High biofilm activity under increased oxygen concentrations in a pressurised biofilm system

K.F. Janning*, S.N. Bak, M. Andersen** and G.H. Kristensen***

*DHI – Water and Environment, Agern allé 5, DK 2970 Hørsholm, Denmark
(E-mail: *kfj@dhi.dk; ghk@dhi.dk*)

**Grundfos Management A/S, Poul Due Jensensvej 7, DK 8850 Bjerringbro, Denmark
(E-mail: *snbak@grundfos.com; martinandersen@grundfos.com*)

Abstract A new pressurised biofilm reactor (PBR) process with a patented disc system that enables constant biofilm control has been developed to treat concentrated wastewater with respect to easily degradable organic matter under pressures of up to 6 bar. The pressurisation enables a six-fold increase of the O_2 saturation level and aeration capacity, which potentially increases the reaction rate of COD as long as O_2 is limiting the reaction rate. Experiments performed in a pilot-scale PBR-reactor fed by synthetic wastewater were conducted to verify the potential and kinetics of heterotrophic conversion of O_2 and acetate. Under O_2-limited conditions the maximum removal rate of O_2 and COD_f was measured to $r_{A,O2} = 60$ g $O_2/m^2/d$ and $r_{A,CODf} = 150$ g $COD_f/m^2/d$ at 70 mg O_2/l. Experiments verified that half-order kinetics could be applied but liquid film diffusion apparently influenced the reaction rate considerably. The observed half-order rate constant was experimentally determined to $K_{\frac{1}{2}A,O2} = 7.0$ (g $O_2)^{1/2}m^{-1/2}d^{-1}$ but this value is underestimated by 15% due to the observed liquid film diffusion. Based on this the intrinsic zero-order reaction rate was estimated at $k_{0f,O2} = 190$ kg O_2/m^3 biofilm/d when both liquid film and biofilm diffusion were taken into account.

Keywords Biofilm; half-order kinetics; hydraulic film diffusion; oxygen limited reaction rate; pressure

Introduction

Treatment of concentrated industrial wastewaters in new innovative high-rate biological fixed film reactors has proven to be gradually more efficient and compact as fundamental problems like biofilm control, hydraulics and mass transfer are recognised and solved in new reactor designs (Lazarova and Manem, 2000). Today, biological fixed film reactors offer a more compact design than traditional activated sludge processes for both heterotrophic and autotrophic conversion due to a high active biomass concentration attached to larger surface areas.

The significance of diffusion limitation in aerobic conversion processes often leads to only partly effective biofilms, which could be utilised better if higher oxygen concentrations or better mass transfer conditions were introduced. Increasing the oxygen partial pressure by supplying pure oxygen has proven to be an efficient method for enhancing tertiary nitrification rates with thin biofilms by more than 200% (Boller *et al.*, 1997; Bonomo *et al.*, 2000). For heterotrophic conversion this phenomenon is expected to be even more pronounced due to higher activity and growth of heterotrophs in biofilms. Increasing the pressure of the wastewater treatment process can also increase the oxygen saturation level. Pressurisation of biological processes has mostly been practised in deep-shaft systems where activated sludge is repeatedly cycled up and down shafts with depths of up to 150 metres. Only few findings regarding the effect of pressure in closed fixed film reactors have been published. Ellis *et al.* (1992) reported the effects of pressures of up to 6 bar on the operation of a laboratory-scale RBC-reactor for simultaneous nitrification and BOD removal.

This study demonstrates the first pilot-scale investigations of a new pressurised biofilm reactor technology designated the PBR-process (pressurised biofilm reactor). It focuses on demonstrating the potential of the PBR process and investigating the kinetics of the pressurised process into which increased oxygen concentration levels are introduced.

The PBR-process

The PBR-process has been developed by Grundfos A/S to treat highly concentrated industrial wastewaters, with respect to easy degradable organic matter and nitrification under pressures of up to 6 bar. The PBR-reactor can best be characterised as an aerated fixed bed reactor with a new patented moveable disc system enabling biofilm control. Inside the reactor the biofilm is attached to polypropylene discs with a well defined surface structure, which ensures protection against biofilm sloughing (Figure 1). Dynamic and continuous biofilm abrasion then controls the biofilm thickness (500 μm) by rotation of the disc system. The reactor is operated using fixed discs and rotating discs. Every second disc rotates while the remaining discs are fixed. In this way the rotation of every second disc ensures biofilm abrasion between each disc layer.

The pressurisation of the reactor is performed using a multistage centrifugal inlet pump with automatic pressure sensor and an outlet control valve with flow control. The purpose of the pressurisation is to increase the maximum oxygen saturation proportionally to the increase in pressure in order to obtain high O_2-concentration levels in the reactor. An increased O_2-saturation concentration leads to an equivalent increase in the flux of O_2 into the biofilm, which is necessary in order to supply enough oxygen for the high O_2-removal rates.

Materials and methods

The experimental set-up

The experimental set-up (Figure 2) consisted of a continuously fed PBR-reactor with recirculation. The air was injected by a diffuser in a small aeration tower followed by a de-aeration tower, which prevented air build-up inside the reactor and released produced CO_2 that could result in a decrease in pH. Oxygen was measured in the recirculation stream using two specially designed microelectrodes, which were capable of measuring high and transient oxygen concentration levels under pressure. The physical properties of the reactor and the experimental set-up are shown in Table 1. The pressurised biofilm reactor was operated with synthetic wastewater based on tap water with the addition of sodium acetate (3,000 mg COD/l) and sufficient amounts of the nutrients required.
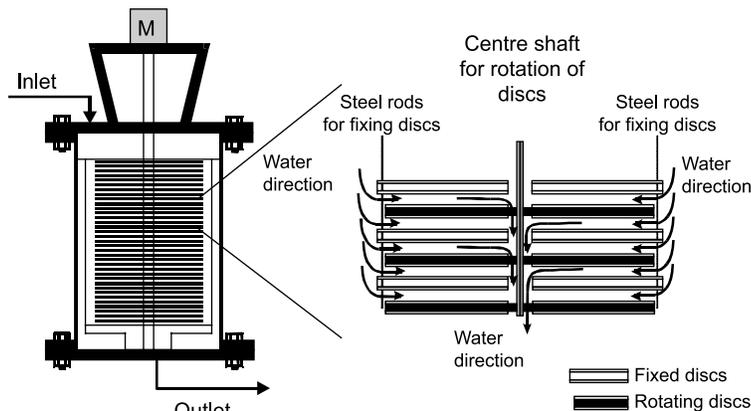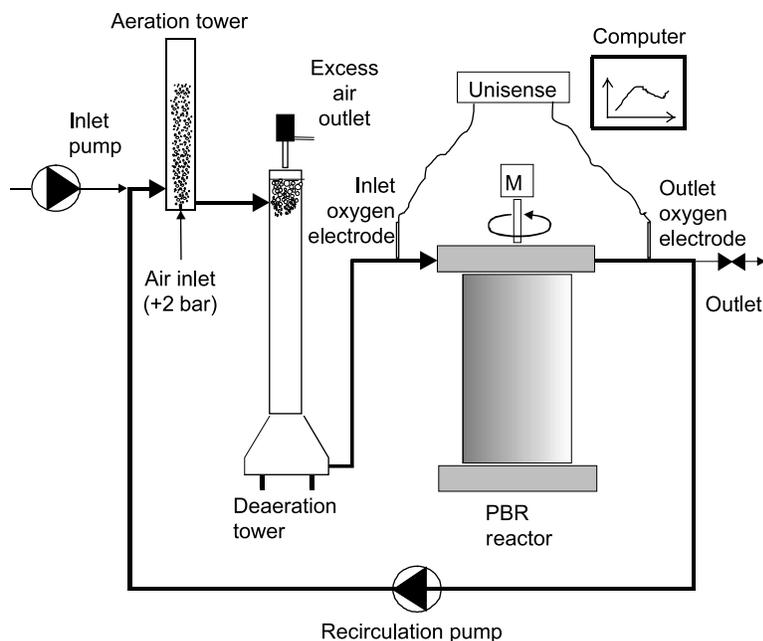

Figure 1 Principle of disc operation in the PBR process

K.F. Janning *et al.*

Figure 2 Experimental set-up

To prevent growth in the wastewater equalisation tanks (three tanks each containing 1,000 l), phosphorus was supplied to the inlet before the pressure pump using a dosing pump.

Experimental procedure

The performance and the kinetic evaluation of the heterotrophic process activity of the pressurised reactor were determined in a series of short-term phases, in which the concentration of oxygen was altered in a wide concentration span from 1 to 70 mg O_2/l.

The purpose of the kinetic experiment was to determine: (1) the O_2-limited removal rate and COD_f removal rate, (2) the reaction order and (3) the oxygen concentration necessary for obtaining a zero-order reaction in a fully penetrated biofilm. During the experiment acetate was kept constant and in excess in order to prevent COD limitation on the reaction rate at all times. The length of each phase was balanced between having a sufficient wash-out period from the previous phase (four residence times in the ideally mixed system) and a minimal growth of the biofilm when higher oxygen concentrations were introduced.

Table 1 Physical properties and condition of the experimental set-up

Inlet flow	m^3/day	2.45
Recirculation flow	m^3/day	52.8
Reactor volume (empty bed)	m^3	0.035
Number of discs	–	172
Biofilm area	m^2	15
Specific surface area	m^2/m^3	400
Hydraulic residence time	min.	30
Pressure (total)	bar	5.6
pH, outlet	–	7.0–7.6
Temperature, outlet	°C	16–19

71

Results and discussion

The start-up and running in of the PBR-reactor was carried out over two weeks. After inoculation with activated sludge the removal rate of O_2 and COD increased and reached a constant maximum level after 2–3 weeks. A 2-month test period following the start-up phase verified that biofilm control could be obtained with no drop in performance of the reaction rate. During that period the reactor was operated at a pressure of 6 bars with an average oxygen concentration level of 35–40 mg O_2/l over the reactor. The kinetic performance of the O_2-limited process was evaluated after the test period (Figure 3).

It appears that the transient O_2-variation had a direct impact on the removal rate of O_2, COD_{tot} and COD_f, showing that the process rate was O_2-limited up to 70 mg O_2/l. It also appears that the length of each phase ($\approx$ 4 residence times) was long enough to obtain a steady removal rate at the end of each phase, except for the last two phases of the experiment, when the removal rates were not sufficiently equalised due to shorter wash-out periods. During the last two phases of the experiment the O_2-concentration was increased further by addition of pure oxygen in order to see whether a zero-order reaction could be obtained; however, the reaction rate increased, showing no signs of full biofilm penetration. The O_2-concentration used to characterise the removal rate levels was calculated as the average O_2-concentration over the reactor discs since it was assumed that the mixing in the layer between the slowly rotated discs was closer to plug flow than to ideal mixing.

The surface specific removal rates obtained at high O_2-concentrations are significantly higher than those obtained in conventional O_2-concentration regimes as a result of the increased utilisation of the biomass. It appears that the surface specific reaction rates obtained are considerably higher than other high-rate biofilm reactors operating in conventional O_2-concentration regimes (Lazarova and Manem, 2000 ($r_{A,COD} = 5-10$ g COD_{tot}/m^2/d), Johnson et al., 2000: $r_{A,CODmax} = 40$ g COD_{tot}/m^2/d).

An evaluation of the process kinetics reveals that half-order kinetics apparently describes the process well (Figure 4). When the O_2-concentration is increased in half-order the removal rates of both O_2 and COD_f are increased proportionally (Figure 4B).

The half-order theory described by (Harremoës, 1978) assumes that the biofilm is homogenous in composition and that a zero-order intrinsic reaction rate occurs in the biofilm for concentrations higher than twice the half-saturation concentration of the limited substrate (which for O_2 would be 1–2 mg O_2/l). In the lowest O_2-concentration regimes a certain deviation from half-order kinetics would be expected due to the transition to intrinsic first-order reaction in the biofilm, but as it appears in Figure 4, the deviation from half-order kinetics occurs for much higher O_2-concentrations, indicating that liquid
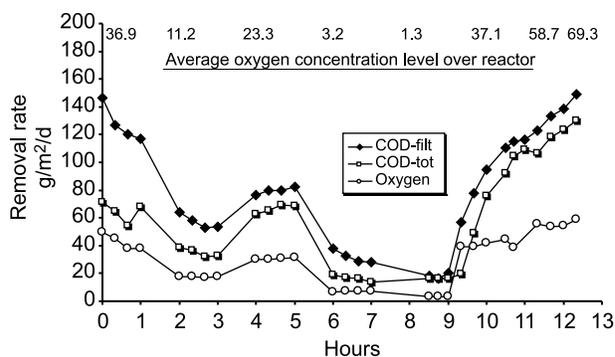

Figure 3 Effects in O_2-removal rate, COD_{tot} and COD_{filt}-removal rate during transient variation of O_2-concentration over the reactor
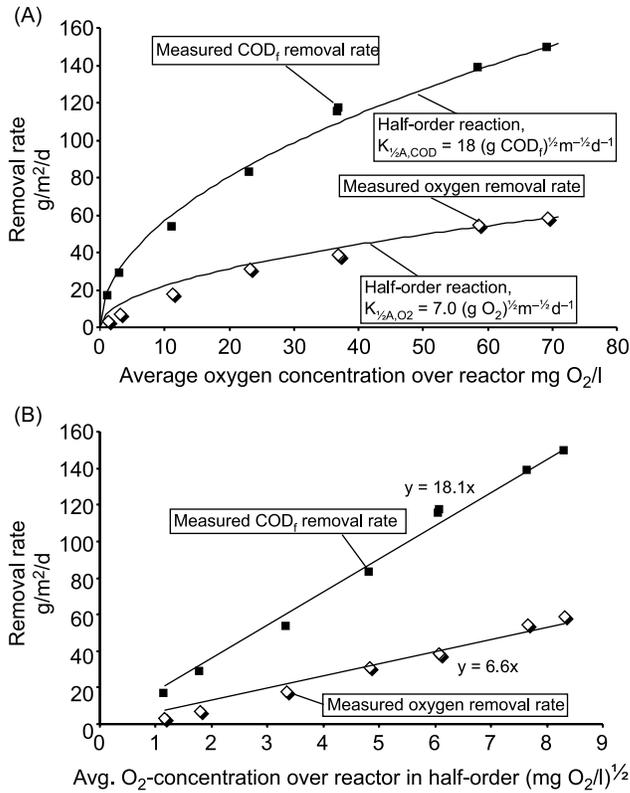
Figure 4 O_2-concentration in first-order versus removal rate of O_2 and COD_f (A). O_2-concentration in half-order versus removal rate of O_2 and COD_f (B)

film diffusion influences reaction kinetics significantly. The apparent half-order rate constant is $K_{\frac{1}{2}A,O2} = 7.0\,(g\;O_2)^{1/2}m^{-1/2}d^{-1}$ based on the highest O_2-removal rates obtained (Figure 4A).

The special construction of the carrier type (parallel plates with low distance in between) makes liquid film diffusion very relevant to consider when evaluating the process kinetics. Although the rotation of the discs can reduce this phenomenon significantly, it was not possible to increase the rotation higher than 2 rpm with this experimental set-up. Since the liquid film diffusion is directly related to the Reynolds number, (Re $\approx$ 5), it was evident that this phenomenon had to be taken into account. Harremoës (1978) analytically describes the influence of liquid film diffusion when this phenomenon is coupled with the theory of half-order kinetics. Assuming that the transport of substrate through the liquid film layer is only caused by diffusion, the flux of the limited substrate through the liquid film in a partly penetrated biofilm with a zero-order intrinsic reaction rate can be described as:

Flux through the liquid film $N = h \cdot (S - S_b)$

$$= \text{Flux into the biofilm } K_{1/2A,S} \cdot \sqrt{S_b} = r_{A,S} \qquad (1)$$

where:

N = flux of substrate through the liquid film into the biofilm [g/m^2/d]

$r_{A,S}$ = surface specific reaction rate [g/m^2/d]

$K_{\frac{1}{2}A,S}$ = half-order rate constant [g$^{1/2}$m$^{-1/2}$ d^{-1}]

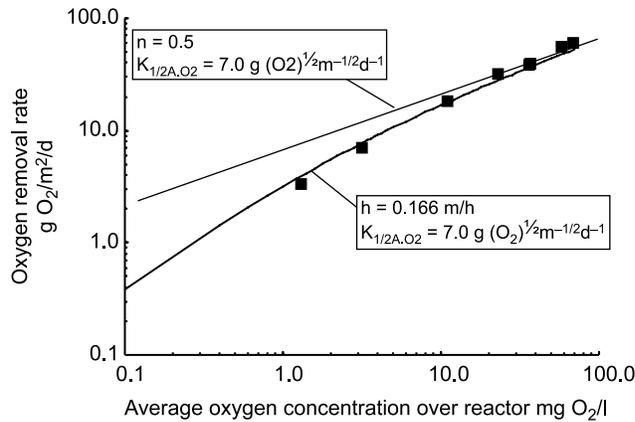S = concentration of limited substrate in the bulk liquid [g/m^3]

73

Figure 5 Effect of liquid film diffusion on the O_2-reaction rate

$S_b =$ concentration of limited substrate on the biofilm surface [g/m^3]

$h =$ transfer coefficient through the liquid film [m/d]

According to Harremoës (1978) the half-order reaction rate with influence of liquid film diffusion can be expressed as:

$$r_{A,S} = K_{1/2A,S} \cdot S^{1/2} \cdot \left(\sqrt{1 + \frac{1}{4\lambda^2}} - \frac{1}{2\lambda} \right), \quad \lambda = \frac{h \cdot S}{K_{1/2A,S} \cdot S^{1/2}} \tag{2}$$

By curve fitting the experimental results with (2), the best fit is obtained when $h = 0.166$ m/h (Figure 5). From Figure 5 it appears that the reduction in oxygen concentration on the biofilm surface caused by liquid film diffusion is significant. Below 20 mg O_2/l the reaction rate deviates from a half-order towards a first-order process.

The significance of liquid film diffusion, expressed by (1), verifies that the more the O_2-bulk concentration is increased the more the O_2-concentration is reduced from the bulk liquid to the biofilm surface. In the O_2-concentration range 35–70 mg O_2/l the reduction of O_2 through the stagnant film layer is calculated to be gradually reduced by 10–15 mg O_2/l. This would lead to an increase of $K_{\frac{1}{2}A,O2}$ of 15% if liquid film diffusion could be eliminated. Based on this the intrinsic reaction rate constant of oxygen can be calculated to be $k_{0f,O2} = 190$ kg O_2/m^3/d when liquid film diffusion is taken into account. Based on the half-order theory, biofilm penetration of the O_2 is calculated to be 310 μm if the liquid film is assumed to be uniform over the entire disc and the biofilm is considered to be homogenous with an oxygen diffusion coefficient of 1.7×10^{-4} m^2/d.

The importance of this is that two thirds of the approximate 500 μm biofilm thickness is probably penetrated but if liquid film diffusion could be eliminated or reduced significantly by increased rotation of the discs an even more efficient process could be obtained. However, the experiment also demonstrates that more knowledge about the mass transfer of rate-limited substrates over the discs is important for interpreting of the amount of biomass that such a biofilm reactor should maintain.

Conclusions

Experiments with a pilot-scale pressurised biofilm reactor have demonstrated that a constant high surface specific removal rate of COD based on acetate can be obtained when the O_2-concentration is increased due to the pressurisation. A new patented disc system enables full biofilm control by maintaining a constant biofilm thickness caused by constant biofilm abrasion on the discs. Under O_2-limited conditions the maximum removal rate of COD and O_2 was $r_{A,COD_f} = 150$ g COD_f/m^2/d and $r_{A,O2} = 60$ g O_2/m^2/d at O_2-

concentrations up to 70 mg O_2/l. Experiments verified that half-order kinetics could be applied but liquid film diffusion apparently influenced the reaction rate considerably. The observed half-order rate constant was $K_{\frac{1}{2}A,O2} = 7.0\,(g\ O_2)^{1/2}m^{-1/2}d^{-1}$ but this value is underestimated due to the observed liquid film diffusion. The influence of liquid film diffusion was characterised by determining the transfer coefficient of oxygen through the liquid film layer, which was estimated to be 4 m/d based on the experimental data. The significance of this is that the O_2-concentration in the higher O_2-concentration ranges (35–70 mg O_2/l) reduces O_2-concentration through the liquid film layer by 10–15 mg O_2/l resulting in an increase of $K_{\frac{1}{2}A,O2}$ to $8.0\,(g\ O_2)^{1/2}m^{-1/2}d^{-1}$ if liquid film diffusion could be eliminated. Based on this the intrinsic zero-order reaction rate is estimated to be $k_{0f,O2} = 190\,kg\ O_2/m^3$ biofilm/d when liquid film diffusion and biofilm diffusion are taken into account.

References

Boller, M., Tschui, M. and Gujer, W. (1997). Effects of transient nutrient concentrations in tertiary biofilm reactors. *Wat. Sci. Tech.*, **36** (1), 101–109.

Bonomo, L., Pastorelli, G. and Rinaldi, G. (2000). Tertiary nitrification in pure oxygen moving bed biofilm reactors. *Wat. Sci. Tech.*, **41**(4–5), 361–368.

Ellis, K.V., Mortimer, G.H. and Berktay, A. (1992). Biological wastewater treatment under the influence of pressure. *J. IWEM.*, **6**, 468–474.

Harremoës, P. (1978). Biofilm kinetics. In *Water Pollution Control Microbiology*, **Vol. 2**, Michell, R. (ed.), Wiley, New York, pp. 71–109.

Johnson, C.H., Page, M.W. and Blaha, L. (2000). Full scale moving bed biofilm reactor results from refinery and slaughter house treatment facilities. *Wat. Sci. Tech.*, **41**(4–5), 401–407.

Lazarova, V. and Manem, J. (2000). Innovative biofilm treatment technologies for water and wastewater treatment. In *Biofilms II: Process Analysis and Application*, Bryers, J.D. (ed.), Wiley, New York, pp. 159–206.