Environmental Technology, Vol. 22. pp 000-000

HYDRAULIC CHARACTERISTICS OF AN ANOXIC ROTATING BIOLOGICAL CONTACTOR: INFLUENCE OF BIOFILM

* P. TEIXEIRA, M. ALVES AND R. OLIVEIRA*

Centro de Engenharia Biológica - IBQF, Universidade do Minho, 4700 Braga, Portugal

(Received 10 April 2001; Accepted 19 April 2001)

ABSTRACT

The hydraulic characteristics of an anoxic rotating biological contactor were studied under different flow rates. The experiments were carried out with the reactor clean (without biomass) and containing denitrifying biofilm (*Alcaligenes denitrificans*) covering the disks. Residence Time Distribution (RTD) experiments were performed by the stimulus-response technique using lithium chloride as tracer. Experiments without biomass revealed the existence of hydraulic dead volumes (around 40% for hydraulic residence time of 0.94 and 2 hours) that occur in corners, where stagnant eddies form. When in normal operation, with the disks covered by biofilm and with biogas production, these values decreased significantly. For hydraulic residence time (HRT) of 2 hours a minimum dead volume was observed, being appropriate to run the reactor under this condition, from the hydraulic viewpoint. The Dispersion number decreased with increasing HRT from 0.94 h on, for both types of experiment, without, and in the presence of biomass. For this HRT the dispersion number was maximal in both situations. A considerable diffusion of tracer into the biofilm was detected, being faster in the more hydrated biofilm, and justifying the long tails observed in the RTD experimental curves.

Keywords: Rotating biological contactor, residence time distribution, dispersion model, dead space, diffusivity

INTRODUCTION

The rotating biological contactor (RBC) is widely used as a fixed-film biological system in wastewater treatment. The principal reasons are the operational simplicity, treatment efficiency, low area requirement, low energy consumption and robustness of the system. Hydraulic characteristics as well as the kinetics of the reaction determine the relationship between influent and effluent quality, defining the performance of the reactor. Regarding the mixing conditions within the reactor, no common agreement exists whether a RBC behaves like a plug-flow or a completely mixed reactor [1]. In practice, the hydrodynamic behaviour of any biofilm reactor lies somewhere between these two flow patterns and is always affected by the existence of by-pass or short circuiting, recycling and dead zones. The use of closed rotating biological contactors is relatively new in biological wastewater treatment. It combines advantages of the aerobic RBC (high biomass concentration, short hydraulic retention time) and of the anaerobic process (low quantities of waste biological solids) [2]. Some studies, conducted at laboratory and pilot-scale and focused on the hydraulic characteristics of anaerobic RBCs, concluded that high disk rotational speed and low disk submergence enhance mixing conditions in those reactors [3,4]. This type of studies can give useful information about the potential hydrodynamic malfunctions of full scale RBC.

In the present work, the effect of biofilm in the non-ideal behaviour of a laboratory anoxic RBC (AnRBC) was evaluated by determining the residence time distribution (RTD), using the stimulus-response technique [5], with lithium chloride as tracer. Although this compound is a widely accepted tracer for biological reactors [6] possible interactions with the biofilm can occur [7]. More precisely, diffusion of tracer in and out of the biofilm can distort the shape of the residence time distribution and the apparent mixing characteristics of the bulk fluid. In order to investigate this effect of diffusion of tracer into the biofilm, RTD experiments were performed with the reactor clean (without biomass) and containing denitrifying biofilm covering the disks. Culture medium was continuously fed in both experiments and identical hydraulic residence times were applied.

Dispersion model

Several models can describe the fluid flow pattern in a reactor. One example is the single parameter "Dispersion Model" [5] that was used to describe the flow pattern in the present case. According to this model, the ideal plug flow pattern is affected by some degree of axial dispersion. It predicts flow pattern from ideal plug flow (dispersion number=0) to ideal mixing (dispersion number=∞). A value of 0.2 defines a large degree of dispersion and 0.02 an intermediate degree of dispersion.

If closed vessel conditions are applied, *i. e.* when both tracer injection and collection take place in points of ideal plug flow (zero dispersion), the equation of the dispersion model is [8]:

$$E(\theta) = L^{-1}\left[G(s)\right] = \frac{1}{2}\sqrt{\frac{\mathrm{Pe}}{\pi\theta^3}} \times \exp\left[-\frac{(1-\theta)^2\,\mathrm{Pe}}{4\theta}\right] \qquad \text{(i)}$$

For low deviations from the plug flow pattern, *i. e.* for low axial dispersion, the results are not highly influenced by the applied boundary conditions [5,8].

Diffusion of tracer into and out of the biofilm

When performing RTD experiments in biofilm reactors, the diffusion of tracer into and out of the biofilm can affect the experimental curve. Thus, as the tracer flows throughout the reactor, if the bulk concentration is high there is diffusion into the biofilm and, when the bulk concentration is low there is diffusion out of the biofilm. This phenomenon retards the tracer output, introducing a long tail.

The characteristic time for diffusion of the tracer into and out of the biofilm is defined by:

$$t_d = \frac{\delta^2}{D_e} \qquad \text{(ii)}$$

where δ is the biofilm thickness (cm) and D_e (cm^2s^{-1}) is the diffusivity of the tracer. Stevens *et al.* [7] defined the conditions that allowed the importance of this phenomenon to be evaluated. If the residence time based on the liquid volume (excluding the biofilm) of a tracer in a reactor segment is t_S, three situations can occur:

1. $t_d/t_s > 100$: diffusion of tracer into the biofilm is not significant. Tracer concentration in the biofilm remains essentially zero; the biofilm behaves as a non-porous material;
2. $t_d/t_s < 0.1$: diffusion of tracer into the biofilm is very rapid. Tracer concentration in the biofilm is essentially equal to the concentration in the bulk liquid;
3. $0.1 < t_d/t_s < 100$: as the tracer flows through the reactor, the concentration changes in the biofilm, and the RTD profile will have a long tail.

MATERIALS AND METHODS

Experimental set up

The reactor is an anoxic single stage RBC consisting of 13 poly-methylmethacrylate disks, with a disk submergence of 64.5%, mounted in a rotating shaft. A schematic description of the reactor is illustrated in Figure 1. The rotational speed

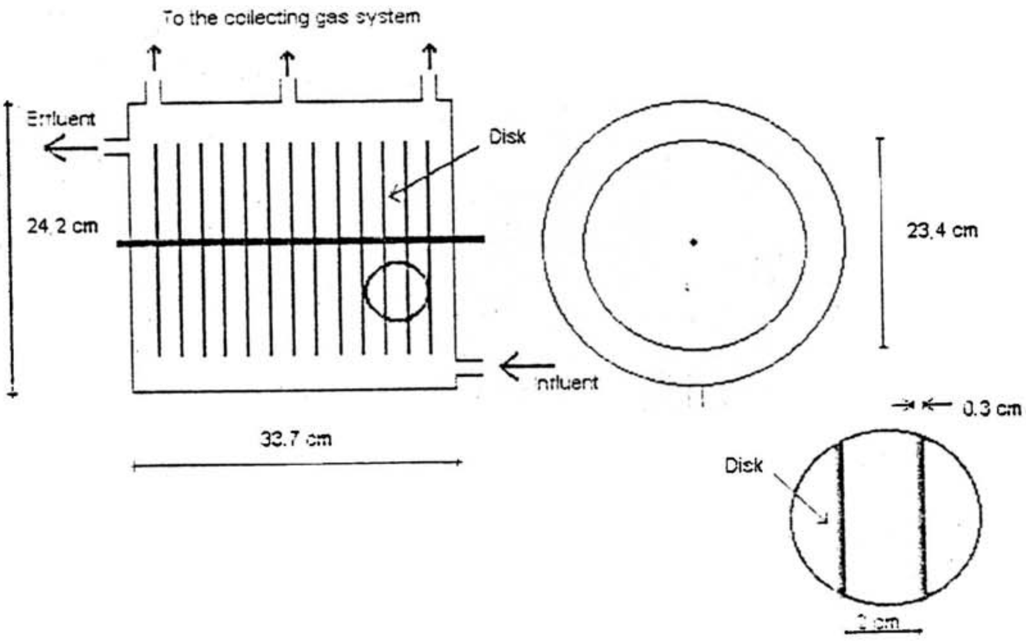

Figure 1. Schematic diagram of the AnRBC.

was 2 rpm and temperature was maintained around 26°C by means of a water jacket. The liquid volume was 13 l.

Operation mode, substrate and inoculum

The reactor operated with hydraulic retention times of 0.5, 0.94, 2.0, 2.8 and 3.8 hours and was fed with a synthetic medium with 50 mg N- NO_3^- l^{-1}, 200 mg P l^{-1} and using citrate as carbon source [9].

Cultures of *Alcaligenes denitrificans* ATCC 15173 were grown in batch mode for 3 days at 26 °C in an orbital shaker at 150 rpm. The reactor was inoculated with 600 ml of this culture and operated under batch mode for a week, in order to favour and promote initial biofilm formation.

Analytical methods

The biofilm thickness was measured with a vernier calliper. Average values were obtained from 10 determinations in each disk. Total solids were used as a measure of biomass concentration and were determined in accordance with the Standard Methods [10].

Tracer experiments

The residence time distribution (RTD) studies were performed by the stimulus-response technique [5], using lithium chloride as tracer. Aliquots of 2 ml of a solution containing 20 g Li^+ l^{-1} were injected, as a pulse, in the influent stream. Effluent samples were collected immediately after the injection and at frequent intervals, for at least 3 hydraulic residence times, until no tracer was detected. Lithium concentration in the samples was measured in a flame photometer (Jenway PFP7). The exit concentration was always below 10 mgl^{-1}. The "Optimisation Toolbox" from MATLAB (The Mathworks, Inc., USA) was used to obtain the optimal parameter by non-linear regression, using the Levenberg-Marquardt method [11].

RESULTS AND DISCUSSION

Comparing the results obtained with biomass and the clean reactor (Figures 2, 3 and 4), it can be seen that the peak of the curves of the experimental data obtained with biomass inside the reactor, always appeared later. This was to be expected due to the presence of the biofilm, which delays the passage of the tracer through the reactor.

Table 1 presents the results from the experiments without biomass. In all runs the recovered tracer was always in the range of 100±7% of the injected amount.

In these experiments, since there was no biomass, the dead volume represents only hydraulic dead space that occurs in corners, and possibly between the disks, where stagnant eddies form.

Good correlations of the dispersion model to the data

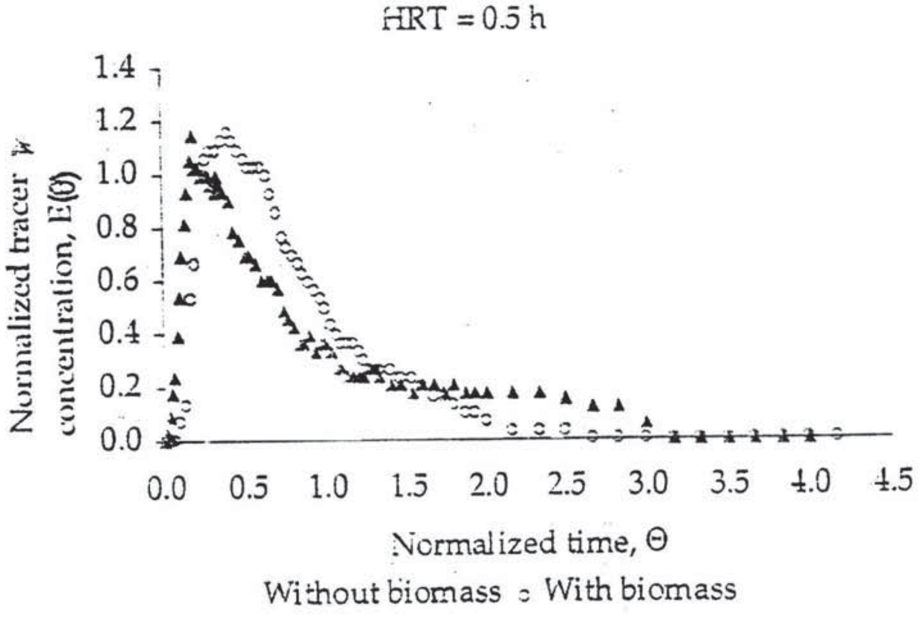

Figure 2. Experimental data from the residence time distribution with and without biomass in the AnRBC for the hydraulic retention time of 0.5 hour.

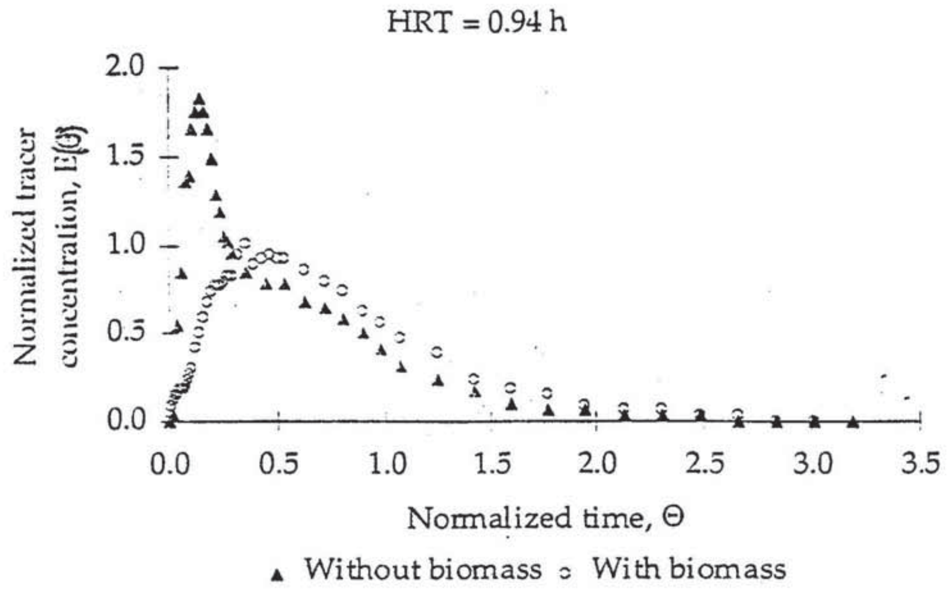

Figure 3. Experimental data from the residence time distribution with and without biomass in the AnRBC for the hydraulic retention time of 0.94 hours.

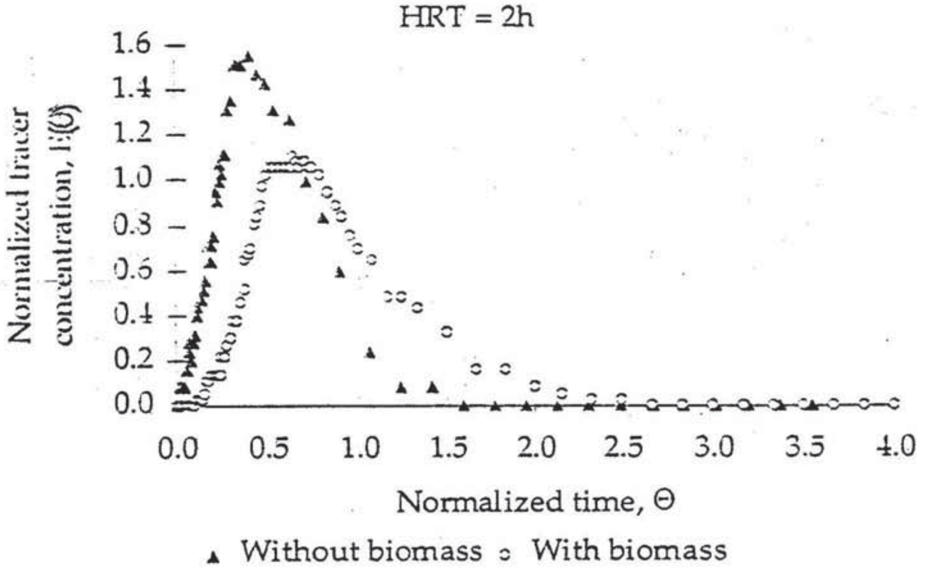

Figure 4. Experimental data from the residence time distribution with and without biomass in the AnRBC for the hydraulic retention time of 2 hour.

Table 1. Experimental results without biomass inside the AnRBC.

HRT (h)	D/uL	MRT (h)	V_d (%)	R^2
0.47	0.65	0.41	13	0.941
0.94	1.33	0.56	40	0.953
2.0	0.49	1.0	47	0.816
2.8	0.24	2.5	11	0.973
3.8	0.12	3.8	0	0.978

MRT – mean residence time; R^2 – correlation coefficient; V_d – Volume of dead space [=(1-MRT/HRT)*100]

were obtained for all the experiments. The worst was obtained for HRT = 2 h, which can be explained by the high dead volume detected (47%). For the experiment of HRT = 0.94 h the detected dead volume was also very high (40%). In general, the long tail in the experimental RTD curve shows a discrepancy between the mean residence time and the theoretical residence time. High values of the hydraulic dead space were not expected in the runs without biomass. However, it is possible that stagnant hydraulic zones exist near the inlet or between the disks where tracer can be trapped and slowly released. It must be noted that, in this reactor, the liquid volume between the disks represents 79% of the total liquid volume. Furthermore, the small space between the disks (2 cm) can hinder the tracer flow, resulting in high dead volumes for some conditions of HRT. However this hydrodynamic malfunction is overcome when biofilm is present.

RTD studies, for three hydraulic retention times, performed with denitrifying biomass in the AnRBC (disks fully covered with biofilm) were carried out after the reactor had been started up and operated for at least 100-fold the hydraulic retention time. Table 2 summarizes the experimental results and the calculated parameters, including those related to diffusion of tracer into the biofilm (t_d). As can be seen, there was again a good fit between the dispersion model and the experimental data.

Figure 5 represents the influence of HRT and presence of biomass on the dead volume.

In these experiments, the volume of dead space includes the hydraulic dead space and the biological volume occupied by the biomass and by the gas produced, but stimulus-response techniques do not allow for the distinction between these two forms of dead volume. In spite of the high values of dead space encountered for the reactor empty of biomass, when in normal operation with biomass and biogas production, the fraction of dead volume decreased significantly, except for HRT of 0.5 hours. This suggests that the presence of biomass and biogas contributed to a significant decrease in the existing hydraulic stagnant zones. However, for that HRT, probably due to greater biomass growth and biogas production, the dead volume was higher than when the reactor was empty of biomass. In this case, due to the high flow rate applied, sloughing of biofilm and its accumulation in the bulk liquid was observed. From the viewpoint of hydraulic operation, the HRT of 2 hours is advisable, since it corresponds to the lowest dead volume detected.

Figure 6 represents the influence of HRT and presence of biofilm on the dispersion number.

Table 2. Experimental results with biomass in the AnRBC.

HRT (h)	Biomass (g l^{-1})	δ (mm)	Peclet number	D/uL	R^2	MRT (h)	V_d (%)	t_d (h)	t_d/t_r	ww/dw
0.50	2.5	-	2.6	0.39	0.955	0.38	24	-	-	-
0.94	1.6	2.34	2.1	0.48	0.984	0.75	20	1.1	1.1	96
2.0	2.3	4.32	6.5	0.16	0.986	1.84	9.0	3.7	1.9	52

δ - Biofilm Thickness; t_d – diffusion time; ww - biofilm wet weight; dw – biofilm dry weight

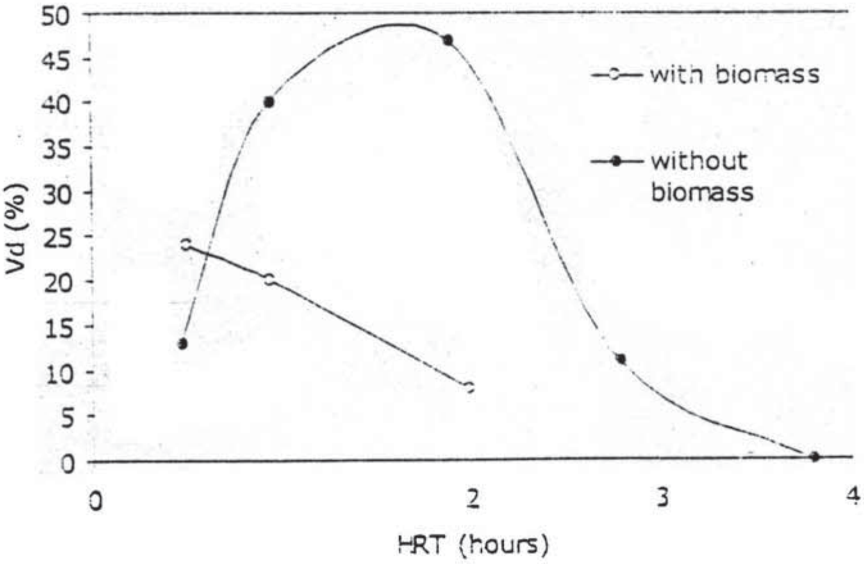

Figure 5. Dead volume versus HRT with and without biomass in the AnRBC.

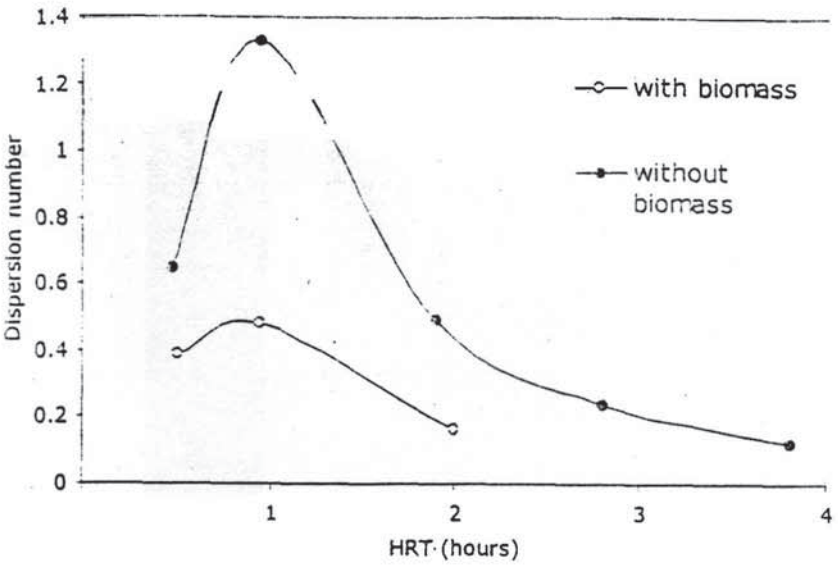

Figure 6. Dispersion number versus HRT with and without biomass in the AnRBC.

The presence of biomass decreased significantly the dispersion number, particularly for HRT of 0.94 hours, where a maximum dispersion was detected in both situations. In the experiments without biomass, a significant decrease in dispersion was observed when the HRT increased from 0.94 to 3.8 hours. However, according to the classification of Levenspiel [5], in all the runs the degree of dispersion detected was high. A similar result was obtained by Lin *et al.* [12], who concluded that the dispersion number increases with flow rate in the same type of reactor.

Regarding the diffusion of tracer into and out of a biofilm, according to Stevens *et al.* [7], it is controlled by the biofilm thickness and tracer diffusivity. In this work, the diffusion coefficient of lithium chloride at 26°C (1.4×10^{-5} cm^2 s^{-1}) was calculated according to Perry and Chilton [13]. As this value was the same for the three HRTs, the time of diffusion of the tracer was only dependent on biofilm thickness. However, it should be stressed that biofilm structure, which is strongly influenced by hydrodynamic conditions and shear stress, can also affect the diffusion. A more hydrated and porous biofilm is more easily penetrated, as was observed in the experiment with HRT of 0.94 h (Table 2). In this case, the diffusion time was about one third of that obtained for HRT of 2 h and the corresponding ratio of wet weight / dry weight for the biofilm was almost two times higher. The obtained values for t_d / t_r indicate a considerable diffusion of tracer into the biofilm. The combination of this effect with the possible presence of hydraulic dead zones is responsible for the long tails observed in the RTD curves (Figures 2, 3 and 4).

CONCLUSIONS

RTD experiments without biomass revealed the existence of hydraulic dead volumes (around 40% for HRT of 0.94 and 2 hours) that occur in corners, and in the space between the disks, where stagnant eddies form. When in operation with the disks covered by biofilm and with biogas production, these values decreased significantly. In those conditions, the minimum dead volume was observed for HRT of 2 hours, in the investigated interval of 0.5-2 hours. From the hydraulic viewpoint, it was considered appropriate to run the reactor under this condition of HRT.

The dispersion number decreased with increasing HRT from 0.94 h on, for both experiments without and with biomass. For this HRT, the dispersion number was maximal in both situations.

A considerable diffusion of tracer into the biofilm was detected, being faster in the more hydrated biofilm.

ACKNOWLEDGMENTS

The authors fully acknowledge the financial support provided by Instituto de Biotecnologia e Química Fina (IBQF) and PRAXIS XXI through grant BD/9121/96 and to Dr. Roberto Canziani (D.I.I.A.R. - Sez. Ambientale, Politecnico di Milano) for his helpful suggestions.

REFERENCES

1. Banerjee G., Hydraulics of bench-scale rotating biological contactor. *Water Res.*, 31, 2500-2510, (1997).
2. Lu C., Lin M.R. and Lee L.Y., Temperature effects on the performance of an anaerobic rotating biological contactor. *Environ. Technol.*, 18, 711-720 (1997).
3. Lu C., Li H.C. and Lee L.Y., Effects of disc rotational speed and submergence on the performance of an anaerobic rotating biological contactor. *Environ. Int.*, 23, 253-263 (1997).
4. Friedman A.A., Effect of disk rotational speed on biological contactor efficiency. *J. Water Pollut. Control Fed.*, 51, 2678-2690 (1979).
5. Levenspiel O., Nonideal Flow. In: *Chemical Reaction Engineering*. John Wiley & Sons, Inc., New York, pp. 253-325 (1972).
6. Anderson G.K., Campos C.M.M., Chernichard C.A.L. and Smith L.C., Evaluation of the inhibitory effects of lithium when used as a tracer for anaerobic digesters. *Water Res.*, 25, 755-760 (1991).
7. Stevens D.K., Berthouex P.M. and Chapman T.W., The effect of tracer diffusion in biofilm on residence time distributions. *Water Res.*, 20, 369-375 (1986).
8. Rodrigues A.E., Theory of residence time distributions. In: *Multiphase Chemical Reactors, Volume I-Fundamentals*, (Rodrigues, A, Calo, J. and Sweed, N. Eds.), Nato ASI, Plenum Publishing Corporation, London, pp. 226-285 (1981).
9. Teixeira P. and Oliveira R., Denitrification by *Alcaligenes denitrificans* in a closed rotating biological contactor. *Biotechnol. Lett.*, 22, 1789-1792, (2000).
10. Standard Methods for the Examination of Water and Wastewater. 18th edition, Greenberg, A. E., Clescer, L. S., Eaton, A. P. and Franson, M. H. A. (eds) American Public Health Association), Washington D. C., USA, (1992).
11. Marquardt J.D., An algoritm for least-squares estimation of non-linear parameters. *J. Soc. Ind. Appl. Math.*, 11, 431-441 (1963).
12. Lin M.R., Lu C. and Yeh A., Hydraulic characteristics and startup of anaerobic rotating biological contactors. *J. Chin. Inst. Eng.*, 18, 801-812 (1995).
13. Perry R.H. and Chilton C.H., Physical and chemical data. In: *Chemical Engineer's Handbook*. Fifth Edition, International Student Edition. McGraw-Hill, Kogakusha Ltd, Tokyo, pp 230-235, (1973).