NITRIFICATION KINETICS AND SIMULTANEOUS REMOVAL OF BIOMASS AND PHOSPHORUS IN ROTATING BIOLOGICAL CONTACTORS

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ABSTRACT

This paper presents some important aspects of the Rotating Biological Contactor. (1) Steady-state biofilm kinetics and its application to the design of an RBC aiming at nitrification: Using the proposed kinetics in which the flux of rate-limiting substrate is expressed as a function of the bulk substrate concentration, liquid boundary layer thickness, liquid film thickness, and molecular diffusion coefficient and intrinsic reaction rate of the substrate, the relationship between the bulk ammonia concentration and ammonia flux was predicted at various sizes and rotating speeds of disk. Experimental verification of the predicted results was also made. A new disk media, i.e., reticulated media with surface protrusions, was proposed to promote the external diffusion of soluble substrates to the biofilm, and to reduce the disk weight. (2) Simultaneous removal of the detached biomass and precipitated phosphorous in a two-storey RBC: A two-storey RBC, whose upper and lower parts function as the RBC trough and storage space of the detached biomass, was operated in a four-staged unit. Experimental investigation showed that the phosphorus precipitated by aluminium was adsorbed to the biofilm, and settled into the lower part as the detached biomass. The removal efficiency of the detached biomass was very high resulting in an effluent suspended solids concentration of about 10 ppm.

KEYWORDS

Rotating biological contactor; Biofilm kinetics; External diffusion; Detached biomass; Two-storey RBC; Solid-liquid separation; Adsorption; Precipitated phosphorus.

INTRODUCTION

The Rotating Biological Contactor (RBC) is an aerobic biofilm reactor for treating domestic and industrial wastewaters. It consists of series of large-diameter disks, mounted on a horizontal shaft and placed in a trough. The biofilm consists of various bacteria such as heterotrophs and autotrophs that naturally develop on the disk surface. Dominant species and properties of biofilm depend on the wastewater characteristics and the reactor operating conditions. The disks slowly rotate with approximately 40 to 50% of the surface area submerged in the wastewater to be treated. The rotation of the disks plays an important role in the following aspects: (1) Aeration; it provides an alternative exposure of the biofilm to air and water. During the rotation of the biofilm in air, oxygen is supplied to the bio-

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film microorganisms, while during the rotation in the water, substrates diffuse into the biofilm, and (2) Mass transfer: far from the rotating disk, the liquid moves toward the disk surface and, in a thin layer immediately adjacent to its surface, the liquid acquires a rotating motion. The liquid also acquires a radial velocity under the influence of centrifugal force. Therefore, the rotating action of disks hastens the mass transfer to the biofilm. The goal of the mathematical modeling of biofilm reaction is to express the substrate flux as a direct function of the bulk substrate concentration which is readily measurable and the concentration of interest. Watanabe et al. (1980, 1982, 1984) presented the RBC kinetics based on a heterogeneous biofilm model and analyzed the experimental data of the denitrification, nitrification, and simultaneous organic oxidation, nitrification, and denitrification by the simulation and steady-state approximation of the kinetics. In this paper, the proposed biofilm kinetics is applied to predict the relationship between the ammonia flux and bulk ammonia concentration at various sizes and rotation speeds of disk. Experimental verification of the calculated relationship is also carried out. The effect of bulk organic concentration on the ammonia flux is experimentally examined. In order to promote the external diffusion of soluble substrates and to reduce the disk weight, a new media, i.e., reticulated media with surface protrusions is proposed, and the performance of the RBC with new media is tested by the nitrification experiment. In a conventional RBC system, the final clarifier has been used to separate the treated wastewater and detached biomass. The detached biomass is exposed to the turbulent shear in the trough during the transport to the final clarifier. Due to such an exposure, the detached biomass is broken down into smaller particles which can not settle in the clarifier. As a result, it has been reported that the effluent from the RBC system contains a lot of small organic particles. In this paper, the performance of two-storey RBC is investigated to demonstrate that it has a high removal efficiency of the detached biomass. It means that the final clarifier may not be necessary in the two-storey RBC. It is also reported the effect of direct aluminium addition to the RBC on phosphorus removal and upgrading the treated wastewater quality.

NITRIFICATION KINETICS IN RBC

Model Development
The biofilm attached to a partially submerged RBC rotates alternately into air and water. During the rotation in the air phase, oxygen is supplied to the microorganisms inhabiting the biofilm, while the substrates diffuse into the biofilm during its rotation in the water phase. The following assumptions are made to formulate the biofilm kinetics. (1) The substratum is assumed to consist of flat and impermeable disks, (2) The portion of the disks exposed to air contains a liquid film of thickness, Lw, (3) A liquid boundary layer of thickness, Ld, exists at the biofilm/liquid interface. (4) The wastewater in each RBC stage is assumed to be completely mixed.

Using the derived RBC kinetics, the computer simulation of nitrification was carried out to estimate the concentration profiles of oxygen and ammonia in the biofilm at various sectors of biofilm during rotation in air and water phases. According to the simulation results, it has been clarified that under oxygen limitation, the dissolved oxygen concentration profile in the biofilm system approaches its steady-state profile in a very short time after the biofilm sector contacts the air phase, and under ammonia limitation, the ammonia concentration profile in the biofilm approaches its steady-state profile in a very short time after the biofilm enters the water phase. Based on this evidence, the RBC kinetics can be simplified to steady-state model if the zero-order intrinsic reaction rate is applicable, and Watanabe (1985) formulated an RBC kinetics which is available to calculate the flux of rate-limiting substrate at a given bulk substrate concentration.

With the steady-state assumption, the substrate flux through the liquid boundary layer, \( J_{2\alpha} \), is equal to the substrate flux at the biofilm surface, \( J_{1\alpha} \), if \( D_{r1} \) is a constant fraction of \( D_{w1} \) (\( D_{r1} = \alpha D_{w1} \), where \( \alpha \) is a constant less than or equal to unity), the following expression is obtained:

\[
J_{2\alpha} = \left( \frac{D_{w1}}{L_d} \right) (C_{1\alpha}^b - C_{1\alpha}^t) = (2 \alpha D_{w1} r_1^2 C_{1\alpha}^t)^{1/2}
\]
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The unknown value of $C_{11}$ is calculated from the above equation as follows:

$$C_{11} = C_{11} + \lambda - (\lambda^2 + 2\lambda C_{11})^{1/2}$$  \hspace{1cm} (2)

$$\lambda = \alpha r_1^2 L_d/D_w$$  \hspace{1cm} (3)

If the RBC is operated under oxygen limitation and 50% of the disk area is submerged, the oxidizing substrate flux is given by Eq. 4.

$$J_{x1} = \left(\frac{r_0^2}{r_1^2} \right) (J_{ox} + J_{ow})$$  \hspace{1cm} (4)

From the similar procedure used for deriving Eq. 1, the oxygen flux to the biofilm rotating in the air phase ($J_{ox}$) and that in the water phase ($J_{ow}$) are expressed as:

$$J_{ox} = \left(\frac{D_w}{L_w} \right) \left( C_{10}^0 - C_{10} \right) = (2 \alpha D_w r_0^0 C_{10}^0)^{1/2}$$  \hspace{1cm} (5)

$$J_{ow} = \left(\frac{D_w}{L_d} \right) \left( C_{10}^0 - C_{10} \right) = (2 \alpha D_w r_0^0 C_{10}^0)^{1/2}$$  \hspace{1cm} (6)

Application of Kinetics to Nitrification RBC

The above mentioned RBC kinetics contain two physical parameters: $L_w$ and $L_d$. They express the diffusional resistance of oxygen and substrate to the biofilm during its rotation through air and water. Liquid boundary layer thickness. The liquid boundary layer thickness on the clean surface of a submerged disk is described by Eq. 7 (Levich, 1962).

$$L_d = 1.16 (D_w/N)^{1/3} (\nu/2\pi N)^{1/2}$$  \hspace{1cm} (7)
Watanabe and Nishidome (1989) have evaluated the effect of the submerged ratio, rotating speed, surface roughness, diameter of disks on the liquid boundary layer thickness of the RBC attached by the nitrifying bacteria. As predicted by Eq. 7, the liquid boundary layer thickness is not a function of disk size if the flow near the disk surface is laminar, which is the case of the usual operation of the RBC. It is, however, a strong function of the disk submerged ratio, since the hydrodynamic boundary layer may not completely develop in a partially submerged disk because of its alternate rotation into air and water. According to Levich (1962), a rough surface changes the nature of the flow past that surface very materially and, consequently, changes the size of the diffusional flow to the surface. In the case of laminar flow, assuming that the height of the protrusion is large compared with the hydrodynamic boundary layer thickness, these protrusions rise above the boundary layer and the flow past them will be the main flow, unrestricted by proximity to the surface. If \( Re_{prot} = \frac{U(h)}{\nu} \) (h=height of the protrusion, \( U(h) = \) flow velocity at the top of the protrusion and \( \nu = \) dynamic viscosity of water) exceeds 20 to 50 the flow past the protrusion, as in the case of any other non-streamlined body, will be accompanied by separation of turbulence. On the downstream, turbulence appears, while the upstream side is subjected to laminar flow. Watanabe and Okabe (1986) evaluated the effect of surface protrusion on the liquid boundary layer thickness. The height and location of protrusions on the disk surface are shown in Fig. 1. They observed the appearance of turbulence behind the protrusion. Fig. 2 shows the batch experimental result for various numbers of protrusions at a fixed rotating speed of 5 rpm. Using the biofilm kinetics, many batch experimental data were analyzed to determine the liquid boundary layer thickness (Watanabe and Nishidome, 1989). Fig. 3 summarizes the relationship between the liquid boundary layer thickness and operating parameters such as disk rotating speed, disk submerged ratio and protrusion number.

### Liquid film thickness
There are two expressions available to estimate the thickness of the liquid film. Levich (1962) studied the film thickness entrained on a flat plate vertically withdrawn from a quiescent liquid, and deduced the following equation for the film thickness, \( L_w \):

\[
L_w = 0.944 \left( \frac{\nu}{\sigma} \right)^{1/3} \left( \frac{\rho g}{\sigma} \right)^{1/2}
\]

If the physical properties of the wastewater are similar to pure water at 20 °C, Eq. 9 is simplified to (Famularo et al., 1978):

\[
L_w = 6.85 \nu^{2/3}
\]

An alternate expression for the rotating disk is given by Bintanja et al. (1976):

\[
L_w = 0.93 \left( \frac{\nu R}{g} \right)^{1/2}
\]

### Intrinsic ammonia oxidation rate
The zero-order intrinsic ammonia oxidation rate has been determined by analyzing batch experimental results of ammonia oxidation (Watanabe and Nishidome, 1989). All batch experimental data used for determining the liquid boundary layer thickness were analyzed to calculate the zero-order intrinsic ammonia oxidation rate at various water temperatures, which is shown in Fig. 4.

### Saturation and bulk concentrations of dissolved oxygen
The saturation concentration of dissolved oxygen is readily known in a given water temperature. As far as the bulk dissolved oxygen concentration is concerned, Watanabe et al. (1980) found that it was kept at about 4.0 ppm in the nitrification RBC operated under oxygen limitation.

### Experimental Verification
Experimental verification of the proposed kinetics was made by comparing the calculated and measured ammonia fluxes in various water temperatures and disk rotating speeds. A small scale RBC with the disk diameter of 30 cm was used and the steady-state ammonia flux was measured at a given experimental condi-
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The liquid boundary layer thickness and intrinsic ammonia oxidation rate were obtained from Figs. 3 and 4, respectively. The liquid film thickness was assumed to be 10 \( \mu \)m thicker than that calculated by Eq. 10. Fig. 5 shows the comparison of calculated and measured ammonia fluxes under oxygen limitation at various water temperatures. Fig. 6 shows the comparison of calculated and measured ammonia fluxes in the disk rotating speed of 2 and 8 rpm. As seen in Fig. 6, rotating speed has little effect on the ammonia flux under oxygen limitation. The effect of disk rotating speed was evaluated by calculating the oxygen flux to the biofilm. The disk diameter, water temperature and bulk dissolved oxygen concentration were fixed at 30 cm, 25 °C and 4 ppm, respectively. Fig. 7 shows the calculated result which also demonstrates that the disk rotating speed has little effect on the ammonia flux under oxygen limitation. From Figs. 5 and 6, it may be confirmed that the proposed biofilm kinetics can be applicable to the nitrification RBC. The kinetics can predict the performance of the nitrification RBC at any operating conditions. Fig. 8 shows the relationship between the bulk ammonia concentration and ammonia flux at various disk diameters under a fixed disk peripheral speed of 18 m/min., which is most common to the existing RBC plants in Japan. It clearly shows that the disk peripheral speed is not a criterion for the RBC scale-up.

Based on the above fundamental research, the authors (Watanabe et al., 1988) have innovated a reticulated media with protrusions in order to reduce the disk weight and the liquid boundary layer thickness. A stainless net of 60 mesh was used as reticulated media. The height and location of 8 protrusions are the same as Fig. 1. The performance of the RBC with the new media was examined by measuring the ammonia flux. Figs. 9 and 10 show the experimental results. At a rotation speed of 10 rpm, half-order biofilm kinetics seems to be realized, which means no liquid boundary layer near the biofilm surface. Masuda, Watanabe and Ishiguro (1987) demonstrated that the heterotrophic, nitrifying and denitrifying bacteria inhibit the biofilm treating domestic sewage. These microorganisms change their population and activity, depending...
on the environmental conditions within the biofilm. In aerobic treatment of wastewater with organics and ammonia, competition between heterotrophs and nitrifiers occurs. In a staged RBC, the activity of nitrifying bacteria becomes higher in the later stages where the residual organic concentration is low. Fig. 11 shows the effect of bulk soluble TOC concentration on the ammonia flux under oxygen limitation. These experimental data were obtained in the experiment by the RBC unit described in Fig. 13. The ammonia flux is strongly affected by the bulk soluble TOC concentration. The proposed kinetics can not be applicable to predict the bulk TOC concentration effect on ammonia flux, but the measured ammonia flux approaches the calculated ammonia flux for the nitrification RBC if the TOC concentration is below about 7 ppm.

SIMULTANEOUS REMOVAL OF DETACHED BIOMASS AND PRECIPITATED PHOSPHORUS

Experimental Units
Two-storey RBC was constructed to achieve the simultaneous removal of detached biomass in the trough. Its upper and lower parts function as the RBC trough and storage space of settled biomass, respectively. Two experimental units were used. One was a single-stage unit (Fig. 12) which was used to make a mass balance.
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of suspended solids in a two-storey RBC. The settled wastewater from a dormitory was continuously fed to the unit. The average soluble TOC, SS and ammonia concentrations of the wastewater were about 70, 130 and 60 ppm, respectively. Detention time and disk rotating speed were fixed at 70 min. and 10 rpm, respectively. The other unit was a four-stage RBC (Fig. 13) which was used to evaluate the performance of the two-storey RBC in terms of the effluent TOC, SS and NH₃-N concentrations. It was also used for the simultaneous removal of phosphorus precipitated by the direct addition of Polymerized Aluminium Chloride (PAC). The effluent from the primary clarifier in a municipal sewage treatment plant was continuously fed to the unit. The average soluble TOC, SS, NH₃-N and PO₄-P concentrations of the wastewater were about 40, 100, 25 and 6 ppm, respectively.

Experimental Results
(a) Mass Balance in Two-Storey RBC
Suspended solid concentration in the influent and effluent and the settled sludge volume were measured every day during a week. The same experiment was conducted two times. Table 1 summarizes the average data of mass balance in both experimental runs. It is demonstrated that about 70% of detached biomass was removed into the lower part of the two-storey RBC even in a single-stage operation.

<table>
<thead>
<tr>
<th>Items</th>
<th>Run 1</th>
<th>Run 2</th>
</tr>
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<tbody>
<tr>
<td>Water temp. (°C)</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>Flow rate (m³/d)</td>
<td>2.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Detention time (min.)</td>
<td>72</td>
<td>66</td>
</tr>
<tr>
<td>Influent SS conc. (ppm)</td>
<td>136</td>
<td>135</td>
</tr>
<tr>
<td>Effluent SS conc. (ppm)</td>
<td>27</td>
<td>47</td>
</tr>
<tr>
<td>Weight of effluent sludge (g/d)</td>
<td>73</td>
<td>130</td>
</tr>
<tr>
<td>Weight of settled sludge (g/d)</td>
<td>193</td>
<td>195</td>
</tr>
<tr>
<td>Weight of detached biomass (g/d)</td>
<td>266</td>
<td>325</td>
</tr>
<tr>
<td>Removal efficiency (%)</td>
<td>76</td>
<td>66</td>
</tr>
</tbody>
</table>

(b) Performance of Four-stage RBC
The performance of the two-storey RBC operated in a four-stage unit was examined with and without direct addition of PAC. The experiment was repeated four times at the same hydraulic loading or detention time, and averaged concentrations of the measured water qualities used to evaluate the performance of the RBC. Fig. 14 shows the TOC (soluble and total) concentration in each stage. The coagulant dosage is indicated as the aluminium concentration. TOC removal was improved by the addition of PAC, because the coagulated colloidal organics was effectively adsorbed to the biofilm, as explained in Table 2. Figs. 15 and 16 show the SS concentration and turbidity in each stage, respectively. Detached biomass was effectively removed in each stage resulting in the effluent SS concentration of about 10 ppm, and the PAC addition had little effect on the SS removal, but the PAC addition improved the turbidity removal, because the colloidal particles were coagulated and adsorbed to the biofilm, and removed into the lower part of the unit. Fig. 17 shows the effect of the PAC addition on the phosphorus removal. As previously reported (Ishiguro, Watanabe and Masuda, 1977), in the direct addition of PAC to the RBC, lower coagulant

<table>
<thead>
<tr>
<th>Items</th>
<th>Run 1</th>
<th>Run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium dosage (mg/L)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOC in filtrate with PAC</td>
<td>0</td>
<td>18.6</td>
</tr>
<tr>
<td>TOC in filtrate without PAC</td>
<td>12.5</td>
<td>9.4</td>
</tr>
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</table>

They are TOC concentration in the filtrate with a membrane filter of 0.45 and 0.1 μm, respectively.
Dosage was required to get the same phosphorus removal efficiency as compared to the usual chemical phosphorous removal process with chemical precipitation and sedimentation basins. The reason is the adsorption of the small aluminum phosphorus to the biofilm surface. Fig. 18 shows the relationship between the phosphorus removal efficiency and aluminum dosage. As a result, nitrification seems to be inhibited at a higher hydraulic loading, as seen in Fig. 19. However, the coagulant dosage had little effect on the nitrification in the operation with a lower hydraulic loading.

![Fig.14 TOC removal in two-storey RBC](image)

![Fig.16 Turbidity removal in two-storey RBC](image)

![Fig.15 SS removal in two-storey RBC](image)

![Fig.17 PO₄-P removal in two-storey RBC](image)
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**SUMMARY AND CONCLUSIONS**

In the RBC treating domestic wastewater, it is necessary to understand the behavior of both soluble-biodegradable and suspended matters. This paper presented the biofilm kinetics applicable to the design of the nitrification RBC. Using the kinetics, the flux of rate-limiting substrate is expressed as a function of the bulk substrate concentration, liquid boundary layer thickness, liquid film thickness, and molecular diffusion coefficient and zero-order intrinsic reaction rate of the substrate. The comparison between calculated and measured ammonia fluxes was made to verify the proposed kinetics. The performance of the nitrification RBC with various disk diameters was predicted. It was clearly shown that the disk peripheral speed was not a criterion of an RBC scale-up. The performance of an RBC consisted of reticulated media with surface protrusions, which was innovated to reduce the disk weight and liquid boundary layer thickness was examined. It was demonstrated that the half-order biofilm kinetics which is the case of no liquid boundary layer was realized in the rotating speed of 10 rpm.

A two-storey RBC, whose upper and lower parts function as the RBC trough and storage space of detached biomass was operated in a four-stage unit. Experimental investigation proved that the removal efficiency of detached biomass in the two-storey RBC was very high, resulting in effluent SS concentration of about 10 ppm. It means that a final clarifier may not be required if the two-storey RBC is operated in a four-stage unit. Precipitated phosphorus was removed efficiently in the two-storey RBC. In the direct coagulant addition to the RBC, required coagulant dosage to obtain the same removal efficiency of phosphorus is lower as compared to the usual chemical phosphorus removal process with chemical precipitation and sedimentation basins, because small aluminium phosphorus can be adsorbed to the biofilm surface and it settled as the detached biomass into the lower part of the two-storey RBC.
Nomencature

\( C_{b,i} \) - bulk substrate concentration (ML\(^{-3}\))
\( C_{i,0} \) - influent substrate concentration (ML\(^{-3}\))
\( C_{i,1} \) - substrate concentration at biofilm surface (ML\(^{-3}\))
\( C_{i,o} \) - DO concentration at biofilm surface during air phase (ML\(^{-3}\))
\( C_{o} \) - DO concentration at biofilm surface during water phase (ML\(^{-3}\))
\( C_{o}^* \) - DO saturation concentration (ML\(^{-3}\))
\( D_{t} \) - molecular diffusion coefficient in biofilm (L\(^2\)T\(^{-1}\))
\( D_{w} \) - molecular diffusion coefficient in water (L\(^2\)T\(^{-1}\))
\( D_{wo} \) - molecular diffusion coefficient of dissolved oxygen (L\(^2\)T\(^{-1}\))
\( L_{a} \) - effective biofilm depth (L)
\( L_{d} \) - liquid boundary layer thickness
\( L_{w} \) - liquid film thickness (L)
\( r_{i}^0 \) - zero-order intrinsic reaction rate of biofilm (ML\(^{-3}\)T\(^{-1}\))
\( r_{o}^0 \) - zero-order intrinsic oxygen utilization rate of biofilm (ML\(^{-3}\)T\(^{-1}\))
\( N_{r} \) - Disk rotating speed (T\(^{-1}\))
\( R \) - Disk radius (L)

References

Watanabe Y. et al. (1988): Performance of RBC with reticulated media, Proc. of the Annual Conference of Seibu Shibu, Japan Society of Civil Engineers.