

Application of residence time distribution technique to the study of the hydrodynamic behaviour of a full-scale wastewater treatment plant plug-flow bioreactor

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Abstract: The hydrodynamic behaviour of a full-scale wastewater treatment plant (WWTP) bioreactor treating municipal wastewater, situated in Granollers (Barcelona, Spain), has been studied by means of a residence time distribution (RTD) technique using lithium (chloride) as tracer. The bioreactor studied is designed to work as a plug-flow reactor and it is divided into two independent lanes (1 and 2), each one composed of four compartments in series resulting in a total volume of 3970 m³ per lane. During the RTD experiments, working flow was 1000 m³ h⁻¹ per lane, which implied an ideal mean residence time of 3.97 h. When a lithium chloride tracer was injected in the bioreactor, both lanes showed a similar highly non-ideal hydrodynamic behaviour, which had an important effect on the reactor's performance. This global RTD was complemented by means of local RTDs in different locations of the bioreactor in order to determine qualitatively the reactor's mixing regime. Different non-ideal models (namely axial dispersion, tanks-in-series and some simple compartment models) have been tested for the modelling of the experimental RTD. The best model fitting RTD data for Lanes 1 and 2 was a configuration consisting of four mixed tanks in series. The RTD study proposed in this work will permit improvement of the reactor's mixing performance, which is of special interest in future projects including simultaneous removal of carbon, nitrogen and phosphorus.

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Keywords: flow modelling; hydrodynamic behaviour; mixed tank; plug-flow reactor (PFR); residence time distribution (RTD); wastewater treatment plant (WWTP)

NOTATION

BOD ₅	Biological Oxygen Demand at 5 days (mg dm ⁻³)
C	Tracer concentration (mg dm ⁻³)
CSTR	Continuous Stirred Tank Reactor
HRT	Hydraulic Residence Time (h)
Pe	Peclet number
PFR	Plug-Flow Reactor
RTD	Residence Time Distribution
t	Time (h)
WWTP	Wastewater Treatment Plant

INTRODUCTION

The study of hydrodynamics and mixing conditions in an operating reactor is crucial in order to achieve the designed specifications for a given system and to solve problems that generally provoke

a lower efficiency in the reactor.¹ Also, hydraulic modelling of a bioreactor is essential in further development of biological models that permit monitoring and control of a wastewater treatment plant (WWTP).²

Residence time distribution (RTD) based on a stimulus–response technique is a useful test to determine important parameters such as the effective mean residence time, which is often quite different to the designed hydraulic residence time (HRT) due to ideal flow patterns assumed in the reactor design.¹ RTD has been widely used in chemical reactors,^{3,4} enzyme reactors,⁵ wastewater bioreactors,^{6,7} ponds⁸ or even rivers^{9,10} and generally consists of a fast injection (impulse) of a small quantity of an inert tracer into the inlet stream of the reactor. Samples are then taken from the outlet stream for the determination of tracer concentration and the construction of an RTD curve.

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Different tracers have been used in RTD experiments for wastewater bioreactor studies, including soluble salts such as lithium salts,^{11,12} chlorides,^{13,14} dyes,⁷ radioactive compounds^{9,15} or microorganisms.¹⁰ Among them, the utilisation of lithium is very common because of its low and constant influent concentration and because it is neither degraded nor adsorbed by microorganisms.¹²

RTD is also used in the description of non-ideal flow behaviour due to the presence of dead zones, channelling or short-circuiting. Some methods have been proposed to model flow non-ideality, generally based on combinations of ideal continuous stirred tank reactor (CSTR) or plug-flow reactor (PFR) models. Among them, non-ideal typical models include:¹

Axial dispersion model: consists of an ideal plug-flow reactor with a diffusive component in the axial direction, which can be quantified by the dimensionless Peclet number: $Pe = uL/D$, where: Pe : Peclet number, u : fluid velocity, L : length of reactor, D : axial dispersion coefficient. Peclet number is 0 for an ideal mixed tank and goes to infinity for an ideal plug-flow.

Tanks-in-series model: the reactor is divided into a number of perfectly mixed tanks (N). Again, for $N = 1$ an ideal CSTR is modelled, whereas for $N = \infty$ a PFR is obtained.

Compartment models: based on the combination of ideal CSTR and PFR arranged in different configurations.

Several units found in wastewater treatment plants have been modelled by using some of the patterns previously mentioned, for example, biofilters for tertiary nitrification,¹² anaerobic reactors,^{13,14} primary clarifiers¹⁶ or complete activated sludge processes.¹² In all these works, however, it is usual to carry out one single tracer experiment, which is used to simulate the behaviour of the overall studied system.

In this work, an RTD experiment was carried out in a full-scale two-lane plug-flow bioreactor using lithium as tracer, showing a highly non-ideal hydrodynamic behaviour. The global RTD was completed by local RTDs in some critical points of the bioreactor (Lane 1). Different non-ideal models have been tested for the modelling of experimental RTD and the best model fitting RTD data was a configuration of four tanks in series.

EXPERIMENTAL

Tracer analysis

Lithium chloride (analytical grade, Panreac, Spain) was used as tracer because previous studies have shown that lithium is not adsorbed onto microorganisms.¹² Our experiments concluded that the maximum amount of lithium absorbed onto sludge was approximately 10% (data not shown). LiCl, 8.75 kg previously diluted in 200 dm³ of tap water, was quickly injected in a pre-chamber of 4 m³ that is located just before

the first compartment of each lane of the biological reactor (4.375 kg of LiCl injected to each lane). Samples (1 dm³ volume) were collected from the outlet stream of the reactor. Samples were then filtered and digested previously to the lithium determination using a flame photometer according to standard methods (Normalised Method 3500-Li D) with a lithium limit detection of 0.025 mg dm⁻³.¹⁷

Reactor configuration

A complete description of the configuration and working parameters of the plug-flow reactor (Lane 1) is presented in Fig 1 and Table 1. The values and the scheme presented in Fig 1 and Table 1 are equivalent for Lane 2 (Lane 2 is adjacent to Lane 1 in the interior zone). Global RTD of each lane was performed following lithium concentration at the output streams of both lanes (1 and 2), whereas local RTDs were performed at the 12 points marked in Fig 1 at height of 2 m (which corresponded to the half-depth of the reactor).

During the RTD experiment, a nitrification–denitrification system for nitrogen removal was present in the start-up phase in the bioreactor. Thus, the first compartment was operating under anoxic conditions (and

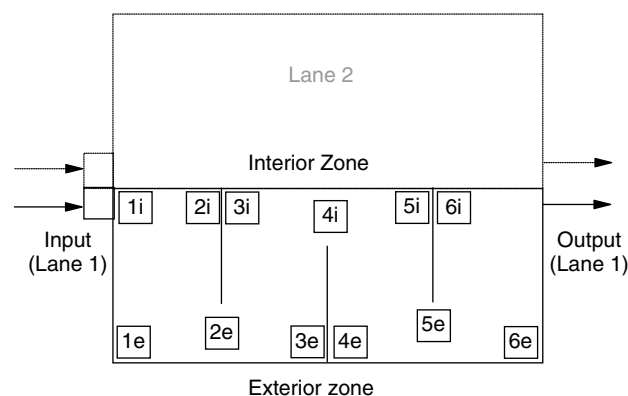


Figure 1. Schematic view of the bioreactor.

Table 1. Summary of the main operational parameters of the bioreactor: the values are equivalent for both lanes

Parameter	Value
Total volume (m ³)	3970
Average hydraulic flow (m ³ h ⁻¹)	1000 (100) ^a
Theoretical HRT (h)	3.97
Number of compartments	4
Volume of each compartment (m ³)	992
Dimensions of each compartment (m × m)	12 × 22
Depth of compartments (m)	4
Average input BOD ₅ (mg dm ⁻³)	322 (50) ^a
Average output BOD ₅ (mg dm ⁻³)	25 (10) ^a
Average temperature (°C)	22
Average oxygen requirements (kg h ⁻¹)	330
Volume of air diffusers (% of compartment volume)	5
Secondary settler volume (m ³)	2400
Sludge recirculation ratio	1:1

^a In parentheses: standard deviation.

hence without aeration), whereas the three following compartments of each lane were operating under aerobic conditions (aeration supplied by submerged diffusers). However, in order to simplify the interpretation of RTD data, internal nitrate recirculation (ratio 1:1 to feed) from aerobic (nitrifying) to anoxic (denitrifying) compartments was not operative during RTD experiments.

Numerical procedures

All the mathematical calculations (eg integration of RTD curves or model fitting) were carried out by means of a home-made program developed with Microsoft Visual Basic 6.0.

RESULTS AND DISCUSSION

Global RTD

Results for the global RTD obtained for both Lanes 1 and 2 are presented in Fig 2. Previous sampling

of the raw wastewater entering the bioreactor had shown that lithium concentration was negligible, which implied that the total amount of tracer came from the RTD injection. On the other hand, only data from the first 8 h of the RTD experiments were considered, since after this period of time, it was observed in independent experiments (data not shown) that tracer coming from the recirculation of the secondary decanter was detected in the influent stream of the biological reactor. Under these conditions, mass balances for tracer were closed for Lanes 1 and 2 in percentages of 89 and 92%, respectively.

Similar patterns were obtained for both lanes of the bioreactor, indicating a similar flow regime. Specifically, a high sharp peak of tracer was present at a time around 2 h for both lanes, whereas ideal plug-flow RTD would be a horizontal infinity lane at a time of 3.97 h. On the other hand, integration of the curves presented in Fig 2 permitted calculation of the mean effective HRT, according to eqn (1):

$$\text{Effective HRT} = \frac{\int_0^{\infty} t C dt}{\int_0^{\infty} C dt} \quad (1)$$

Application of eqn (1) to experimental data of Figs 2(a) and 2(b) resulted in an effective HRT of 3.85 h and 3.63 h for Lanes 1 and 2 respectively. These effective HRTs are similar to that corresponding to the theoretical value, which was 3.97 h for both identical lanes. The shapes of Fig 2(a and b) clearly indicated that an important amount of tracer was washed out of the reactor in the first 2 h of the RTD experiment, while the rest of the tracer was slowly removed from the reactor in a long tail that is always found in mixed tanks.^{13,14} This long tail, present in both lanes, decreased with time in an oscillating form. These oscillations could be due to analytical errors or internal tracer recirculation in the reactor. Nevertheless, at the end of the RTD experiment (16 h), tracer concentration was in the range of the lithium detection limit (0.025 mg dm^{-3}). This fact, jointly with a closed mass tracer balance, indicated that all the lithium injected in the inlet stream was found in the outlet stream.

Local RTDs (Lane 1)

Global RTD was useful for the determination of the main characteristics of bioreactor flow and for the calculation of the effective HRT. However, due to the limitations of the global RTD in a complex system, some other flow conditions (eg presence of dead zones) or bioreactor flow modelling could not be studied with this technique. In order to overcome these limitations, located RTDs in different points (Fig 1) were performed on Lane 1 of the bioreactor at different periods of time (Figs 3 and 4). The points

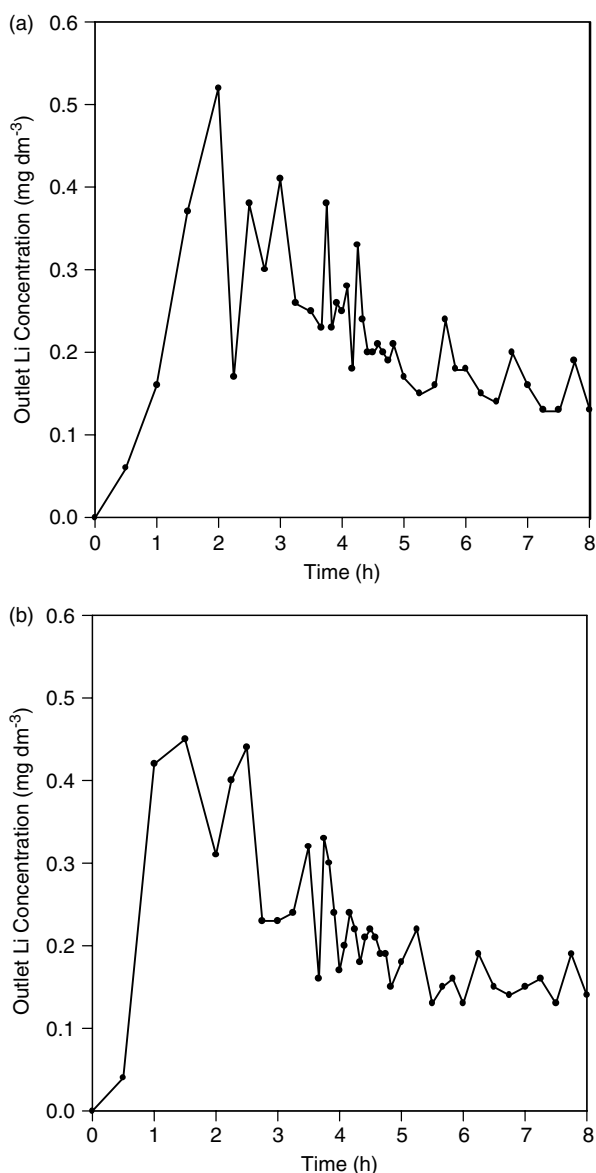


Figure 2. Global RTD for the plug-flow bioreactor. (a) Lane 1, (b) Lane 2.

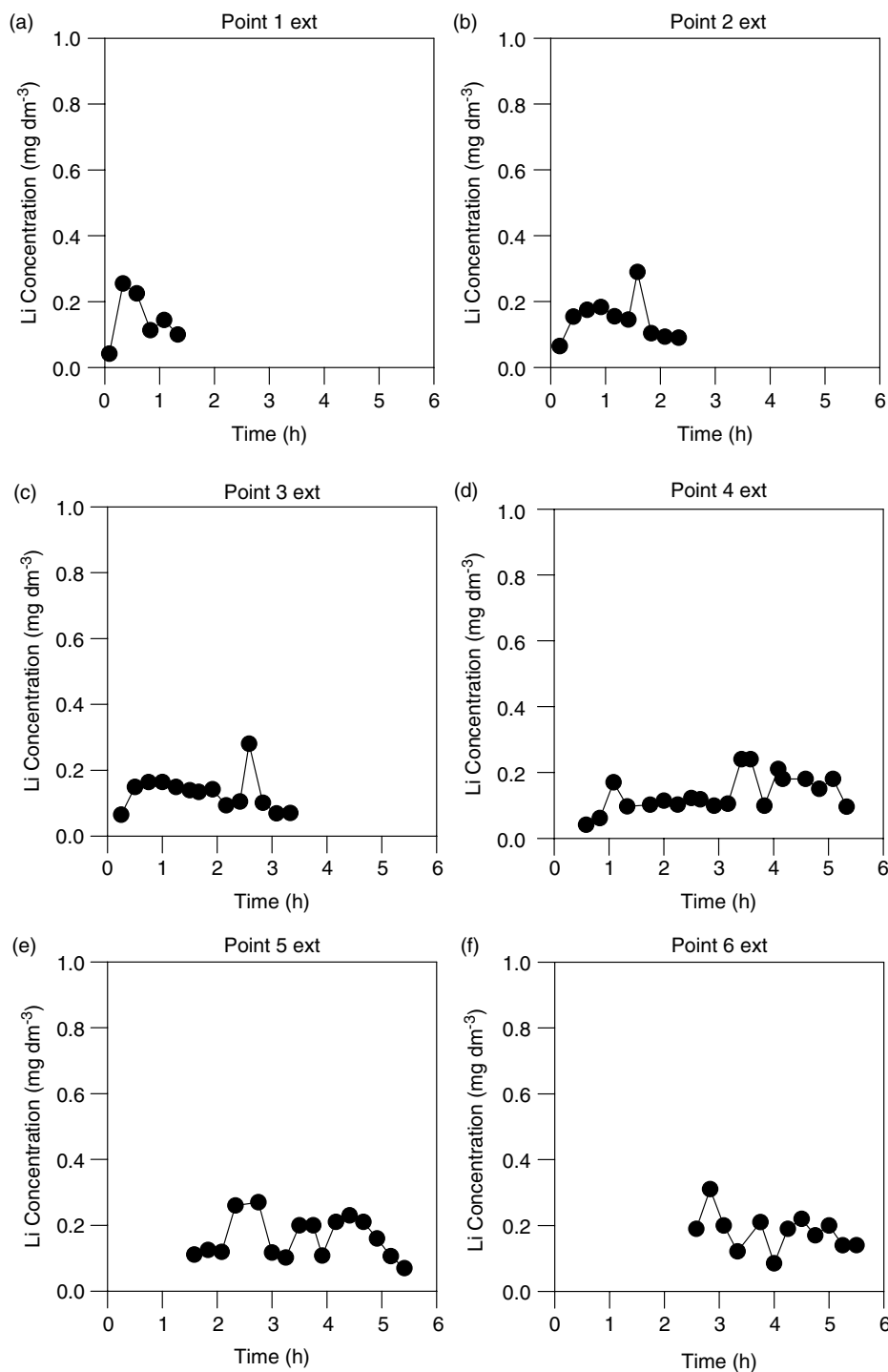


Figure 3. Local RTDs for Lane 1 (exterior points).

were selected as the most probable zones where problems associated with non-ideal flow might be found, and were classified as exterior points (Fig 3) and interior points (Fig 4).

From Figs 3 and 4, it can be seen that interior and exterior points did not present similar behaviour. Specifically, it was evident that maximum concentrations of tracer found in exterior points ($0.2\text{--}0.3\text{ mg dm}^{-3}$) were significantly different from those found in interior points ($0.4\text{--}1\text{ mg dm}^{-3}$). Thus, it seemed that a tracer channel following the interior points was present, especially in the first and second

compartment of the reactor. This channel might have been due to the location of the reactor inlet stream, which was precisely located in point 1 interior (Fig 1). However, in the final points of the reactor (points 5 and 6, Figs 3 and 4), maximum tracer concentrations presented similar values for interior and exterior points ($0.2\text{--}0.4\text{ mg dm}^{-3}$), which was probably due to a higher dispersion of tracer caused by the presence of aeration in compartments 2, 3 and 4.

In the interior channel it could be observed that concentrations of points 2i, 3i and 4i were different for a given time. Tracer concentration at point 2i at

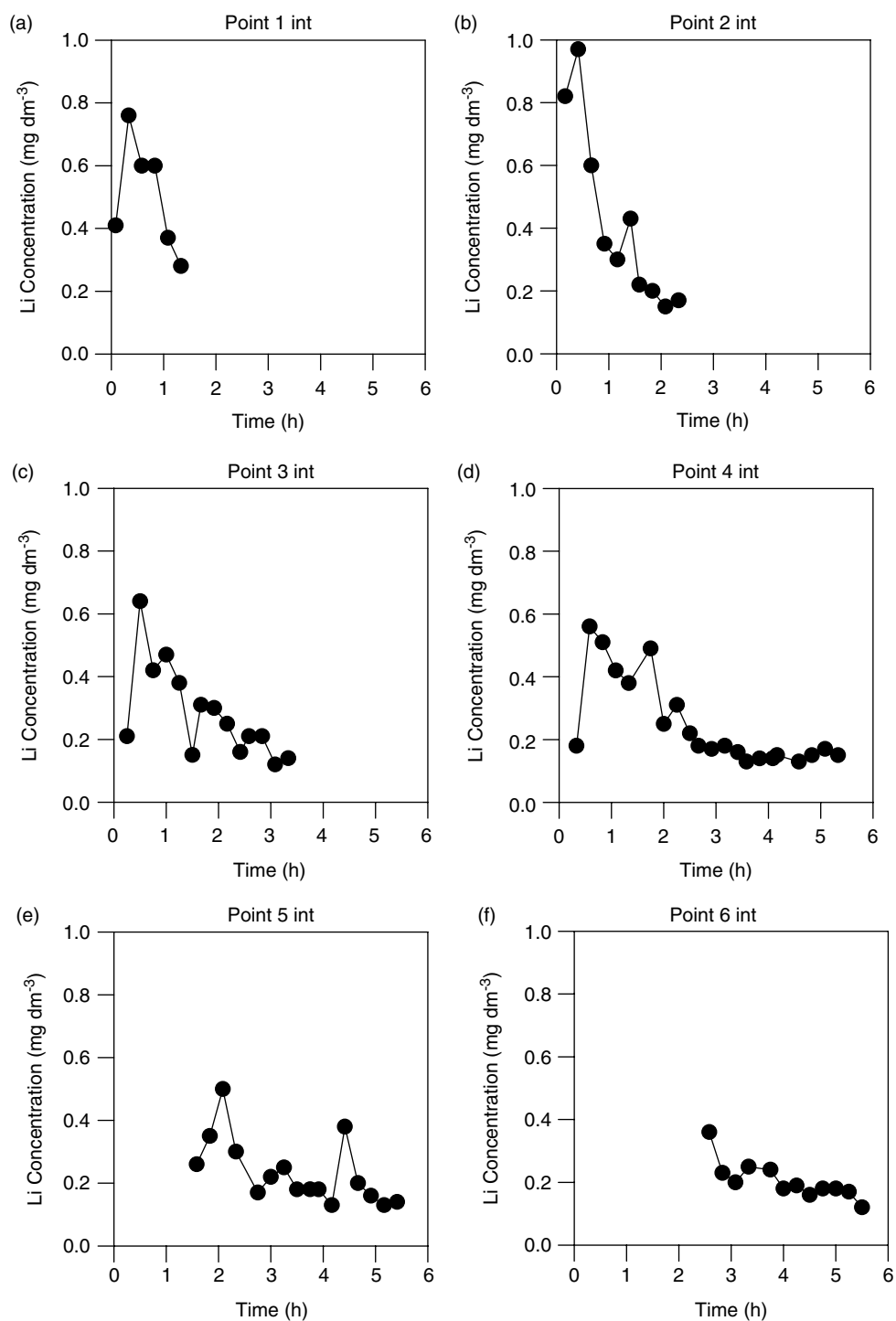


Figure 4. Local RTDs for Lane 1 (interior points).

0.5-h time was near 1 mg dm^{-3} , whereas in the case of points 3i and 4i tracer concentration was below 0.7 mg dm^{-3} at the same time. Furthermore, the fact that tracer concentration at point 2i was significantly higher than 3i and 4i tracer concentrations (which are similar) indicated that a highly dispersed plug-flow pattern or a mixed tank was suitable to describe the experimental RTD data. This behaviour was also observed in exterior points. Nevertheless, dispersion levels on the exterior points were more important than that of the interior line, which suggested behaviour closer to a CSTR pattern.

The high mixing rate of the compartments was confirmed by the shape of local RTDs presented in Figs 3 and 4. Sharp high tracer peaks (eg Fig 3(b) and Fig 4(b)) could be observed in the first compartments of the reactor (points 2 interior and 2 exterior), often followed by a non-oscillating short tail. This pattern is often associated with well mixed reactors.

Finally, it is important to observe from Figs 3 and 4 that significant values of tracer concentrations were found in all the points investigated, which indicated that none of these points corresponded to a dead zone. Nevertheless, a more exhaustive study (eg RTDs

performed at different heights) would be necessary for ensuring a complete availability of the bioreactor volume.

Bioreactor modelling

According to global (Fig 2) and local RTD data (Figs 3 and 4) it was evident that the flow bioreactor could not be represented by ideal CSTR or PFR flow patterns. Thus, different non-ideal models were fitted to RTD experimental data.

Axial dispersion models are commonly used in the description of PFR with slight deviations from ideal flow,¹ which was not the case under study. In fact, calculation of the Pe number for a system with high non-symmetrical dispersion resulted in values of 1.37 and 1.20 for Lanes 1 and 2 respectively, which indicated that bioreactor flow pattern was neither near CSTR ($Pe = 0$) nor near PFR ($Pe = \infty$).

A tanks-in-series model is *a priori* one of the most suitable non-ideal models to describe the biological reactor, given the configuration of the reactor in four compartments. The presentation of experimental data and simulation of an impulse of tracer for the four tanks-in-series reactor is shown in Fig 5(a and b for Lanes 1 and 2, respectively). As can be seen in Fig 5, the model fitted reasonably well the experimental data. The deviations from the model can be attributed to two factors. On one hand, the lack of aeration in the first anoxic compartment provokes a low mixing regime in the first compartment, whereas in the three following compartments aeration contributes to a well mixed regime. This is confirmed by local RTDs in the compartments 2, 3 and 4 (Figs 3 and 4), which present a high dispersion of tracer. On the other hand, the differences between interior and exterior points indicate that although there is a good mixing regime in most of the compartments (except compartment 1), a channelling phenomenon is also present, probably due to the position of the influent stream. The deviations from Lane 2 appear to be more important than those corresponding to Lane 1 (Fig 5(b)), however, the interpretation of this fact is difficult since no local RTDs were conducted in Lane 2.

Additionally, several modifications can be added to the four tanks-in-series model to improve the accuracy of the fitting:

- (1) Inclusion of a small dead zone corresponding to the volume of air diffusers in aerated compartments 2, 3 and 4. This dead zone accounts for approximately 5% of the total volume of each compartment, which in fact is in accordance with the slightly lower experimental HRT compared with the theoretical value.
- (2) Addition to the hydraulic model of the external recycle from the secondary settler. The settler has a volume of 2400 m³ and the sludge recirculation ratio to the biological reactor is 1:1. As can be seen in Fig 5 the fitting obtained with these modifications is more accurate.

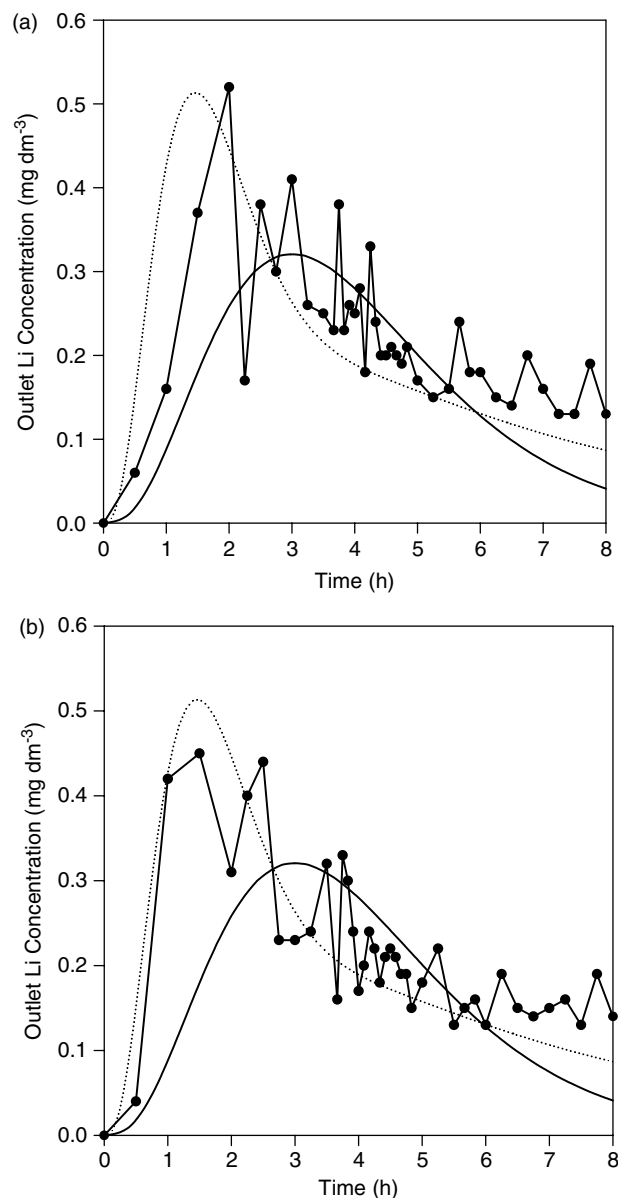


Figure 5. Theoretical global RTD curve using a four tanks-in-series model (continuous line), improved four tanks-in-series model (dotted line) and experimental data (point line). (a) Lane 1, (b) Lane 2.

From a practical point of view, however, the fact that the reactor can be modelled as four independent compartments is of special interest, and the improvement of the mixing regime of the different compartments is feasible by means of mechanical devices.

Compartment models are based on the combination of ideal CSTR and PFR arranged in different configurations and include dead zones, recirculation and by-pass phenomena.¹ As compartment models can be extremely complex, they can be used to model almost any situation found in real reactors. However, in practice, only reasonable compartment models make sense. In the case under study, only two compartment models were tested with the experimental RTD data: a plug-flow reactor (first compartment) in series with three mixed tanks (three following compartments) and two parallel plug-flow

reactors. In both cases, the fitted data did not improve the results obtained with the four tanks-in-series model. In the first case, the initial compartment acting as a plug-flow reactor will lead to a delay of 1 h (the residence time of the first compartment) in the tracer detection, which was not observed in Fig 2. In the second case, two-distinct peaks corresponding to the two channels are not clearly observed in global and local RTDs. Both compartment models were finally rejected in favour of the improved four tanks-in-series model.

Therefore, it is worth noticing that results from a unique RTD experiment can be used for the hydraulic modelling of a complex bioreactor, but the selection of a proper model to describe the reactor behaviour should be based on a more complete study of the system including local RTDs.

Modifications of the bioreactor

The hydraulic model can be used to improve the current state of biological reactor performance. In order to improve the operation of the bioreactor several proposals are presently being tested:

- (i) Improvement of mixing in the first anoxic (denitrifying) compartment by including submerged mixers. This is of special interest, since some aspects related to the biological performance of the whole bioreactor depend on the level of agitation of this compartment, such as mixing of recycled sludge or nitrate denitrification. Since local RTDs of compartment 1 showed a low level of mixing, the inclusion of mechanical stirrers would produce a positive effect.
- (ii) Flow redirection between the compartments in order to favour an ideal CSTR behaviour in the three last compartments. The main objective of these modifications has been the transformation of the studied designed plug-flow reactor to a real reactor consisting of four tanks in series.

Finally, it must be pointed that RTD data have been obtained with the internal recirculation necessary for denitrification turned off. At present, the plant is working with an internal recirculation equal to influent flow (ratio 1:1) that can be considered as low¹⁸ due to the low content of total nitrogen in the influent stream. Although an RTD experiment of the reactor including the recirculation rate has not been carried out due to the probable complexity in the data interpretation, it is likely that the effect of this recirculation rate on the plant performance will be an increase in the mixing regime of the reactor, so that the global RTD would be closer to that of the proposed model of four tanks in series.

CONCLUSIONS

An RTD technique has been useful in the determination of flow conditions in a plug-flow bioreactor

treating municipal wastewater. However, the determination of a unique global RTD may not provide enough information to accurately describe local mixing regime conditions in complex systems such as full-scale bioreactors in which at least three phases are involved (namely biomass, air and liquid phase).

In the system under study, local RTDs have been used for the qualitative determination of particular situations of insufficient mixing, recirculation or channelling and the type of flow (plug, dispersed or mixed). Specifically, the adaptation of the bioreactor to four CSTRs in series is presently being tested by means of submerged mechanical stirring systems in the first compartment with optimal results.

Therefore, local RTDs have permitted a qualitative description of the hydraulic behaviour of the bioreactor. This flow model is necessary in order to develop biological strategies to improve BOD removal and the implementation of future nitrogen and phosphorus removal strategies. At present this hydraulic model is being used to perform changes in the mixing elements of the reactor.

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