Study of rotating biological contactor performance in wastewater treatment using multi-culture biofilm model

S. Dutta, E. Hoffmann and H.H. Hahn

Department of Aquatic Environmental Engineering, Institute for Water and River Basin Management, University of Karlsruhe (Technical University), Adenauerring 20, 76128 Karlsruhe, Germany
(E-mail: *dutta@iwg.uni-karlsruhe.de*; *Erhard.Hoffmann@iwg.uni-karlsruhe.de*)

Abstract The rotating biological contactor (RBC) process offers the specific advantages of a biofilm system in treatment of wastewater for removal of soluble organic substances and stabilisation of nitrogen compounds. Being a unique adaptation of the moving-medium biofilm system, it facilitates easy and effective oxygen transfer. However, process optimisation and adaptability under different conditions remain challenging tasks for the efficient use of this technology. Although modelling helps to study system performance under various external conditions, satisfactory mathematical representation is lacking due to the dynamic nature of the RBC system. In this work, it has been attempted to frame a mathematical model for a three-stage RBC process in simple and realistic ways. The model is based on the well-known principles of one-dimensional mass transfer and transport of substances. The biochemical conversion process is adopted from the Activated Sludge Model No. 3 which represents a mixed-culture biomass environment. Owing to the dynamic nature of oxygen transfer, which is the typical limiting substrate in municipal wastewaters, the boundary layer is assumed to be completely mixed and concentrations averaged over the entire volume. A part of the boundary layer is assumed to be exposed to air and the rest submerged in bulk liquid at all times. The model results are compared with laboratory-scale experimental data available at 25 °C. Sensitivity analysis is performed with the model to study the significance of variation of different system parameters or the surrounding environment. In essence, the model helps to explore the flexibilities within a RBC system and optimise the process design accordingly.

Keywords Activated Sludge Model No. 3 (ASM No.3); biofilm modelling; multi-culture biofilm; nitrification; oxygen transfer coefficient (K_L); rotating biological contactors

Water Science & Technology **Vol 55 No 8–9 pp 345–353** © IWA Publishing 2007

Introduction

Aerobic treatment of wastewater using fixed biofilm technology has been established as an efficient and proven technology with relatively stable end-products. Biofilm mechanisms have inherent advantages as a consequence of the high biomass packing density and compactness of the system. The specific advantage of such a system is the coexistence of an aerobic, anoxic and sometimes anaerobic environment in a single composite system, facilitating different removal regimes, such as carbon oxidation, nitrification and denitrification (Müller *et al.*, 1980; Boller *et al.*, 1990; Masuda *et al.*, 1990). Rotating biological contactors (RBC) are a unique adaptation of the fixed film process wherein a series of discs mounted on a common shaft undergo continuous rotations. These discs provide the surface for biofilm growth. A part of the discs is immersed in bulk liquid inside the reactor and the rotations generate a thin liquid film acting as a boundary layer over the biofilm surface (Figure 1). The large specific surface area of biofilm (150–250 m^2/m^3) facilitates high removal efficiency even at short contact periods. The economic advantage and compactness of the system compared with conventional treatment processes such as activated sludge plants make it a favourable choice especially suited to the concept of decentralised wastewater treatment systems (Patwardhan, 2003). They present an added advantage by

doi: 10.2166/wst.2007.276

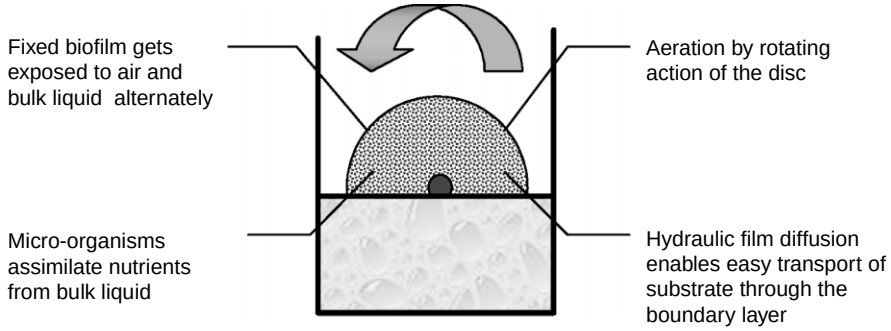

Figure 1 Sketch of RBC disc with liquid film and biofilm in operation

facilitating easy and effective oxygen and substrate transfer through hydraulic film diffusion across the air–liquid boundary. They offer an ideal alternative as a secondary or tertiary treatment unit.

Mathematical modelling helps to predict the system performance under various physical and bio-chemical conditions. Biofilm models require formulation of the inter-dependency between substrate transport and solids displacement inside the biofilm matrix as well as suitable estimation of the surface processes, such as attachment and detachment of biomass. Although the traditional 1D multispecies and multisubstrate models (Wanner and Gujer, 1986; Gujer and Boller, 1990; Wanner and Reichert, 1996; Rauch *et al.*, 1999) are well-established for the prediction of biofilm behaviour and substrate removal rates, RBC modelling remains unique because of the dynamic nature of the system. The biofilm model needs to be suitably customised to take into account the transient conditions at the boundary of an RBC.

In addition to the requirement of being a robust prediction tool, the required computational time is also an important factor in choosing the level of complexity of any model. Many of the complex 2D or 3D models are often slow unless suitable compromises have been made in obtaining solutions to the partial differential equations for the slow and fast dynamics simultaneously (Picioreanu *et al.*, 2000). In most cases, where the principal aim is to study biofilm growth and population dynamics at the individual cell level, a compromise is made by using an analytical solution approach to the substrate profiles in the biofilm. However, this paper attempts to apply the fundamental concepts underlying the system and develop an efficient modelling tool which can predict the system performance of an RBC effectively.

Method

The biofilm model is essentially adopted from the mathematics of the one-dimensional multi-culture biofilm (MCB) model formulated by Wanner and Gujer (1986) and RBC model of Gujer and Boller (1990). The process kinetics has been suitably modified based on the Activated Sludge Model No. 3 (Gujer *et al.*, 1999). The liquid film boundary layer is customised for the RBC process. Biomass in biocenosis is constantly getting displaced as a result of the advective-diffusive transport mechanism. Moreover, the density of particulate components inside the biofilm matrix is constantly varying as a result of the above mechanisms as well as surface reactions such as attachment of solids at the biofilm surface from the bulk and detachment of biomass (Reichert and Wanner, 1997). This may be visualised as shown in Figure 2. These changes invariably affect the nutrient transport into the biofilm.

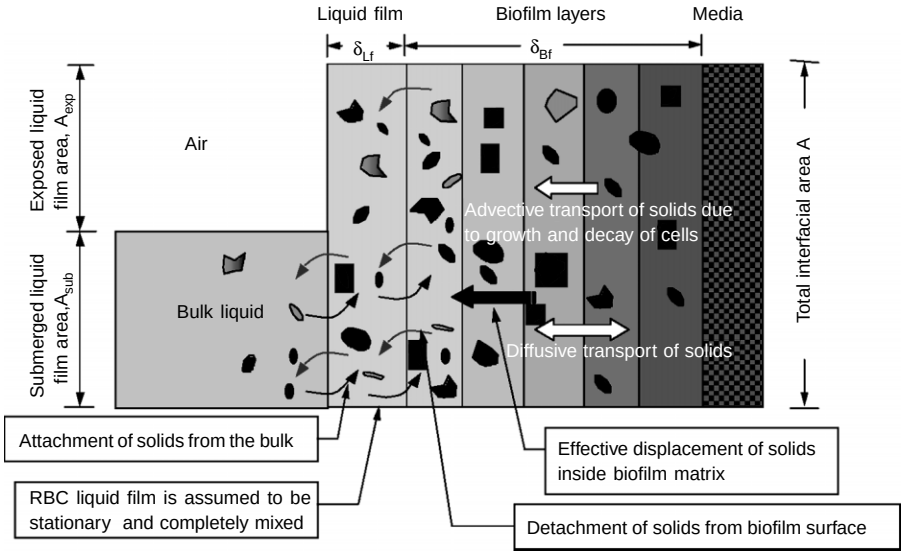

Figure 2 Transport and detachment of solids occurring in a RBC biofilm

Boundary layer equations

The boundary layer liquid film is conceptually divided into two parts at all times: one part is exposed to air and the other is in contact with bulk liquid as displayed in Figure 2. For ease of mass balance, it is assumed to be stagnant and concentrations are averaged over the total volume of the diffusive film. A material balance over the liquid film is necessary to maintain mass transport across the system. Equation 1 expresses the mass transfer for oxygen across the boundary layer at the top of the biofilm.

$$\frac{dS_{O_2}^{Lf}}{dt} = K_L^{air}\frac{A_{exp}}{V_{Lf}}\left(S_{O_2}^{*} - S_{O_2}^{Lf}\right) + K_L\frac{A_{sub}}{V_{Lf}}\left(S_{O_2}^{T} - S_{O_2}^{Lf}\right) - K_L\frac{A}{V_{Lf}}\left(S_{O_2}^{Lf} - S_{O_2}^{Bf}|_{x=\delta_{Bf}}\right) \quad (1)$$

(Transfer from air) (Transfer from/to tank) (Transfer to biofilm)

where V_{Lf} is average volume of the liquid film, i.e. δ_{Lf}^{A} [L^3]; δ_{Lf} is thickness of the boundary layer (liquid film) averaged over the whole disc area [L]; δ_{Bf} is thickness of biofilm at time t [L]; $S_{O_2}^{Lf}$ is dissolved oxygen concentration in the liquid film [ML^{-3}]; $S_{O_2}^{Bf}|_{x=\delta_{Bf}}$ is oxygen concentration at the biofilm surface [ML^{-3}]; $S_{O_2}^{T}$ is dissolved oxygen concentration in tank [ML^{-3}]; $S_{O_2}^{*}$ is equilibrium concentration of oxygen in the bulk at a given temperature [ML^{-3}]; K_L^{air} is oxygen transfer coefficient from the air into the liquid film [LT^{-1}]; K_L is oxygen transfer coefficient from bulk liquid to liquid film/biofilm, i.e. D_{O_2}/δ_{Lf} [LT^{-1}]; and D_{O_2} is diffusivity coefficient of oxygen at a given temperature [LT^{-2}].

For other substrates, the first term in Equation 1 is omitted and S_{O_2} is replaced by S_i representing any substrate and K_L by K_{S_i} signifying mass transfer coefficient of that substrate from bulk liquid to the liquid film or biofilm. K_{S_i} may be estimated as D_{S_i}/δ_{Lf} where D_{S_i} is the diffusivity coefficient of the substrate S_i. An assumption made for the boundary layer for simplification is that it contains no biomass and is assumed to be non-reactive in nature.

Biofilm model

The modelling of the transport of soluble components through the biofilm is essentially based on Fick's law because diffusion is the dominant process here (Gujer and Boller, 1990). The reaction kinetics is adopted from ASM No. 3 although storage of organic substrate by the heterotrophs as an intermediate step for subsequent hydrolysis has been avoided as it is not well documented for biofilm.

For particulate components, the transport is assumed to occur as a combination of diffusive and advective forms of movement (Wanner and Reichert, 1996). All fluxes are assumed to be zero at the media boundary as it is assumed to be impermeable. The model assumes attachment of solids into biofilm by first-order equation (Gujer and Boller, 1990) and detachment from the biofilm surface by regular shear using quadratic equations to stabilise the biofilm thickness, since not much experimental evidence is available for these processes. The temporal variation of biofilm thickness is modelled depending upon the net advective velocity flux at the biofilm surface. The detachment velocity can be calculated using the following equation:

$$u_{\text{det}} = \frac{\left(k_{\text{det,j}}\,\delta_{Bf}^{2}\right) X_{j}^{Bf}|_{x=\delta_{Bf}}}{X_{tot}^{Bf}} \tag{2}$$

where $k_{\text{det},j}$ is detachment rate coefficient [$L^{-1}T^{-1}$] of particulate species j [$ML^{-2}T^{-1}$]; $X_j^{Bf}|_{x=\delta_{Bf}}$ is concentration of particulate species j at the surface of the biofilm [ML^{-3}]; and X_{tot}^{Bf} is density of the biofilm [ML^{-3}].The bulk liquid reactor tank is assumed to be completely mixed and mass balance equations are based on advective mass fluxes and reaction inside the tank (based on ASM No.3). Figure 3 shows the schematic representation of the RBC system based on the laboratory-scale set-up used for model verification. The RBC is compartmentalised into three stages with maximum area and nutrient loading on the first stage.

The model has been developed in Matlab using finite difference solution methodology and spatial discretisation of the partial differential equations into ordinary differential equations. Owing to the stiff nature of the system of differential equations, a fully implicit variable time-step integrator based on stiff algorithm has been used. It is essentially based upon numerical differentiation formulae as well as backward differentiation formulae (Gear's method) for stability generation. The system of algebraic and differential equations is solved simultaneously for all the three stages with the effluent from each stage entering into the subsequent stage. Flow recirculation may also be introduced from the last stage to

Figure 3 Schematic view of the laboratory-scale RBC set-up and data specifications

the first stage depending upon requirements of the system performance. The resulting dilution effect is considered in the model accordingly.

Results and discussions

Simulation runs were conducted with the biofilm model and verified with the experimental results where available. All runs were made for 300 days to obtain near steady-state parameter values. The organic substrate is assumed to be soluble and readily biodegradable. The total dry density of solids in the biofilm was taken as 45 $kgCODm^{-3}$ based on experimental measurements. The liquid film thickness was assumed as 100 μm on average for a rotational speed of 2 rpm.

Variation of influent loading rates

It is observed that for a given hydraulic loading rate, the removal flux in a RBC system or any stage increases with influent nutrient loading rate up to a limit. Beyond that point, removal rates are fairly constant for that stage and the system capacity is exhausted. Figure 4(a) and (c) compare the simulated and experimental overall removal rates of organic carbon and ammonium in the three-stage RBC set-up. Ammonia flux remains the governing criterion in the selection of the physical capacity of a RBC system for combined nitrification. There is variation in the trajectory of the removal flux lines for each stage owing to variation of the characteristics of each stage, such as interfacial area, biofilm thickness. Figure 4(d) reveals that stage 3 has the least nitrification potential. There is a limitation of substrate when nitrification is complete by the end of the second stage and consequently, decay and inactivation processes start taking dominance over the growth of autotrophic micro-organisms (Gujer and Boller, 1990). This leads to a poor nitrifying bacteria density and hence a reduction in the removal rates compared with the

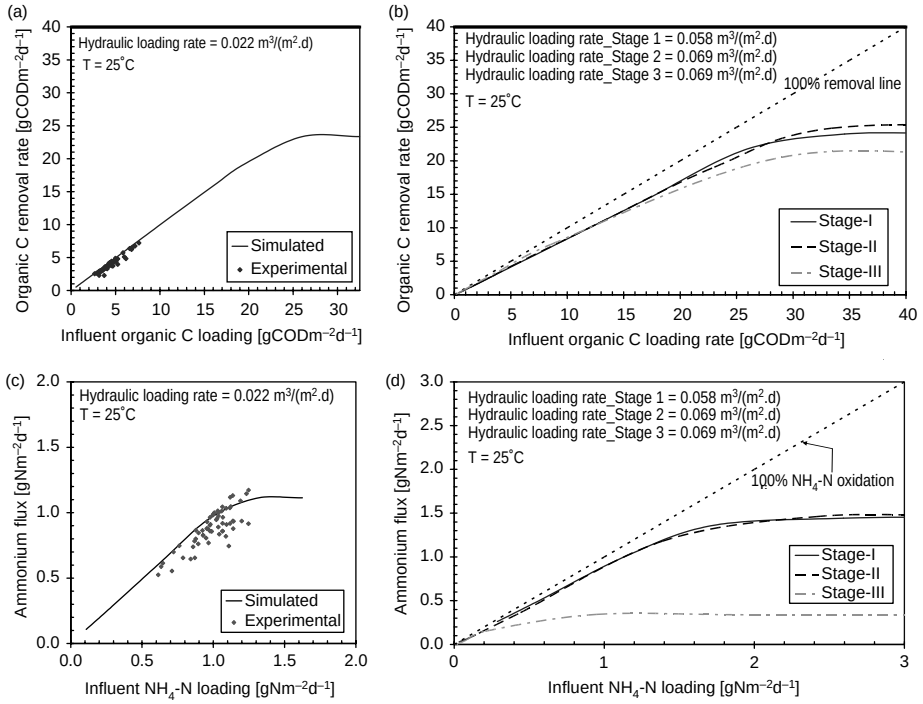

Figure 4 Effect of variation of influent loading rates: (a) soluble organic carbon removal in the overall system and (b) in each stage; (c) NH_4-N oxidation in the overall system and (d) in each stage

former stages. Temperature has a big influence on the removal fluxes and runs reveal that the fluxes decrease with dip in temperature owing to reduced growth and metabolic activities of the micro-organisms. Similarly, thickness of the diffusive boundary layer as at a given rotational speed pronounces a big effect on the removal efficiency of the system.

Biomass distribution and substrate profiles in biofilm

Figure 5(a) shows the typical distribution of particulate species inside the biofilm matrix for each stage. The effective diffusion coefficient for the particulate species D_{X_j} is adjusted at 6×10^{-9} m^2/d, based upon a similar value in the literature (Wanner and Reichert, 1996). It allowed the particulate components to become "diffuse" mixed inside the biofilm. For the first stage biofilm, the deeper biofilm layers have mostly inert matter and the heterotrophic species are concentrated in the surface layers of the biofilm. Apparently, the heterotrophs offer strong competition at high nutrient loadings and autotrophic organisms are able to grow only in the deeper layers of the biofilm and in the latter stages of the RBC when the organic load is substantially reduced. Figure 5(b) shows that when the biofilm in any stage is not nutrient limited, the active aerobic zone is approximately 300 μm from the biofilm surface. Owing to increased dominance of heterotrophs and

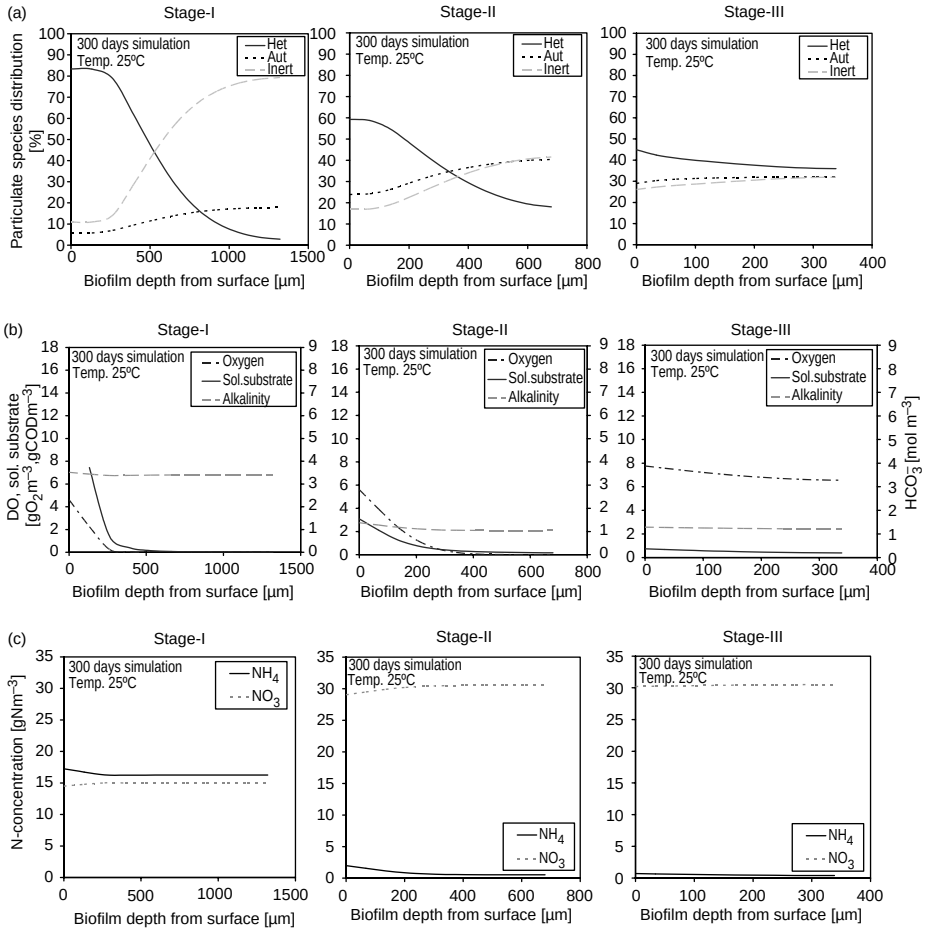

Figure 5 Profile of biomass and substrate concentrations inside the biofilm matrix for each stage at 25 °C: (a) Relative abundance of particulate species; (b) Dissolved Oxygen (DO), soluble organic carbon and alkalinity concentrations; (c) NH_4-N and NO_3-N concentrations

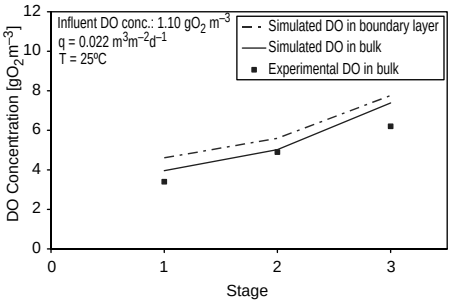

Figure 6 Simulated and observed DO concentrations in the bulk liquid in RBC stages

availability of DO in the upper layers, most of soluble organic substrate is degraded towards the surface. After stage 2, nutrient concentrations become considerably reduced and the distribution of the solids becomes more uniform inside the bio-matrix. Oxygen remains the limiting substrate in the deeper layers of the first two stages which account for nearly 98% removal of soluble organic substrate and 93% oxidation of NH_4-N. There is only partial denitrification in the RBC biofilm as revealed from the high concentration of NO_3-N in Figure 5(c). Maximum denitrification occurs in the first stage due to high heterotrophic density and the presence of nitrate from ammonia oxidation. The denitrification rate in this stage is predicted to be $0.176\,gNm^{-2}\,d^{-1}$. The alkalinity concentrations steadied at $3.60\,mol/m^3$ in stage I and $1.2\,mol/m^3$ in stage II and showed substantial uptake by the microbial species from the influent value of $6\,mol/m^3$. Thereafter, alkalinity consumption was minimal in stage III as little substrate was left behind.

Similarly, DO concentrations in the tank were relatively high in the latter stages (Figure 6) while high uptake rate by the biomass results in lower concentrations in stage 1. The advantage of high oxygen diffusion during the air exposure cycle in RBCs is clearly evident. This annuls the requirement of external aeration in the tank as the DO in the tank does not fall below $1.5–2.0\,gO_2m^{-3}$, usually required to achieve nitrification. However, scale-up operations may change this scenario. The results compared well with the observed values. The average DO concentration in the laminar boundary layer is always found to be slightly greater than in the reactor compartment.

Effect of flow recirculation

Sensitivity analysis with variation of flow recirculation ratio from 0.25 to 2.0 reveals that owing to reduction of the organic carbon concentration by dilution, nitrification improved appreciably in the first stage as evident from the effluent NH_4-N concentrations in Figure 7. However, the effluent concentration after stage 2 stays nearly the same and reveals little improvement in the overall ammonia oxidation. This illustrates that the stages of the RBC serve the purpose of dividing the nutrient load gradually during the

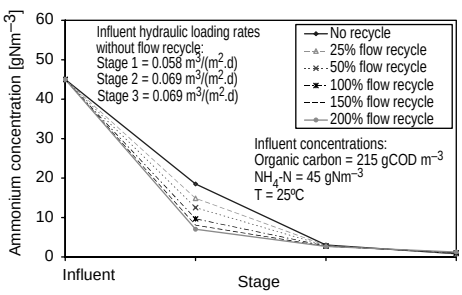

Figure 7 Effect of flow recycle on ammonia oxidation in the three-stage RBC

treatment process and therefore no additional recirculation is normally required. Wilson and Lee (1997) also observed in their experiments that recirculation did not improve the removal efficiency significantly.

Conclusions

The MCB model serves as a simple efficient engineering tool for design and process optimisation and helps to draw the following conclusions through its application on a three-stage RBC set-up:

- Average DO concentration in the boundary layer usually remains higher than the bulk due to high gas-liquid transfer rate through the exposed liquid film surface. Consequently, requirement of external aeration in the reactor compartment can be avoided.
- As observed in most biofilm systems, increase of nutrient loading rate increases the removal fluxes up to a certain limiting capacity.
- In a mixed-culture biomass environment subjected to multi-substrate feed, the ammonia removal flux serves as the governing criterion in system design for optimal performance.
- The stages under high nutrient loading rates show a non-uniform biomass distribution with heterotrophs dominating the surface layers when soluble organic substrate concentration is high. The nitrifying species become dominant once the heterotrophs start to dwindle.
- Denitrification is only partial in RBC systems and occurs predominantly in the initial stages of the RBC where high heterotrophic population and anoxic ambience are readily available.
- Flow recirculation reveals little improvement in the overall removal efficiency of the RBC system.

For a specific surface area of $233\,m^2\,m^{-3}$ of flat media under a hydraulic loading of $0.022\,m^3\,m^{-2}\,d^{-1}$, an overall removal efficiency of 99% for soluble organic substrate and 98% for NH_4-N is observed at an influent concentration of $4.7\,gCODm^{-2}\,d^{-1}$ and $1.0\,gNm^{-2}\,d^{-1}$, respectively. Therefore, RBCs can offer an ideal alternative as a secondary or tertiary biological treatment unit for simultaneous removal of organic carbon and nitrogen. The relative economy and compactness of the system compared with many conventional treatment processes make it a favourable choice especially suited to the concept of decentralised wastewater technologies gaining popularity today.

Acknowledgements

This model is part of the PhD research, sponsored by International Postgraduate Studies in Water Technologies (*IPSWaT*) programme of the Federal Ministry of Education and Research (BMBF), Germany.

References

Boller, M., Gujer, W. and Nyhuis, G. (1990). Tertiary rotating biological contactors for nitrification. *Wat. Sci. Tech.*, **22**(1/2), 89–100.

Gujer, W. and Boller, M. (1990). A mathematical model for rotating biological contactors. *Wat. Sci. Tech.*, **22**(1/2), 53–73.

Gujer, W., Henze, M., Mino, T. and Van Loosdrecht, M.C.M. (1999). Activated Sludge Model No. 3 (IAWQ). *Wat. Sci. Tech.*, **39**(1), 183–193.

Masuda, S., Watanabe, Y. and Ishiguro, M. (1991). Biofilm properties and simultaneous nitrification and denitrification in aerobic rotating biological contactors. *Wat. Sci. Tech.*, **23**, 1355–1363.

Morgenroth, E. and Wilderer, P.A. (2000). Influence of detachment mechanisms on competition in biofilms. *Wat. Res.*, **34**(2), 417–426.

Müller, J.A., Paquin, P. and Famularo, J. (1980). Nitrification in rotating biological contactors. *J. Wat. Poll. Control Fed.*, **52**, 688–710.

Patwardhan, A.W. (2003). Rotating biological contactors: A review. *Indian Eng. Chem. Res.*, **42**, 2035–2051.

Picioreanu, C., Van Loosdrecht, M.C.M. and Heijnen, J.J. (2000). Effect of diffusive and convective substrate transport on biofilm structure formation: A two-dimensional modelling study. *Biotechnol. Bioeng.*, **69**(5), 504–515.

Rauch, W., Vanhooren, H. and Vanrolleghem, P.A. (1999). A simplified mixed-culture biofilm model. *Wat. Res.*, **33**(9), 2148–2162.

Reichert, P. and Wanner, O. (1997). Movement of solids in biofilms: significance of liquid phase transport. *Wat. Sci. Tech.*, **36**(1), 321–328.

Wanner, O. and Gujer, W. (1986). A multispecies biofilm model. *Biotechnol. Bioeng.*, **XXVIII**, 314–328.

Wanner, O. and Reichert, P. (1996). Mathematical modeling of mixed-culture biofilms. *Biotechnol. Bioeng.*, **49**, 172–184.

Wilson, F. and Lee, W.M. (1997). Rotating biological contactors for wastewater treatment in an equatorial climate. *Wat. Sci. Tech.*, **35**(8), 177–184.