Using sequencing batch biofilm reactor (SBBR) to treat ABS wastewater

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Abstract  Ratio of total Kjeldahl Nitrogen to COD for ABS (acrylnitrile, butadiene and styrene) wastewater is in a range of 0.12–0.17, which is significantly higher than that needed for optimal growth of an activated sludge. In this work, an automated Sequencing Batch Biofilm Reactor (SBBR) system at lab-scale is applied to reduce the amount of ABS; this system is controlled by an on-line monitoring of oxidation-reduction potential (ORP). A comparison of the operation efficiency for the lab-scale SBBR operated with the control of fx-time method and ORP-based real-time automatic method is presented. The results show that the system ORP can be used as an available parameter for achieving a real-time operation and control of the lab-scale SBBR. It is found that the reaction time is reduced of 11.1–55.2% if an ORP-based real-time control is used, instead of the fixed-time control. Also, the SBBR system is made more efficient and cost-effective.

Keywords  SBBR system; ABS wastewater, ORP; real-time operation

Introduction

The SBBR system has been recently used for treating the wastewater that cannot be satisfactorily treated in a conventional wastewater treatment plant. It has many advantages over the conventional activated sludge process such as larger surface area for fixed bacterial growth that makes the system more stable, longer sludge age and smaller quantity of excess sludge produced (Jaar and Wilderer, 1992). White and Schnabel (1998) have found that the SBBR system is effective in treating high-volume but low-concentration toxic wastes, especially the metal processing waste that contains a large quantity of cyanide. The ABS wastewater contains a high proportion of nitrogen. Its N/C ratio (TKN/COD being 0.12–0.17) is much more than the level needed for an optimal microbial growth in a conventional biological system. Hence the ABS waste cannot be efficiently treated in the activated sludge process. The SBBR system has been shown to be effective in treating the ABS wastewater and achieving nitrification and denitrification thus effectively removing the nitrogen to an acceptable level.

Operation of SBBR consists of three biological stages, i.e., anaerobic, aerobic and anoxic followed by sedimentation, to produce a clear effluent. Duration of each stage is controlled at a pre-selected fixed time; it is usually longer than the time needed for treating the wastewater. Performance of the SBBR system can be enhanced by controlling the reaction time, adding extra carbon sources (Nyberg et al., 1996) and adjusting the dissolved oxygen (DO) concentration (Fillos et al., 1996). Adjusting the operation time according to variations of the system ORP values in a “Two-point ORP controller” method (Zipper et al., 1998) has lead to the development of an ORP-based real-time control (Yu et al., 1998). Online ORP measurements can indicate the activity of electrons that are involved in the biochemical reaction. Thus, the end-point of a biochemical reaction is closely related to the system ORP value.

Chang and Chen (1994) have used an ORP-based automatic control of a SBR system for removal of carbon, nitrogen and phosphorus compounds. The results show that with the ORP-based control, the nitrification rate ($K_N$), denitrification rate ($K_{DN}$), uptake rate of
phosphorus ($K_{PR}$) and release rate of phosphorus ($K_{PU}$) are higher than those obtained with the control by fixed-time method. Removal efficiency is raised with shorter operating time, thus the objective for saving treatment costs is achieved. Chang et al. (1995) also reported that if the ORP value of system appeared to a parameter for controlling the SBR system, an adequate quantity of organic carbon was reserved at the end of the biological aerobic stage to match the need for subsequent biological denitrification process. Thus, the production of $\text{N}_2\text{O}$, an unwanted greenhouse effective gas was reduced due to an improved C/N ratio. Specific utilization rates of $\text{NO}_3^-$ and COD were also raised. Later Cho and Chang (1996) observed that the ORP value used for controlling the SBBR system could be estimated based on the system influent COD loading rate. Yu et al. (1998) used an on-line monitoring of the system ORP and pH of a continuous-flow biofilm reactor aided with artificial network to reduce 15.5–45% of the reaction time and 45% of the energy consumption.

The objective of this experiment is to continue earlier studies on the use of ORP as a system parameter for automatic control of an SBBR system for treating ABS wastewater. A mathematical model developed previously will be used to estimate the reaction time and ORP values for an ORP-based real-time control of the SBBR system. Comparisons of the treatment efficiency for the SBBR system using the fixed-time control and the ORP-based real-time will be evaluated and presented.

### Equipment and methods

Four sets of the lab-scale SBBR system are used in this study. Each SBBR reactor consists of a 5-litre sealed reactor. The content is continuously mixed with a magnetic stirrer. Probes for monitoring pH, DO and ORP are inserted and the signals are sent to a computer for data recording and analyzing. Pumps are used for controlling influent, effluent and air so that the system is maintained to simulate the operation of a batch SBBR system, i.e., anaerobic, aerobic and anoxic stages.

Background information is carried out using a fixed-time control for each of the biological stages. Operating conditions are listed in Table 1. Variations of system parameters, i.e., pH, ORP and DO, are continuously monitored. The results are used to develop the strategy for using the ORP-based real-time automatic control of the lab-scale SBBR system.

### Results and discussion

#### Control of the SBBR system using fixed-time control

In earlier study (Cho and Chang, 1996), the lab-scale SBBR was operated using four influent COD loading rates of 0.061, 0.153, 0.213 and 0.314 g COD/L · day, or 0.012, 0.030, ...

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**Table 1** Organic loadings and duration of each step for the fixed-time operation of the lab-scale SBBR system

<table>
<thead>
<tr>
<th>Reactor NO.</th>
<th>SBBR-A</th>
<th>SBBR-B</th>
<th>SBBR-C</th>
<th>SBBR-D</th>
</tr>
</thead>
<tbody>
<tr>
<td>COD Loading (g COD/L · day)</td>
<td>0.061</td>
<td>0.153</td>
<td>0.213</td>
<td>0.288</td>
</tr>
<tr>
<td>DOC Loading (g DOC/L · day)</td>
<td>0.012</td>
<td>0.029</td>
<td>0.041</td>
<td>0.055</td>
</tr>
<tr>
<td>T–N Loading (g T–N/L · day)</td>
<td>0.012</td>
<td>0.023</td>
<td>0.033</td>
<td>0.043</td>
</tr>
<tr>
<td>Biomass (mg/L)</td>
<td>6.027</td>
<td>6.096</td>
<td>6.142</td>
<td>6.207</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cycling operation</th>
<th>Time (min)</th>
<th>Cycling operation</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow-in stage</td>
<td>2</td>
<td>Reaeration stage</td>
<td>120</td>
</tr>
<tr>
<td>Anaerobic stage</td>
<td>480</td>
<td>Settling stage</td>
<td>60</td>
</tr>
<tr>
<td>Aerobic stage</td>
<td>480</td>
<td>Drain-off stage</td>
<td>60</td>
</tr>
<tr>
<td>Anoxic stage</td>
<td>240</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
0.040 and 0.061 g TN/L · day, respectively. In this study, the highest loading of 0.314 g COD/L · day is found to inhibit the growth of even well acclimated sludge, leading to a low removal efficiency and a poor effluent quality. Thus, the highest organic loading rate is reduced to 0.268 g COD/L · day or 0.051 g TN/L · day for carrying out the study.

Figure 1 shows variations of carbon (COD, DOC) and nitrogen (TN, org–N, NH₃-N, NO₂–N and NO₃–N) for the various biological stages in a SBBR system operated at 24 hours (eight hours for anaerobic, eight hours for aerobic, four hours for anoxic, two hours for settling and two hours for reaeration). The results show that carbon is continuously removed with increasing reaction time, but the reaction rate is initially faster at the beginning of each biological stage. Removal of nitrogen follows the similar trend as carbon except that during the beginning of the anaerobic stage, organic nitrogen is converted to ammonia nitrogen leading to an increase of the total nitrogen. Additionally, intermediate products, i.e. nitrite and nitrate, during the conversion of ammonia nitrogen to nitrogen gas may accumulate before they are completely converted to nitrogen gas.

Variation of system parameters versus water quality parameters
Variations of the system parameters, i.e., pH, ORP and DO (Figure 2) correspond to the changes of water quality parameters. The findings are available to develop the strategy for automatic control of the lab-scale SBBR system. For the anaerobic stage, the main biological decomposition consists of anaerobic digestion of carbon-containing organic compounds and conversion of organic nitrogen to ammonia nitrogen (Chui et al., 1996). The biological sorption and system dilution also contributes to the apparent rapid removal of organic matter. This is seen by a fast reduction of COD and DOC during the initial reaction period of the anaerobic biological stage shown in Figure 1. At the completion of the input of influent wastewater, reduction of organic matter concentration due to system dilution stops. Both ORP and pH curves show “bending-points”. Subsequently, COD and DOC are decomposed, and ammonia nitrogen is produced from organic nitrogen leading to an increase of the total nitrogen. When the total nitrogen reaches a maximum level, the removal of COD and DOC approaches a constant level. At this time, the changing rates of both ORP and pH versus time (dORP/dt and dpH/dt) become almost zero.

For the aerobic biological stage, biological reactions cause the carbon organic matter to decompose aerobically as well as nitrification of ammonia nitrogen into nitrites or nitrates. When the nitrification reaction is completed, the ammonia nitrogen concentration reaches a minimum, and both ORP and COD reach a second bending-point (Plisson-Saune et al., 1996). For the anoxic biological stage, denitrification occurs to convert NOₓ–N into nitrogen gas. Results published in the literature have shown that when the knee-point occurs on the ORP curve, the denitrification reaction is completed and NOₓ–N is completely converted into nitrogen gas (Plisson-Saune et al., 1996). Analyses of the data obtained in this study indicate that the knee-point corresponding to the time needed for completion of the biological denitrification reaction has a logarithmic relationship with the influent COD loading. The system ORP value has a linear relationship to COD loading rates. Thus, the time for completing the denitrification reaction can be estimated based on the influent COD loading.

Since the reaction time and the controlling ORP value for each of the three SBBR biological reaction stages the influent COD loading is closely related to the influent COD, the strategy for an automatic control of the SBBR operation can be formulated based on the influent COD loading. Based on the results shown in Figure 3, several relationship equations are obtained and shown as follows.
For the anoxic stage  \[ \text{ORP} = -201 \ln(\text{COD loading}) - 481.6 \quad (R^2=0.982) \]
For the anoxic stage
\[ t = 71.261 \times 10^{4.1(COD\ loading)} \]  
\[ R^2 = 0.989 \]  
(2)

For the anaerobic stage
\[ ORP = -113 \ln(COD\ loading) - 348.68 \]  
\[ R^2 = 0.935 \]  
(3)

For the aerobic stage
\[ ORP = -138.69 \ln(COD\ loading) - 292.58 \]  
\[ R^2 = 0.981 \]  
(4)

Automatic control of the SBBR operation

The reaction time needed for completing biological reactions in each stage, and the corresponding ORP value is estimated using the influent COD loading, and, the automatic control is based on on-line monitoring of system ORP value. When it reaches a pre-determined bending-point (calculated based on the influent COD loading), operation of the biological
stage is terminated and the subsequent stage starts. In other words, instead of using a fixed
time for each biological stage, an ORP-based real-time control based on the influent COD is
used for terminating the operation of each stage. The results show the actual operation con-
dition is better fitted by the model results for influents with higher COD levels. Using the
ORP-based real-time control, the reaction time for completing the aerobic biological stage
is reduced from 480 minutes to 190–400 minutes with 16.7–60.4% of savings on the reac-
tion time; it also saves the power consumption for aeration and mixing. The total time
required to complete the operation of the SBBR system is reduced from 1,440 minutes to
645–1,280 minutes.

For the anaerobic stage, the remaining COD and DOC are 97.0–398.4 mg/L and
19.0–79.4 mg/L, respectively. With the fixed-time control, they are 47.3–353.3 mg/L and
10.6–70.1 mg/L, respectively. Removal efficiencies of carbon organic compounds
(46.9–52.2% for COD and 46.2–57.6% for DOC) using the ORP-based real-time control
are higher than those (56.5–74.1% for COD and 62.3–69.5% for DOC) with fixed-time
control. Although more organic carbon is left in the effluent of the anaerobic stage, the over-
all removal of organic carbon matter is improved; it is found that a system performs with the
ORP-based real-time control, the microorganisms have a better capability of degrading
carbon-containing organic matter (Figure 4).

With the ORP-based real-time control for the aerobic stage, the remaining organic car-
bon is 50.6–134.4 mg/L of COD and 6.8–25.6 mg/L of DOC. The fixed-time control can
achieve residual organic carbon of 15.3–80.8 mg/L of COD and 2.7–12.0 mg/L of DOC.
Removal efficiencies for the real-time control (47.8–65.5% of COD and 63.6–67.7% of
DOC) are lower than those for the fixed-time control (67.7–77.4% of COD and 74.2–82.9%
of DOC). However, the specific COD or DOC utilization rates are higher for the real-time control (Figure 5). The shorter reaction time as dictated by the ORP-based real-time control leads to a slightly higher concentration of organic carbon in the effluent that will be used as a carbon source by denitrification microorganisms in the subsequent anoxic stage.

The anoxic stage is used for achieving denitrification. A supply of sufficient organic carbon is necessary for completing the anoxic denitrification. In this study, the ORP-based on-line control allows a sufficient quantity of residual organic carbon for the anoxic stage. After the anoxic stage, the residual COD and DOC concentrations are 9.6–44.2 mg/L and 1.0–5.3 mg/L, respectively, with an overall removal efficiencies of 94.6% of COD and 97.1% of DOC. With the ORP-based real-time control, the specific carbon organic substrate utilization rate (qSr) is improved (Figure 6) indicating the advantage of using the ORP-based real-time control over the fixed-time control. As stated in the aforementioned sections that the removal of organic carbon during the anaerobic stage is lower for the real-time control than for the fixed-time control. The conversion of organic nitrogen into ammonia nitrogen is accompanied with the degradation of organic carbon. In contrast, the conversion of ammonia nitrogen in the aerobic stage and the removal of nitrogen in the anoxic stage are higher than those using the fixed-time control. The results indicate that using the ORP-based real-time control, the conversion and degradation of organic matter can be effectively controlled for optimizing the removal of carbon and nitrogen organic compounds from the ABS wastewater (Figure 7).

Removal of NH₃-N is accomplished through nitrification in the aerobic stage and denitrification in the anoxic stage. Using the ORP-based real-time control, the decomposition
of organic nitrogen and the utilization of organic carbon for denitrification can be effectively controlled. After the aerobic stage, the residual ammonia nitrogen is 0.1–0.7 mg/L with removal efficiency of 99.0–99.6%. At the end of the SBBR operation, the residual NH₃-N is only 0.0–0.3 mg/L (99.6–99.8%) removal efficiency within shorter reaction time and NH₃-N. Removal of NOₓ-N (NO₂-N and NO₃-N) is achieved through denitrification in the anoxic stage. The use of the ORP-based real-time control will allow the SBBR system to have a better utilization of organic carbon for completing the biological denitrification. At the end of the denitrification period, the residual NOₓ-N amounts to only 1.1–3.8 mg/L. The removal rate of NOₓ-N is raised from 66.7–86.0% (residual NOₓ-N of 2.0–5.0 mg/L) for the fixed-time control to 88.9–90.1% for the real-time control. The residual NOₓ-N concentration is 1.0–3.4 mg/L with a removal efficiency of 88.7–91.5%. Using the ORP-based automatic control is capable of reflecting the progress of biological reactions. The end point for each stage of the biological reaction can be estimated by use of the control model and implemented to achieve savings of the internal organic carbon requirement, reaction time and treatment cost. Especially the C/N ratio (COD/NOₓ-N) at the beginning of the anoxic stage can be raised from 1.55–3.13 to 3.16–5.48 leading to a complete nitrification and a low residual total nitrogen of 2.3–11.3 mg/L or a removal efficiency of 87.9–94.3%.

Figure 6 Comparison of (a) removal percentage of organic carbon; (b) specific removal rate of organic carbon for the real-time control and the fixed-time control

Figure 7 Nitrogen removal rate compared with set-time and real-time system
Conclusions
Implementation of an ORP-based real-time automatic control of the SBBR system is based on the observation that the end-point of a biological reaction and the ORP value corresponding to the end-point are closely related to the influent COD loading rate. Using a mathematical model, the time and the ORP value needed to terminate the operation of the various biological stages can be determined by knowing the influent COD loading rate. Operation of the SBBR system can be automated using the ORP-based real-time control. Comparing to the fixed-time control, the ORP-based real-time control achieves 11.1–55.2% of the total operating time. With the ORP-based real-time control, degradation of the organic carbon in the anaerobic and aerobic stage is controlled to such extent that the excess organic carbon is sufficient but not excessive for the subsequent anoxic biological denitrification without leaving undesirable concentrations of organic carbon in the total treated effluent. The C/N (COD/NOx−N) at the beginning of the anoxic stage is raised from 1.55–3.13 to 3.16–5.48. The ORP-based automatic control can achieve a more complete conversion of organic nitrogen and denitrification. The treated effluent contains 2.3–11.3 mg/L of total nitrogen (87.9–94.3% of removal efficiency), 0–0.3 mg/L of ammonia nitrogen (99.6–99.8% of removal efficiency) and 1.0–3.4 mg/L NOx−N (88.7–91.5% of removal efficiency).

References