Pergamon

Wat. Sci. Tech. Vol. 39, No. 4, pp. 61–69, 1999.

0273–1223/99 $19·00 + 0·00

PII: S0273-1223(99)00058-X

CALIBRATING SIMPLE MODELS FOR MIXING AND FLOW PROPAGATION IN WASTE WATER TREATMENT PLANTS

Bob De Clercq*, Filip Coen*, Bart Vanderhaegen** and Peter A. Vanrolleghem*

** BIOMATH Department, University Gent, Coupure Links 653, B-9000 Gent, Belgium*
*** EPAS NV, Technologiepark 3, B-9052 Gent-Zwijnaarde, Belgium*

ABSTRACT

Mathematical models are useful tools in the prediction of system responses to operational changes in waste water treatment plants (WWTPs). The tanks-in-series model is one of the widespread hydraulic models in waste water treatment. This study shows the applicability of the mentioned model. Next to the mixing of substrate in a conventional activated sludge system, an oxidation ditch and a trickling filter, also the flow propagation in a waste water treatment plant was modelled. These different full-scale examples taken from waste water treatment demonstrate the relative ease of model configuration and calibration. Difficulties like experimental design, modelling the diffusion in biofilms and transients in flow rate were encountered. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved

KEYWORDS

Experimental design; mixing; model calibration; tanks-in-series model; waste water treatment.

INTRODUCTION

Considering only the biology of a waste water treatment plant is not sufficient to model the treatment system: the activity of the micro-organisms depends a lot on the mass transfer of substrates and products, and hence on the mixing properties of the reactor. Consequently, knowledge of the hydrodynamic behaviour is needed for a possible model-based optimisation of the WWTP. In this way it is possible to predict the effect (e.g. the substrate concentration the micro-organisms are exposed to and the time of exposure) of environmental disturbances on the system behaviour. In the following only a description of the propagation of flow through the plant and the mixing behaviour with simple models is considered.

There exist different techniques to simulate the mixing behaviour of a system. The most popular and easy to implement is the tanks-in-series model. This model only gives the overall system response but does not consider the local mixing properties of the reactor. In the case of flow propagation a complete hydraulic modelling will not be used. The problem will be approached more conceptually (Olsson and Stephenson, 1985).

The tanks-in-series model (Levenspiel, 1972) simply consists of the serial connection of Completely Stirred Tank Reactors (CSTRs). By increasing the number of tanks one can cover the complete mixing regime, from a perfectly mixed flow (1 CSTR) to plug flow (∞ CSTRs). The degrees of freedom to consider when modelling a particular system are the number of tanks, their respective volumes and their internal connection. Chambers (1992) proposed an empirical relation between the required number of tanks in series on the one hand and design variables (e.g. flow rates, dimensions) on the other hand. However, the application is restricted to some design boundaries and only gives an approximation of flow behaviour.

Experimentally, the number of tanks in series can be estimated by performing a tracer test. A tracer is an inert substance which is introduced at the entrance of the reactor as a pulse or as a step. The tracer concentration is measured in the effluent, and this evolution of concentration in time can be interpreted in terms of model parameters.

When the system becomes too complicated, it is not easy to discover a satisfying configuration of tanks-in-series that corresponds with the real system response. Londong *et al.* (1998) proposes a strategy of how the hydraulic model can be derived from numeric flow simulations. The dynamic simulation reveals which internal flows are important to take into account and, as a consequence, determines the configuration of the completely mixed tanks.

In this paper, the use of the tanks-in-series model in waste water treatment modelling, and the problems encountered with the approach, are illustrated by means of three full-scale applications: a conventional activated sludge system, an oxidation ditch and a trickling filter. In the fourth example the simple modelling of flow propagation in a waste water treatment plant will be considered.

CONVENTIONAL ACTIVATED SLUDGE SYSTEM

A tracer test with lithium was performed at an industrial WWTP of 100,000 PE (Fig. 1). A pulse of 20 kg of LiCl was introduced in the distribution tank DT. The effluent flow rate was measured and the recycle flow rate was kept constant at 125 m^3/h. The interpretation of this test was quite complicated because a single settler (300 m^3) is connected with the three separated activated sludge reactors (AS1, 1,930 m^3; AS2, 3,050 m^3 and AS3, 3,050 m^3). This leads to a coupling of the activated sludge reactor output concentrations or, in other words, the measurements performed in the effluent of AS1 are not only determined by the hydraulic characteristics of AS1 but are also influenced by those of AS2 and AS3. Lithium samples had to be taken in the effluent of each activated sludge reactor. In Figure 1 the LiCl dosing point and sampling points are indicated.

The mixing in the distribution tank DT was found to be not perfect. To account for this imperfect mixing it was assumed that the three reactors each received different fractions of both influent flow and recycle flow. To determine these fractions mass balances had to be made, not only for the tracer but also for the sludge in the different aeration tanks (Coen *et al.*, 1997).

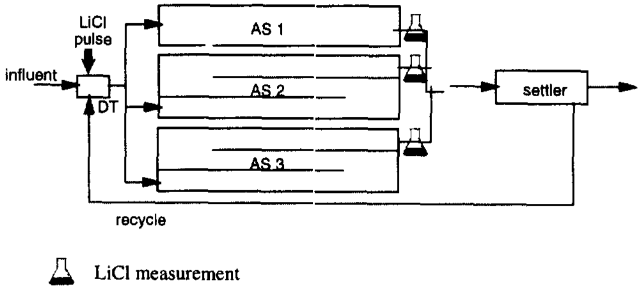

Figure 1. Schematic representation of the industrial WWTP.

After this description of the distribution tank (Table 1, upper), simulation and non-linear parameter estimation were needed to interpret the tracer test results. The best fit to the experimental results was obtained by describing the hydraulics of each activated sludge reactor by two CSTRs in series (Fig. 2). The model for each activated sludge reactor was found to consist of a small tank and a larger tank (Table 1, lower). These volumetric characteristics of the reactors also revealed the existence of a significant dead volume. The dead space in reactors AS1, AS2 and AS3 was found to be 9%, 8% and 20% respectively.

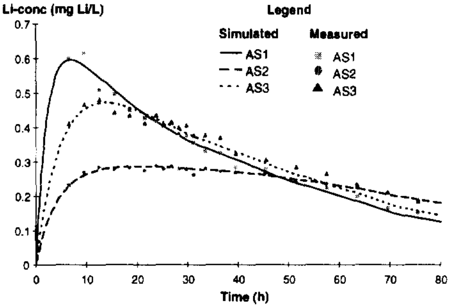

Figure 2. Measured and simulated concentration profiles of the tracer experiment.

Table 1. Distribution fractions of the influent and the recycle flow to the three activated sludge reactors. Also the estimated volume for the two tanks in series together with the inactive volume is mentioned

	AS1	AS2	AS3
Distribution tank (after Coen *et al.*, 1997)			
Influent fractions	0.36	0.24	0.40
Recycle sludge fractions	0.35	0.31	0.34
Estimated tanks-in-series volume (m^3)			
tank 1	175	250	430
tank 2	1,570	2,555	2,010
inactive	185	245	610

Because of the quite long reactor length a more plug flow like mixing behaviour was expected. Instead, the relatively long residence time of two days resulted in a low liquid velocity and, consequently, in an important dispersion in the activated sludge reactor (Gandolfi *et al.*, 1996).

Note that the residence time distribution only expresses the time that the various fractions of the fluid have spent in the reactor. It provides no information on the mixing details. For instance, also the opposite set-up, a large tank followed by a small tank, will give the same hydraulic pattern but the biological conversion can be totally different. This is due to the change in sequence of residence times of the substrate in the two tanks. Because of the different sequence of reactor volumes and temporal exposure of the bacteria to the substrate the outflow substrate concentration profile will be modified. As a consequence, the importance of tank sequence has to be taken into consideration if the hydraulic model needs to be coupled with the biological one.

OXIDATION DITCH

The mixing behaviour of an industrial oxidation ditch (Fig. 3) was determined. The ditch itself has a total volume of 11,000 m^3 with a mean influent flow rate of 180 m^3/h. The recycle flow rate measures 450 m^3/h. The liquid circulation in the ditch results from two double brush aerators, one surface mixer and two surface aerators. As in the previous example lithium was used as tracer, and injected as a pulse in the channel between the influent screw pumps and the ditch. As a result of the inherent circulation in the oxidation ditch an oscillating behaviour could be seen in the concentration-time profile (Fig. 4) measured in the effluent of the ditch. Note that the data point at 0.75 h is an outlier and does not contribute to the real system response.

During the first 15 minutes fast sampling was implemented to allow this observation. For this experimental design knowledge about the circulation velocity (measured with floating objects) was used.

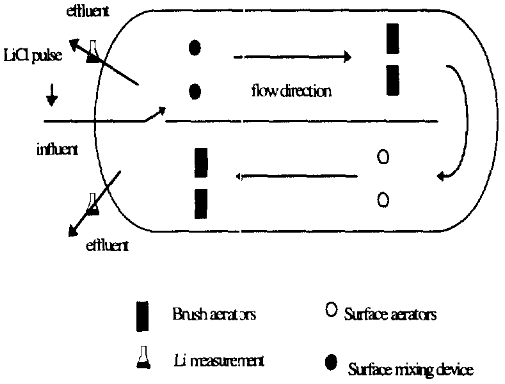

Figure 3. System configuration of the oxidation ditch.

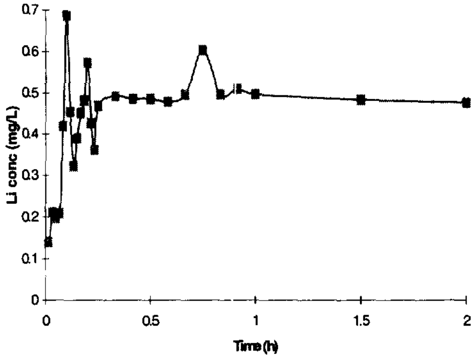

Figure 4. Concentration-time profile of a tracer in the oxidation ditch.

An oxidation ditch is characterised by a high circulation flow rate: the brushes drag the water around in the system. Nevertheless, the studied system does not behave as an ideal plug flow reactor. Otherwise, the oscillatory behaviour would only become extinct with a time constant equal to the residence time of the water in the ditch (= approximately 17 h). Instead, the oscillations already fade away within half an hour. This indicates the existence of a certain mixing capacity.

The time between two oscillations is about 5 to 6 minutes. After half an hour the reactor can be assumed to be completely mixed. The Li concentration after one hour is approximately 0.5 mg/l (Fig. 4). If the measured background concentration of 0.2 mg/l is substracted one obtains the effective increase in concentration caused by the tracer dosing. The tracer injected into the ditch amounted to 3.27 kg Li. Dividing this total amount by the measured equilibrium concentration gives the active volume of the oxidation ditch, namely 10,900 m^3. In other words, the ditch has almost no dead volume.

The hydraulics of the oxidation ditch could be simulated as a system consisting of twenty tanks in series. This conclusion can be corroborated with the calculation of the circulation flow rate. The mean perimeter the water covers during one circulation is 206 m. With a circulation time of 5.5 minutes, this results in a mean circulation velocity of 0.335 m/s. Since the cross section of the ditch is 97 m^2, the mean circulation flow rate becomes 32.5 m^3/s or 117,000 m^3/h. With such a high flow rate it is less presumable that complete mixing occurs. Figure 5 shows the simulation results together with the measurements. As can be seen, the oscillatory behaviour and its fading away is well simulated with 20 serial connected tanks (Fig. 5, left). On the other hand, a good simulation performance for the concentration measurements on the long term was achieved with a model of only one completely stirred tank (Fig. 5, right). This dual model for the hydraulics of the oxidation ditch is obviously a restriction on the practical applicability of the tanks-in-series model.

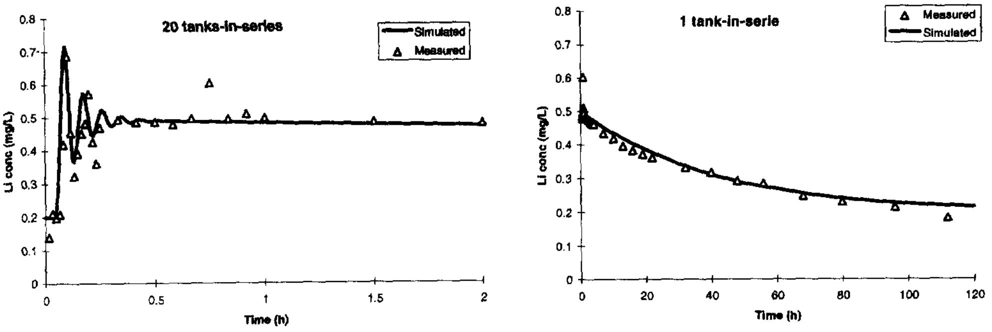

Figure 5. Measurements and simulation results of the lithium concentration in the channel between the oxidation ditch and the settlers.

The surface aeration with brushes causes the oxygen concentration to vary not only in the direction of the flow but also with the depth of the tank. If a simulation of this phenomenon is needed, e.g. to describe denitrification in the lower regions of the reactor, a sequence of CSTR in parallel to the serial ones of the top layer is suggested. Hence a two-dimensional network of CSTR will be created (Fig. 6).

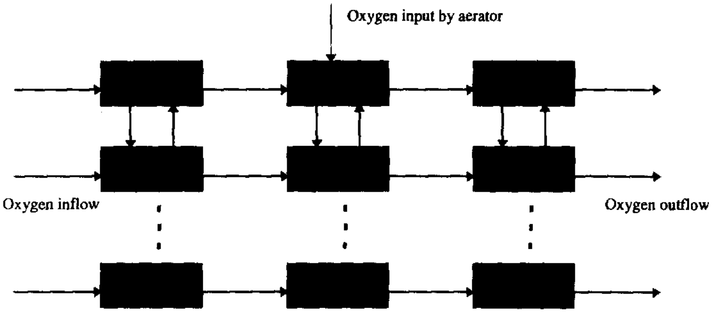

Figure 6. Simulation of oxygen concentration profile with the depth by a network of CSTR.

TRICKLING FILTER

Also the hydraulics of a trickling filter can be modelled with the tanks-in-series principle. In this case it is important to consider the influence of the heterogeneous film structure of the filter. This structure consists of a biofilm, a free flowing and a captured liquid film. In such a system, diffusion has to be taken into account. The modelling of diffusion can be managed by placing tanks in a parallel configuration, linked to the serial connection of CSTR describing the free flowing liquid (Rozzi and Massone, 1995).

The trickling filter under study had a complicated flow path. It was coupled to a pumping tank with considerable volume (160 m^3) and two recycle options, i.e. a short recycle and a long recycle over the clarifier (Fig. 7). The long recycle over the clarifier complicated the flow path considerably, as there is only one clarifier to which two parallel trickling filters were connected. As a result, the dynamics of both filters are not independent. Hence, the possibility was used to temporarily disconnect the clarifier. Also, the sampling points were carefully selected to allow identification of the tanks-in-series model of both the pumping tank and the trickling filter (Fig. 7).

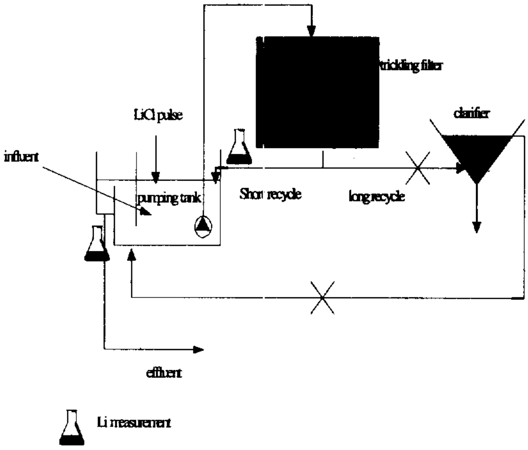

Figure 7. Schematic representation of the trickling filter set-up.

The tracer, 5 kg of LiCl, was injected as a pulse in the pumping tank as close as possible to the pumps. The measurement of the concentration was performed in the short recycle flow and in the effluent of the pumping tank. The former makes it possible to determine the hydraulics of the trickling filter as such. To distinguish between the hydraulics of the pumping tank and the trickling filter, effluent measurements are necessary. Those are also indispensable to make a correct mass balance over the coupled system of reactors. Due to the big volume of the pumping tank and the location of the different flows it could be assumed that an inhomogeneous mixing exists in the pumping tank.

The hydraulics of the pumping tank could be adequately described by two tanks in series. Physically, it can be assumed that they correspond with the volumes before and after the baffle in the tank. Next to this, a considerable dead space was found. Before the baffle only 58% of the volume contributes to the advective flow. Behind the baffle merely 15% of the total volume appears to be active. These values are extremely low and could be the result of a thick sludge layer.

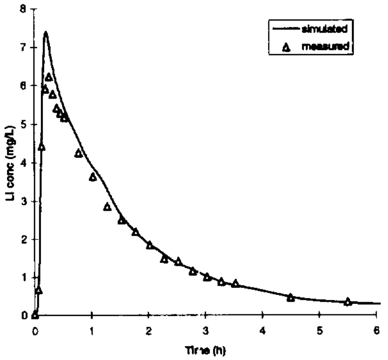

Figure 8. Comparison between model performance and measured lithium concentration in the short recycle stream.

Once the concentration profile in the pumping tank could be simulated (serving as the influent for the filter), it was possible to study the hydraulic behaviour of the trickling filter itself. Figure 8 shows the models ability to simulate the filters effluent concentration in the short recycle stream. It was found that the filter could be described as a two tanks-in-series system. A parallel configuration of tanks was not necessary in the model. As incorporation of the diffusion process in the model was not necessary to adequately describe the lithium dynamics, apparently diffusion appears to be sufficiently fast not to influence the residence time distribution.

TRANSIENT SYSTEM BEHAVIOUR AS A RESULT OF FLOW PROPAGATION

Sudden changes in flow rate, e.g. because of on/off control of pumps, are not observed instantaneously due to system damping and time delays. The consideration of such transient behaviour can be very important towards an optimal operation of the settler (Bergh and Olsson, 1996).

Time delays can be modelled by n-th order differential equations. On the other hand, the flow damping can be described by variable volume tanks with adequate weir geometry defining volume-effluent flow relationships as:

$$\text{Flow rate} = \alpha . \left(\frac{V - V_{min}}{A} \right)^{\beta} \tag{1}$$

V = volume of the tank
V_{min} = volume of the tank between bottom and weir height: no effluent flow rate exists
A = surface of the tank

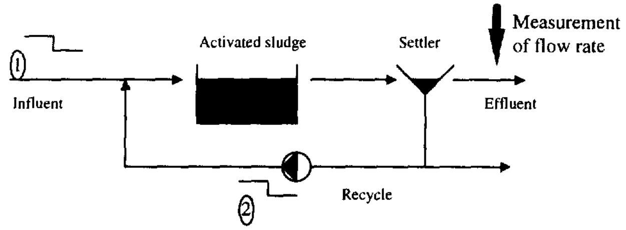

Figure 9. System configuration and applied system disturbances.

In this case study it will be shown that the propagation of flow in a waste water treatment plant can be easily simulated using these simple model formulations. Observations were done at an industrial WWTP with a conventional activated sludge system and a settler (see paragraph conventional activated sludge system). The effluent flow rate was measured to monitor the effect of the following two excitations of the system (Fig. 9):

1. a step decrease in the influent flow rate,
2. a step decrease in the recycle flow rate.

The system response to these disturbances is shown in figure 10. First, a step decrease was introduced at the influent. Secondly, at 0.61 h, the recycle flow rate was reduced from 145 m^3/h to 120 m^3/h. Since the system incorporates a delay, the reduction in influent flow rate is not seen immediately in the settlers effluent flow rate. On the other hand, when the recycle flow rate decreases suddenly, this results in an increase of water height in the settler and, in consequence, in a higher effluent flow rate. After a while this diminishes again. A negative practical implication is that the peak flow through the settler wells up the settled solids and leads to a worse performance of the settler.

With the simultaneous consideration of the two received responses in effluent flow rate it is possible to draw a distinction between the two subsystems, namely the activated sludge and the settler, towards the impact of each on the global transient flow rate.

The activated sludge part was modelled by an 8th-order differential equation (eight tanks in series). To obtain a more deterministic model, the outflow rate of each tank was calculated by the power of the height above a fictive weir (Olsson and Stephenson, 1985; Olsson *et al.*, 1986). Although the real weir design is known, the exponent in the geometry model was a parameter to estimate, as flow propagation is not only due to the weir but happens all over the aeration tank.

The flow propagation in the settler was simulated by a 5th-order differential equation. Again, the calculation of the outflow is weir-based.

A considerable system overshoot in the effluent flow rate simulations was observed when the recycle flow rate is reduced. To avoid this, it was necessary to incorporate the dynamics of the siphon-pump (deduced from the Bernoulli equation) in the model for the sludge recycle from the settler. After this modification the dynamic response was still too fast. Hence, a pure time delay was built in to take into account the flow retardation by the siphon-gutter, piping and screw pump tank. Figure 10 clearly indicates the ability to predict the dynamics of the effluent flow rate.

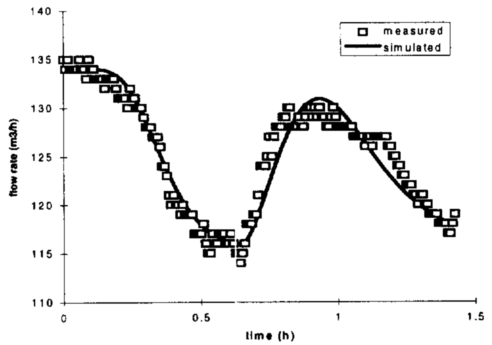

Figure 10. Comparison between observed and simulated effluent flow rate after a step decrease of the influent flow rate (at 0 h) and recycle flow rate (at 0.61 h).

CONCLUSIONS

The tanks-in-series model is a widespread technique to take into account the hydraulics of a system. Only a simple tracer test is needed to build the model, i.e. the number of tanks and their respective volumes.

To demonstrate the practical power of this modelling approach, applications were given for a conventional activated sludge system, an oxidation ditch and a trickling filter. In these examples different problems were encountered, such as the coupling of systems, different volumes of CSTR in the model and two-dimensional profiles for operational parameters.

Besides this, flow propagation in a waste water treatment plant was modelled by imposing consecutively two system disturbances: a decrease in influent and in recycle flow rate. To achieve the necessary time delay it was necessary to model the dynamics of the siphon-pump and to take into account other flow retardations.

ACKNOWLEDGEMENT

This research was financially supported (in part) by the Flemish Institute for the Promotion of Scientific-Technological Research in Industry (IWT) and the Fund for Scientific Research - Flanders (FWO), Belgium.

REFERENCES

Bergh, S. G. and Olsson, G. (1996). Knowledge based diagnosis of solids-liquid separation problems. *Wat. Sci. Tech.*, **33**(2), 219-226.

Chambers, B. (1992). Design methodology for optimisation of aeration efficiency in activated sludge. *Proc. 6th Forum Applied Biotechnology. Med. Fac. Landbouww.* Univ. Gent, **57**, 1631-1642.

Coen, F., Petersen, B., Vanrolleghem, P. A., Vanderhaegen, B. and Henze, M. (1998). Model-based characterisation of hydraulic, kinetic and influent properties of an industrial WWTP. *Wat. Sci. Tech.*, **37**(12), 317-326.

Gandolfi, C., Kraszewski, A. and Socini-Sessa, R. (1996). River water quality modelling. In: *Environmental Hydraulics*, Singh V. P. and Hager W. H. (eds), Kluwer Academic Publishers, Dordrecht, The Netherlands, Chapter 8, 245-288.

Levenspiel, O. (1972). *Chemical Reaction Engineering*. Wiley, New York.

Londong, J., Kolisch, G., Alex, J. and Holthausen, E. (1998). Ein neuer Ansatz zur Ableitung von Modellstrukturen für die dynamische Simulation kommunaler Kläranlagen. *Korrespondenz Abwasser*, **4**, 717-723.

Olsson, G. and Stephenson, J. P. (1985). The propagation of hydraulic disturbances and flow rate reconstruction in activated sludge plants. *Environ. Technol. Lett.*, **6**, 536-545.

Olsson, G., Stephenson, J. and Chapman, D. (1986). Computer detection of the impact of hydraulic shocks on plant performance. *Journal WPCF*, **10**, 954-959.

Rozzi, A. and Massone, A. (1995). Residence time distribution analysis on biofilm reactors: an overview. *Proc. 9th Forum Applied Biotechnology. Med. Fac. Landbouww.* Univ. Gent, **60**, 2143-2153.