbed arsenic was completely separated by the filter using gravity filtration. The ceramic filter achieved high removal performance of arsenic over one full year of operation in a rural area of Bangladesh (Hasan et al., 2012).

The ceramic filter had a pore size of 1 – 5 μm (Shafiquzzaman et al., 2011). This filter is considered for use as an MBR filter media because it is able to separate activated sludge floc as efficiently as a commercial polymeric membrane or mesh filter (Fuchs et al., 2005; Satyawali and Balakrishnan, 2008). A previous study confirmed its use in a laboratory-scale MBR under gravitational pressure (Hasan et al., 2011).

The purpose of this study is to examine the feasibility of suction filtration in an MBR with a simple ceramic filter because suction filtration has been widely used in submerged MBRs. Moreover, the operational factors, filter resistance and its change rate in MBRs using a simple ceramic filter were estimated for comparison of the suction filtration to gravity filtration results.

MATERIALS AND METHODS

Simple ceramic filter

The simple ceramic filter was manufactured according to previous studies (Hasan et al., 2011; Shafiquzzaman et al., 2011). Soil from Bangladesh and rice bran were used as materials. They were dried, ground and sieved by 0.5 mm and 1 mm mesh, respectively. Soil and rice bran (80% and 20% by weight, respectively) were mixed homogeneously and made a dough using sufficient amount of water. The filter was then manufactured in a hollow cylindrical shape (10 cm height with 10 cm outer and 6 cm inner diameters and one side closed) similar to that described in previous studies. After sun drying the filter was burnt at 900°C in the furnace for two hours. The effluent pipe was connected to the open side of the filter using glue and cramp. The filter permeation
surface area was 310 cm². The pore size of the filter was approximately 1 – 5 μm, and the manufacturing cost of one ceramic filter was US$0.2 – 0.3 (Hasan et al., 2011).

**Experimental set up and operational conditions**
The ceramic filter was submerged in the reactors (Fig. 1). The same one filter was used in Run 1 and Run 2, while the other two filters manufactured in the same procedure using the same material as the first one were used in Run 3 and Run 4. The volume of the mixed liquor (ML) in the reactors was 10.2, 12.4, 15.6 and 18.8 L in Run 1, Run 2, Run 3 and Run 4, respectively. Synthetic wastewater containing carbon source (glucose and glutamate salt), nutrient and buffer salts ((NH₄)₂SO₄, CaCl₂, NaCl, MgSO₄, K₂HPO₄ and KH₂PO₄) and alkaline substance (NaHCO₃) was prepared to have a typical domestic wastewater concentration (BOD 200 mg/L, T-N 50 mg/L, T-P 5 mg/L) and was fed continuously into the reactors with a BOD load of 0.1 kg/(m³·d). The synthetic wastewater did not contain peptone nor yeast extract, which might affect the filtration in MBR.

The permeate effluent was drawn through the filter by the suction pump at four different flux rates: 0.16, 0.20, 0.25 and 0.30 m/d in Run 1, Run 2, Run 3 and Run 4, respectively. The hydraulic retention time (HRT) was 2 days for all runs. The pressure gauge was set to measure the trans-membrane pressure (TMP). A diffuser was set below the filter for aeration so that rising air bubbles could provide the filter surface. The ML was aerated intermittently on a 2-hour cycle with aeration for 1 hour and without aeration for the second hour to achieve nutrient removal as well as to reduce the bulking of the ML. The airflow rate was approximately 4.5 L/min during aeration time.

The suction pump was operated continuously during both aeration and non-aeration time to withdraw the permeate effluent through the filter. When the TMP value equaled or exceeded 0.03 MPa, the suction was stopped, and the filter surface was cleaned using soft brush and water. The suction was started again after the cleaning. There was no sludge wastage except for the samples taken for analysis during the operation, resulting in the long SRT of more than 500 days.

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**Fig. 1 - Schematic representation of experimental set up.**
**Monitoring and water quality analysis**

The runs were monitored by daily measurements of temperature, pH and dissolved oxygen (DO) in the reactors using a pH meter and a DO meter; TMP was measured daily using a pressure gauge. Effluent BOD, COD (using the KMnO\(_4\) consumption method), TOC, T-N, T-P and PO\(_4\)-P were measured periodically following the standard methods (Japan Standard Association, 1993). The mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) in the reactors were also measured. All chemical analyses were carried out in duplicate with the appropriate reagents and blanks.

**Estimation of the filter resistance**

To compare the suction and gravitational operational results, the concept of filter resistance is introduced as follows:

The flux \((J; \text{ m/d})\) and the TMP \((P; \text{ MPa})\) can be generally expressed as

\[ J = \frac{P}{\mu R} \]  

(1)

where \(\mu\) is the fluid viscosity and \(R\) is the total resistance of \(R_i\)’s caused by the \(i\)-th fouling factor such as resistance of membrane itself, resistance by reversible fouling and resistance by irreversible fouling (AWWA, 2005).

\[ R = \Sigma R_i \]  

(2)

\(R\) increases with the progress of filter fouling. In case of suction filtration, \(J\) is constant and \(P\) will increase in proportion to the increase in \(R\).

\[ \frac{dR}{dt} = \frac{1}{\mu J} \frac{dP}{dt} \]  

(3)

In contrast, in gravity filtration case, \(P\) is stable and \(J\) decreases.

\[ \frac{dR}{dt} = -\frac{P}{\mu J^2} \frac{dJ}{dt} \]  

(4)

Although the viscosity of the mixed liquor was not measured, it was estimated by MLSS using Eq. (5), which was obtained from the data of Nakajima and Mishima (2005)

\[ \mu = \mu_0 \exp (0.0002 \times \text{MLSS}) \]  

(5)

where \(\mu_0\) was the viscosity of water at temperature \(T\) °C estimated by Eq. (6) (AWWA, 2005).

\[ \mu_0 (T) = 1.777 - 0.052 \times T + 6.25 \times 10^{-4} T^2 \]  

(6)

**RESULTS AND DISCUSSION**

**Operational results**

The runs were operated for the periods shown in Table 1. In all runs, the pH was stable at 8 and the DO exceeded 5 mg/L, whereas the MLSS was rather low (Fig. 2) because of the low BOD load conditions. Although the temperatures in Run 1 and Run 2 were higher...
than those in Run 3 and Run 4, the operations of the ML were within the normal range for activated sludge processes.

Treatment efficiency
The concentrations of BOD, COD, TOC, T-N, T-P and PO4-P in the effluents of all the runs are shown in Table 2. From the very first day of operation, the BOD and TOC concentrations in the effluents were approximately 2 mg/L, and the COD concentrations were approximately 3 mg/L, with the exception of Run 1. These treatment efficiency results demonstrate the quick start-up capability of the system. More than 99% of the BOD was removed, and more than 97% and 98% of the COD and TOC were removed, respectively, for all of the runs. This demonstrates that there was no significant difference among the four runs in terms of removal performance. Although the lower removal efficiencies of COD and TOC than the BOD removal exhibited the residue of non-biodegradable organics in the effluent, their remained concentrations were low enough to reuse the effluent for many purposes. High organic removal efficiency suggests that the effluent could be used for miscellaneous non-potable reuses, such as landscaping, agricultural irrigation, toilet flushing, and gardening. The high removal performance may have been caused by a combination of the effective filtration of the simple ceramic filter and the biological degradation process of the ML under suitable HRT and DO conditions (Sun et al., 2006; Hasan et al., 2011).

Table 1 - Specifications of the runs (average ± standard deviation).

<table>
<thead>
<tr>
<th>Run period (d)</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH 8.07 ± 0.23</td>
<td>8.01 ± 0.16</td>
<td>8.03 ± 0.22</td>
<td>8.19 ± 0.19</td>
<td></td>
</tr>
<tr>
<td>DO (mg/L) 7.1 ± 0.6</td>
<td>6.4 ± 0.7</td>
<td>5.7 ± 1.6</td>
<td>6.9 ± 1.2</td>
<td></td>
</tr>
<tr>
<td>Temp (°C) 24.0 ± 1.4</td>
<td>25.0 ± 1.1</td>
<td>20.7 ± 1.5</td>
<td>20.7 ± 1.6</td>
<td></td>
</tr>
<tr>
<td>MLSS (g/L) 2.6 ± 0.2</td>
<td>3.0 ± 0.2</td>
<td>3.9 ± 0.3</td>
<td>4.2 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>VSS (%) 91 ± 2</td>
<td>88 ± 1</td>
<td>88 ± 1</td>
<td>86 ± 1</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 - Effluent quality of the runs (average ± standard deviation, units: mg/L).

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD 2.0 ± 3.5</td>
<td>0.8 ± 0.6</td>
<td>0.9 ± 1.0</td>
<td>0.9 ± 1.0</td>
</tr>
<tr>
<td>COD 3.4 ± 3.34</td>
<td>2.5 ± 0.6</td>
<td>3.0 ± 0.8</td>
<td>2.6 ± 1.3</td>
</tr>
<tr>
<td>TOC 2.4 ± 2.6</td>
<td>1.5 ± 0.2</td>
<td>2.5 ± 1.1</td>
<td>2.9 ± 0.9</td>
</tr>
<tr>
<td>T-N 27.9 ± 11.6</td>
<td>29.9 ± 5.3</td>
<td>31.6 ± 4.1</td>
<td>33.5 ± 4.5</td>
</tr>
<tr>
<td>T-P 4.1 ± 1.5</td>
<td>4.4 ± 0.7</td>
<td>5.0 ± 2.1</td>
<td>3.4 ± 1.8</td>
</tr>
</tbody>
</table>
The nitrogen and phosphorus removal rates were 32 – 43% and 11 – 32%, respectively, suggesting that the non-aeration time of the intermittent aeration was insufficient for the progress of biological denitrification and EBPR because of the low BOD load. Therefore, the nutrient removal efficiency might be improved by changing the time cycle of aeration and non-aeration.

**TMP changes**

The ceramic filters exhibited successive TMP increase and filter cleaning. The TMP changes of the four runs during their first 20 days of operation are shown in Fig. 3. Although the period until the first filter cleaning was not in order, the interval between the successive cleanings was clearly decreased according to the increase of the flux from Run 1 to Run 4, indicating the increase of cleaning frequency.

The filter was cleaned 7 times in 42 days for Run 2 while 35 and 38 times per 78 days for Run 3 and Run 4, respectively. In Run 1, the TMP was increased to be more than 0.03 MPa twice. After the second cleaning, however, the TMP was kept between 0.01 and 0.02 MPa until the last day (41st day) of operation without cleaning. Although any leakage through the filter was not detected, the reason of the low TMP operation was not clear. Therefore, the following analysis as for Run 1 was carried out using the data before the second filter cleaning.
The increase of cleaning frequency compared to the increase in flux is shown in Fig. 4. The cleaning frequencies were approximately 0.2 times/d or less for Run 1 and Run 2 and exceeded 0.5 times/d in Run 3 and Run 4. Operation with the flux less than 0.2 m/d seemed preferable for low fouling risk operation in the suction filtration mode.

**Estimation of the filter resistance**

The flux was kept constant in each suction filtration run. The filter was cleaned each time the TMP increased to 0.03 MPa. The cleaning frequency was increased with an increase in the flux. In contrast, in the case of gravity filtration in the previous study using the same ceramic filter, the TMP was kept constant and the flux decreased with filter fouling (Hasan et al., 2011).

Both suction and gravity filtration have been applied to actual MBR facilities using MF. It also suggests possibilities for the application of both suction and gravity filtration to MBR using the simple ceramic filter. In order to compare the characteristics of both filtration modes, the total resistance \( R \) of the filter defined by Eq. (1) and Eq. (2) was estimated and compared. Moreover, the resistance change rate \( \frac{dR}{dt} \) was also estimated using Eq. (3) because \( R \) increases with the progress of filter fouling.

The apparent total resistance \( \mu R \) was estimated to be in the range of 0.10 to 0.19 MPa·d/m using Eq. (1) by substituting TMP (0.03 MPa) and the flux for each operational run; the results are shown in Table 3. The \( R \) values here represent the total resistance of the filter when TMP was increased to 0.03 MPa.
Fig. 4 - Cleaning frequency compared to the increase in flux.

Table 3 - Calculated values of the resistance and its change rate.

<table>
<thead>
<tr>
<th>$P$ (MPa)</th>
<th>$J$ (m/d)</th>
<th>$\mu R$ (MPa·d/m)</th>
<th>$R$ ($10^{12}$ 1/m)</th>
<th>$\frac{dR}{dt}$ ($10^{12}$ 1/(m·d))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>0.03</td>
<td>0.16</td>
<td>0.19</td>
<td>11</td>
</tr>
<tr>
<td>Run 2</td>
<td>0.03</td>
<td>0.20</td>
<td>0.15</td>
<td>8.2</td>
</tr>
<tr>
<td>Run 3</td>
<td>0.03</td>
<td>0.25</td>
<td>0.12</td>
<td>4.9</td>
</tr>
<tr>
<td>Run 4</td>
<td>0.03</td>
<td>0.30</td>
<td>0.10</td>
<td>3.9</td>
</tr>
</tbody>
</table>

After the estimation of $\mu$ using Eq. (5) and Eq. (6), the $R$ value was estimated by dividing $\mu R$ by $\mu$, and the results are shown in Table 3. The $R$ value decreased from $11 \times 10^{12}$ to $3.9 \times 10^{12}$ 1/m according to the increase of the flux. The results of the $\frac{dR}{dt}$ estimation are also shown in Table 3. The $\frac{dR}{dt}$ values ranged from $1.4 \times 10^{12}$ to $2.2 \times 10^{12}$ 1/(m·d) showing no relationship to the flux.

Comparison with the gravity filtration
The $R$ values of the gravity filtration case in the previous study were also estimated by the same procedure using the average flux values for $J$. The relationships between the flux and $R$ for both filtration modes are shown in Fig. 5. The $R$ values in the gravitational mode were low compared to those in the suction mode and exhibited a small decrease according to the increase of the flux.

The $\frac{dR}{dt}$ values in the gravitational mode were calculated using Eq. (4). The $\frac{dR}{dt}$ values in the gravitational mode ranged from $< 0.03 \times 10^{12}$ to $0.27 \times 10^{12}$ 1/(m·d). They were quite lower than the $\frac{dR}{dt}$ values in the suction mode as shown in Fig. 6. All of the runs in the suction mode showed $\frac{dR}{dt}$ values of more than $1 \times 10^{12}$ 1/(m·d). The high $\frac{dR}{dt}$ value seemed to cause the necessity of filter cleaning. On the contrary the low $\frac{dR}{dt}$ value ($< 0.5 \times 10^{12}$ 1/(m·d)) in the gravity filtration resulted in unnecessary filter cleaning.

Therefore, the gravity filtration was suggested to be a more advantageous operation than the suction filtration in MBR using the simple ceramic filter because the filter cleaning was less necessary.
CONCLUSIONS
This feasibility study of suction filtration in an MBR with a simple ceramic filter in laboratory-scale experiments under different flux conditions showed the following:

1) More than 99% of BOD was removed by the suction filtration MBR using a simple ceramic filter, which demonstrated the possible reuse of effluent for many purposes.
2) The MBR runs with a flux less than 0.2 m/d showed a lower risk of fouling; increasing the flux caused an increase in fouling risk.
3) Total resistance of the filter ($R$) decreased from $11 \times 10^{12}$ to $3.9 \times 10^{12}$ 1/m according to the increase of the flux. The resistance change rate ($dR/dt$) ranged from $1.4 \times 10^{12}$ to $2.2 \times 10^{12}$ 1/(m·d) showing no relationship to the flux in the suction filtration.
4) The $R$ and $dR/dt$ values were estimated lower in the gravity filtration compared to those in the suction filtration. The gravity filtration was suggested to be a more advantageous operation than the suction filtration in MBR using the simple ceramic filter.

Fig. 5 - Relationship between the flux and the total resistance ($R$).

Fig. 6 - Relationship between the flux and the increase rate of the total resistance ($dR/dt$).
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REFERENCES