Modelling Nutrient Removal in a Sequencing Batch Reactor with Respirometry

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PROPOSITIONS

1. Aerobic sludge in the endogenous phase of respiration uses oxygen at a uniform rate over a relatively long period, only if this long period is related to minutes.

   Ros, M. (1993). *Respirometry of activated sludge.* Technomic Publishing Co. Inc., Pennsylvania, USA.

2. "Biological systems are not simplified representations of the conception of the biologist, even though current trends in agriculture might seem to be moving that way. Therefore, it may be that the approach that has been so successful in technology is not as useful in biology." It is always important to remember that biological wastewater treatment is more biology than technology.

   de Wit, C.T. (1993). Philosophy and terminology. In *On systems analysis and simulation of ecological processes.* Leffellar, P.A. (ed.). Kluwer Academic Publishers, Dordrecht, The Netherlands.

3. In an activated sludge system with biological phosphorus removal, only the fraction of phosphorus accumulating organisms that passes through an anaerobic environment can be modelled by the equations proposed by Gujer *et al.* (1994).

   Gujer, W., Henze, M., Mino, T., Matsuo, T., Wentzel, M.C. and Marais, G.v.R. (1994). The Activated Sludge Model No. 2: biological phosphorus removal. *Proc. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes.* Copenhagen, Denmark. section 1.

4. The background for modelling the endogenous respiration rate by an empirical exponential equation is that the hydrolysis of slowly biodegradable matter can be modelled as a first-order reaction.

   Present thesis.

5. Working a set of data from an experiment while writing a paper improves its intrinsic quality to a maximum. Time has a deteriorating effect on the data's quality. The actual quality is the sum of both effects, although there is a tendency to not consider the latter.

6. In looking at the propositions in PhD. theses in Dutch society, one can agree to the relevance of the fable about the four blind men and the elephant.

   The Panchatantra (c. 400 A.D.), translated by V.S. Naravane.

7. "..., has de poner los ojos en quien eres, procurando conocerte a ti mismo, que es el más difícil conocimiento que puede imaginarse." All research should start with ourselves.

Cervantes. *Don Quijote de La Mancha.*

8. A simplified model, if it has a comprehensive model as background, is a useful instrument for monitoring complex wastewater treatment systems.

Present thesis.

9. How far can we go with our selfishness?
"...
Why did the stream dry up?
I put a dam across it to have it for
my use, that is why the stream dried up.
..."
We must try to understand our limits.

Rabindranath Tagore. Anxious Love, In *The gardener.*

10. "Volkstuinen" can be a very important factor in improving people's health. Not only through the production of healthy vegetables, but also (and perhaps more so), by decreasing stress.

11. The use of bicycles demonstrates how equilibrated people are.

12. To give a more accurate idea of the work involved, "from the liquid phase" should be added to biological phosphorus removal.

Abstract

Bernardes, R.S. (1996) Modelling Nutrient Removal in a Sequencing Batch Reactor with Respirometry. Ph.D. Thesis, Wageningen Agricultural University, Wageningen, The Netherlands. 173 p.

The main objectives of the present thesis can be summarized as: i) the development and validation of simplified mathematical models for activated sludge processes in an SBR treating real domestic wastewater; ii) the application of these simplified models for analysing the respirometric response and for obtaining information about the oxygen uptake for the different processes; iii) the application of the monitored respirometric values for model calibration and determination of parameter values, which are used to predict the processes in the next cycle; iv) the use of models as theoretical background for the development of control strategies for plug-flow systems and for SBR; v) relating the basic time scale for the models to the short term.

The starting points for the model development and simplification were: i) the Activated Sludge Model No. 1, for carbon oxidation, nitrification and denitrification; and ii) the Activated Sludge Model No. 2, for biological phosphorus removal .

In this study an SBR pilot plant was used and seen as a model for a plug-flow system. During the two and a half years of operation, the plant underwent three different technological phases. The first phase began with the removal of organics and nitrification. Denitrification was incorporated in the second phase. The last phase included biological phosphorus removal.

In the first phase, two simplified mathematical activated sludge models are presented. The first model gives the response of the respiration rate in an SBR with nitrification, the oxidation of readily biodegradable matter, and endogenous respiration during one cycle. This model is used to predict the respiration rate during a complete SBR cycle. For this, it uses parameter values calibrated during the previous cycle, some default values and information about the ammonia concentration in the influent. The endogenous respiration rate is described with an exponential equation. The second model is used to predict the changes in nitrification capacity after a change in the loading rate and/or sludge wastage rate. For model calibration and validation, an SBR pilot plant receiving domestic wastewater was operated for nine weeks.

In the second phase, a mathematical model is presented for the behaviour of the respiration rate and nitrate removal in an SBR with nitrification, denitrification and carbon oxidation. This model is based on the response of the respiration rate measured during nitrification and carbon oxidation and the nitrate removal rate during the post-denitrification period. For model calibration and validation, an SBR pilot plant receiving domestic wastewater was operated for three months. The respiration rate was used to calibrate several parameters of the model.

In the third phase, a mathematical model for an activated sludge SBR with nitrification, denitrification, carbon oxidation and phosphate removal is presented. This model is based on

the response of the respiration rate measured during nitrification, carbon oxidation and phosphate removal, together with the behaviour of phosphate and acetate as proposed in the Activated Sludge Model No. 2. For model calibration and validation, an SBR pilot plant receiving settled domestic wastewater plus acetic acid solution was operated for five months.

In all the three phases the model for the respiration rate (r) in an SBR during one cycle, including nitrification, oxidation of readily biodegradable matter, endogenous respiration and a fraction for the respiration rate for phosphorus uptake, gives a good simulation of the measured respiration rate. A good prediction of the total oxygen consumption and distribution during one cycle is found from a simulation, using parameters calculated from the previous cycle together with the variables from the influent. Therefor this model can be used in control strategies as long as it is used for a short time-scale. During long-term operation, parameter variation is significant and too complex to be predicted. In the particular case of nitrification capacity variation in an SBR during long-term operation, the model can explain the variation trend but cannot explain the abrupt changes.

Simplified mathematical models for the activated sludge process on the bases of the respiration rate are validated. On short-time scale, the models give a good response prediction of the activated sludge process feed with wastewater. The models are good tools for control strategies, however periodical parameter calibration is needed.

Samenvatting

De belangrijke doelstelling van het proefschrift is samen te vatten als: i) het ontwikkelen en valideren van vereenvoudigde wiskundige modellen voor actiefslibprocessen in een SBR waarin echt huishoudelijk afvalwater behandeld wordt; ii) de toepassing van deze modellen voor het analyseren van de respirometrisch respons en voor het verkrijgen van informatie over de zuurstof opname voor de verschillende processen; iii) de toepassing van de gemeten respiratiesnelheden voor model calibratie en bepaling van parameters, die te gebruiken zijn voor het voorspellen van de processen in de volgende cyclus; iv) het gebruik van modellen als theoretische basis voor het ontwikkelen van regel- en stuurstrategieën; v) het relateren van de tijdschaal van het model tot de korte termijn.

Het startpunt van de modelontwikkeling en vereenvoudiging ligt in i) het Actief Slib Model No 1, voor oxydatie van organische stoffen, nitrificatie en denitrificatie; en ii) het Actief Slib Model No.2 voor biologische fosfaatverwijdering.

In dit onderzoek is een SBR semi-praktijk installatie gebruikt en toegepast als een model voor een propstroomreactor. De SBR is twee en half jaar in gebruik geweest en gedurende die periode zijn drie verschillende technologische fases te onderkennen. De eerste fase begon met de verwijdering van organische stoffen en nitrificatie. Denitrificatie werd geïncorporeerd tijdens de tweede fase en in de laatste fase biologische fosfaatverwijdering.

In de eerste fase zijn twee vereenvoudigde actiefslib modellen gepresenteerd. Het eerste model geeft de respons van de respiratiesnelheid in een SBR met nitrificatie, oxydatie van snel biodegradeerbare stoffen en endogene verademing tijdens een cyclus. Dit model wordt gebruikt om de respiratiesnelheid gedurende een volledige SBR-cyclus te voorspellen. Hiervoor worden parameter waarden gebruikt die gecalibreerd zijn gedurende de vorige cyclus, een aantal default waarden en de ammonium concentratie in het influent. De endogene verademing wordt beschreven met een exponentiële functie. Het tweede model wordt gebruikt om de veranderingen in de nitrificatie capaciteit te beschrijven na een verandering in de slibbelasting en/of spuislib snelheid. De SBR is in gebruik geweest gedurende negen weken voor model calibratie en validatie.

In de tweede fase wordt een wiskundig model gepresenteerd voor het gedrag van de respiratiesnelheid en nitraatverwijdering in een SBR met nitrificatie, denitrificatie en organische stof oxydatie. Dit model is gebaseerd op de respons van de respiratiesnelheid gemeten tijdens nitrificatie en oxydatie van organische stof en de nitraatverwijdering snelheid gedurende de post-denitrificatie periode. Voor modelcalibratie en validatie is een SBR bedreven gedurende drie maanden. De respiratiesnelheid werd gebruikt om verschillende parameters van het model te calibreren.

In de derde fase wordt een wiskundig model gepresenteerd voor een SBR met nitrificatie, denitrificatie, oxydatie van organische stof en fosfaatverwijdering. Dit model is gebaseerd op de respons van de respiratiesnelheid gemeten tijdens nitrificatie, organische stof oxydatie en fosfaatverwijdering samen met het gedrag van fosfaat en acetaat zoals voorgesteld in het Actief Slib Model No.2. Voor model calibratie en validatie een SBR gevoed met huishoudelijk afvalwater plus azijnzuur is in bedrijf geweest gedurende vijf maanden.

In alle drie fasen geeft het model voor de respiratiesnelheid in een SBR gedurende een cyclus met nitrificatie, oxydatie van Snel Biodegradeerbare Stoffen, endogene verademing en een fractie voor de respiratiesnelheid gedurende fosfaat opname, een goede beschrijving van de gemeten respiratiesnelheid. Een goede voorspelling van het totale zuurstofverbruik en verdeling gedurende een cyclus gevonden door parameters te gebruiken, die berekend zijn gedurende de voorgaande cyclus samen met gegevens over het afvalwater. Daarom kan het model gebruikt worden in regel- en stuurstrategieën zolang er sprake is van een korte tijdschaal.

Over een langere periode is de variatie in de parameters aanzienlijk en te complex om voorspeld te worden. In het geval van veranderingen in de nitrificatiecapaciteit in een SBR over een lange tijdsperiode kan het desbetreffende model de trend in de verandering voorspellen, maar niet de plotselinge veranderingen.

In dit onderzoek zijn eenvoudige wiskundige modellen voor het actiefslib proces, waarin de belangrijkste processen aan de hand van respiratiesnelheid gedurende een cyclus beschreven zijn, gevalideerd. De modellen geven binnen een kort tijdbestek een goede voorspelling van de respons van het actiefslib na voeding met afvalwater. De modellen zijn goed bruikbaar in stuur- en regelstrategieën, maar er moet wel regelmatig parameter calibratie plaatsvinden.

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About my "Dutch experience", it is really difficult for me to express all the feelings involved. However, as always, I will try, even at the risk of being incomplete. The Netherlands opened up its society to us, in every way possible. I, my wife and our two children had the opportunity to experience a pleasant period in our lives. We are changed, and in my opinion for the better.

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☼

Guto Caicó

Marilena

Jair Cida Tata

CONTENTS

CHAPTER 1

GENERAL

INTRODUCTION

1 GENERAL INTRODUCTION

Wastewater collected from cities and towns must ultimately be returned to receiving waters or to the land. Determining which contaminants in wastewaters need to be removed to protect the environment is an increasingly complex issue, as the composition of wastewater has become more complex. The impracticality of finding sufficient areas for the disposal of untreated wastewater, particularly for large cities, has led to the adoption of more intensive methods of treatment. The early concept of physical removal of suspended solids as treatment has progressively incorporated biological processes to comply with stricter effluent quality standards. In this evolution, the biological nutrient removal step, together with concern about energy consumption, has led to the idea of process control.

Plant design is an important requisite for effective wastewater treatment. Later on, control plays a critical role in the plant's performance. For design and control, a good knowledge of the related treatment processes are essential. Along with other approaches, mathematical models have been successfully used to characterize the present knowledge about wastewater treatment plants. For understanding treatment processes, there is a tendency to include as much knowledge as possible in these models. For a control strategy, however, the models should be as simple as possible. The question is: To what extent can the models be simplified and, in combination with a measuring system, still give a good prediction of the behaviour of the relevant variables over the short and long term?

One wastewater treatment system is the Sequencing Batch Reactor (SBR), an activated sludge process which can include carbon, nitrogen and phosphorus removal; each of these processes having its own particular design and operation. To describe the plant with a mathematical model, therefore, it is crucial that the description of the different processes be combined. One factor common to all three processes is the use of oxygen by the microorganisms, which results in a measurable rate of oxygen uptake. Analysis of the oxygen consumption by the microorganisms involved in the wastewater oxidation is called respirometry. In addition to normal analysis, respirometry is also used to obtain information about the processes.

The essence of the present thesis is the development and validation of mathematical models for the activated sludge process in an SBR treating real domestic wastewater. The simplified model for the SBR is used to analyse the respirometric response and to provide information about the oxygen uptake for the different processes. The monitored respirometric values are also used for calibration and determination of parameter values, which are used to predict the processes in the next cycle. These models should be framed in such a way as to represent the scientific background for the processes' understanding and they should be able to be used as the theoretical background for the development of control strategies. Although the basic time scale for the models is related to a short-term process, the process behaviour during long-term operation is also evaluated.

To shed more light on the scope of the study, four items are discussed: i) biological nutrient removal, ii) Sequencing Batch Reactor, iii) modelling and iv) respirometry.

1.1 BIOLOGICAL NUTRIENT REMOVAL

During the biological degradation of carbon, a fraction of the nutrients present in the wastewater is used by the microorganisms. Because of this, even treatment plants designed to remove only organic carbon can achieve some nutrient removal (Stensel and Barnard, 1992). However, the concentration of nitrogen and phosphorus in the effluent of such systems is considerably high, creating conditions for eutrophication. Eutrophication is the enrichment of the aquatic environment with nutrients, which is a prerequisite for the blooming of algae and other photosynthetic organisms (Vinçonneau *et al.*, 1985; Yeoman *et al.*, 1988).

1.1.1 BIOLOGICAL NITROGEN REMOVAL

Nitrogen can be biologically removed in two stages. First, ammonia is oxidized to nitrate, in a process known as nitrification. In the second stage, denitrification occurs, where nitrate is reduced to nitrogen gas.

Nitrification is carried out by autotrophic organisms in a two-step process. First, ammonia is converted to nitrite, mostly by the group of *Nitrosomonas*. Then, nitrite is converted to nitrate by the group of *Nitrobacter*. The general equations for both processes are:

$$2\ NH_4^+ + 3\ O_2 \xrightarrow[Nitrosomonas]{} 2\ NO_2^- + 2\ H_2O + 4\ H^+ + energy$$

$$2\ NO_2^- + O_2 \xrightarrow[Nitrobacter]{} 2\ NO_3^- + energy$$

Based on the above, the oxygen required for complete oxidation of ammonia is 4.57 g O_2 per g N oxidized, with 3.43 g for the nitrite production from ammonia and 1.14 g for the nitrate production from nitrite.

In active nitrifying systems, the nitrite concentration is usually very low compared to the ammonium concentration, due to the higher nitrite oxidation rates by *Nitrobacter* compared to the ammonia oxidation rates by *Nitrosomonas*. Thus, the kinetics are usually based on ammonia-nitrogen utilization rates or the activity of the *Nitrosomonas* bacteria. In some cases however, nitrite accumulation has been observed, indicating distinct rates for the two steps in the overall nitrification (Gee *et al.*, 1990).

The values for the maximum specific growth rate of nitrifiers are affected by temperature. Several authors have presented models for the maximum specific growth rate as a function of temperature, with a wide range of variation at single temperature, indicating that other factors may have an effect on the growth rate (Antoniou *et al.*, 1990; Barnard, 1975; Beccari *et al.*, 1979; Downing *et al.*, 1964; Lawrence and Brown, 1976; Painter and Loveless, 1983). These factors could include reactor mixing intensity, activated sludge floc size, pH and dissolved oxygen level.

There is a consensus that pH has an effect on the maximum specific growth rate of nitrifiers, although there is some discussion about the ranges of pH where positive or negative effects

occur. There is some indication however, that little effect is observed at pH changes between 7.2 and 8 (Dold *et al.*, 1980; Downing *et al.*, 1964).

The effect of dissolved oxygen concentration on the rate of nitrification has been investigated by several researchers using both pure and mixed cultures and cultures found in wastewater treatment systems. In a review paper, Stenstrom and Poduska (1980) state that the maximum growth rate of both nitrification reactions are reported to be affected by a dissolved oxygen concentation from above the range of 0.3 mg/l to as high as 4.0 mg/l. Some instances have been reported where a dissolved oxygen concentation in excess of 4.0 mg/l is required to achieve a maximum nitrification rate, while other investigators have found that only 0.5 to 1.0 mg/l is required. Stenstrom and Poduska conclude that the lowest dissolved oxygen concentration at which nitrification can occur appears to be approximately 0.3 mg/l. The effect of the dissolved oxygen concentration is modelled as a Monod-function with 0.5 mg/l as a typical value for the half-saturation coefficient (Henze *et al.*, 1987).

Denitrification in biological systems is coupled to the respirating electron chain and involves the reduction of nitrate to nitrogen.

$$NO_{3^-} \rightarrow NO_{2^-} \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Denitrification is considered an anoxic process, occurring in the absence of oxygen, and requiring an organic or inorganic electron donor (Klapwijk, 1978). Denitrification is carried out by a wide group of bacteria, both heterotrophic and autotrophic. From the heterotrophic group, some identified bacteria are: *Achromobacter, Bacillus, Brevibacterium, Enterobacter, Lactobacillus, Micrococcus, Paracalobactrum, Pseudomonas* and *Spirillum* (Payne, 1981).

The effect of dissolved oxygen as denitrification inhibitor has been observed at concentrations around 0.2 mg/l (Dawson and Murphy, 1972). Denitrification reactions produce alkalinity, resulting in an elevation of the pH level. No significant influence on denitrification rates for pH levels between 7.0 and 8.0 have been reported (Dawson and Murphy, 1973). Denitrification kinetics are influenced by the type of substrate used as electron donor. These substrates can be grouped as readily biodegradable matter, resulting in high rates, and slowly biodegradable matter which results in low rates (Haandel *et al.*, 1981).

1.1.2 BIOLOGICAL PHOSPHORUS REMOVAL

Biological wastewater treatments achieve some phosphorus removal through the use of phosphorus for cell synthesis. Phosphate can also be taken up in excess of what is strictly needed for growth and stored intracellularly as polyphosphate.

Biological phosphorus removal is carried out by a group of aerobic microorganisms called phosphorus accumulating organisms (PAOs), of which some species are: *Acinetobacter, Aeromonas, Arthrobacter, Escherichia coli, Klebsiella, Microthrix, Moraxella, Proteus, Pseudomonas* and *Xantobacter* (Appeldoorn, 1993). The enrichment of activated sludge with PAOs requires alternating aerobic and anaerobic cycles. Up to now, several theories have been developed to explain the phenomena of biological phosphorus removal, the most accepted being that in an anaerobic environment these organisms, using fermentation products such as acetate, store poly-ß-hydroxyalkanoates (*PHA*) and release phosphate to have energy. In a subsequent aerobic environment, they use the stored *PHA* for the uptake and storage of

phosphate (Comeau *et al.*, 1986).

One important inhibition factor in the biological phosphorus removal process is the presence of nitrate. Nitrate inhibits the release of phosphate during the anaerobic period and, consequently, inhibits the phosphate uptake during the aerobic period (Hascoet *et al.*, 1984; Wentzel *et al.*, 1984). Although inhibition can be explained by the competition for organic carbon between denitrifiers and PAOs (Chiesa *et al.*, 1987; Iwema and Meunier, 1984; Mostert *et al.*, 1988), other explanations have been given, such as phosphate precipitation due to a change in pH and the high redox potential due to nitrate (Arvin, 1983; Peirano *et al.*, 1983).

1.1.3 COMBINED PROCESS

The biological nutrient removal process has to combine nitrogen removal with phosphorus removal. The main conditions for this combination can be summarized as follows.

In an activated sludge system, nitrification requires an aerobic environment. Because nitrifiers grow slowly, to ensure the presence of nitrifiers in the active sludge, it is important that the cellular detention time be long enough. The growth rate of nitrifiers is strongly dependent on temperature, indicating that at different temperatures, the cellular detention times should be adjusted.

Denitrification requires an anoxic environment and a carbon source. An anoxic environment is achieved when all the dissolved oxygen is used up by the other aerobic heterotrophic organisms present in the activated sludge. The carbon source can be either external or endogenous.

Biological phosphorus removal requires both an anaerobic and aerobic ambience. The activated sludge passes first through the anaerobic zone and then through the aerobic zone. Because denitrifiers are a strong concurrent of PAOs, anoxic conditions cannot substitute for anaerobic conditions.

1.2 SEQUENCING BATCH REACTOR

In a wastewater treatment system, reactors are the physical units in which transformations take place. For biological treatment, a reactor is the tank that contains the biomass responsible for the biochemical transformation. To obtain different biochemical reactions, the reactor requires different inputs in order to create the proper conditions for the biomass, such as aeration, mixing, the addition of chemicals, etc.

The influent can be added to the reactor continuously or intermittently. A reactor in the first scenario is called a continuous reactor and in the second, a batch reactor. The hydraulic characteristics of a continuous-flow reactor range from plug-flow to complete-mix. In a batch reactor, the liquid contents are completely mixed (Metcalf & Eddy, 1991).

For the application of a batch reactor to the treatment of wastewater, the concept for the Sequencing Batch Reactor (SBR) was developed. In this concept, the activated sludge settles after the reaction, the effluent is drawn and new influent is added. The period between two consecutive influent additions is called a cycle. An SBR system may be composed of one or more tanks. In biological waste treatment, each tank in the system has five basic operating modes or periods. These periods are: FILL, REACT, SETTLE, DRAW and IDLE, in a time sequence (Irvine and Busch, 1979). A more detailed discussion of each period is presented by Irvine and Ketchum (1989).

During FILL, the influent wastewater is added to the biomass and the liquid volume in the tank rises from the initial level to the maximum level. Different FILL strategies can be used:

- STATIC FILL (no mixing or aeration);
- MIXED FILL (mixing without aeration);
- AERATED FILL.

FILL is typically terminated either when the tank is full, when a maximum FILL time is reached, or when the next tank is available.

Reactions which are initiated during FILL are completed during REACT. Depending on the dissolved oxygen concentration, we have:

- MIXED REACT (low oxygen concentration or anoxic/anaerobic conditions);
- AERATED REACT (high dissolved oxygen concentration).

Sludge wasting during REACT is a simple means to control the sludge age. The sludge age in days is equal to the reciprocal of the fraction of the reactor liquid volume wasted each day. The end of REACT may be dictated by the time specification or a level controller in an adjacent tank.

During SETTLE, solids separation takes place in a tank with a volume of more then 10 times of the secondary clarifiers used for conventional continuous-flow activated sludge plants. This major advantage in the clarification process results from the fact that the entire aeration tank serves as clarifier during the period when no flow enters the tank. The time in SETTLE insures that the sludge blanket remains in the tank during DRAW and does not rise (because of gas formation) before DRAW is completed. The sludge can also be wasted during SETTLE, instead of during REACT. Sludge wasted near the end of SETTLE is more concentrated than that during REACT.

To avoid possible problems with rising sludge, the time in DRAW should not be too long. The withdrawal mechanism can be a simple pipe fixed at some predetermined level to a submersible pump.

After DRAW, the tank is ready to receive new wastewater. In some SBR modifications, after completing DRAW, the tank must wait. This period between DRAW and FILL is termed IDLE.

Each tank in the SBR system is filled during a set period of time and then operated as a batch reactor. The SBR can simulate any conventional continuous-flow activated sludge system. The

essential difference between the SBR and a conventional continuous-flow activated sludge system is that each tank carries out functions such as equalization, aeration and sedimentation in a time rather than a space sequence (Irvine and Ketchum, 1989).

The SBR has been shown to be an appropriate technology for the selection of specific groups of organisms required for the different removal processes. There are studies showing organism selection on nitrogen removal (Alleman and Irvine, 1980a; Alleman and Irvine, 1980b; Irvine *et al.*, 1979; Irvine *et al.*, 1983; Jones *et al.*, 1990), biological phosphorus removal (Irvine *et al.*, 1985; Ketchum *et al.*, 1987; Manning and Irvine, 1985; Okada *et al.*, 1987; Okada *et al.*, 1991), control of filamentous organisms (Chiesa and Irvine, 1985; Chiesa *et al.*, 1985; Dennis and Irvine, 1979; Irvine *et al.*, 1983; Irvine *et al.*, 1987), the removal of specific organics in industrial wastes and the destruction of hazardous waste (Herzbrun *et al.*, 1985; Irvine *et al.*, 1984).

Due to its operation's flexibility, the SBR can be used in both research and as a full-scale system. Several laboratory-scale SBRs have been used to study aspects of the activated sludge process. Vlekke *et al.* (1988) studied biological phosphate removal with oxygen or nitrate; Oleszkiewicz and Berquist (1988) and McCartney and Oleszkiewicz (1990) investigated nitrogen removal at low temperatures; Koh *et al.* (1989) used an SBR to study the bio-oxidation of methanol; Ng and Tan (1990) carried out research on biokinetics determination; Comeau *et al.* (1987) conducted research on the dynamics of carbon reserves on biological phosphorus removal; Matsuzawa and Mino (1991) investigated the relationship between the feeding pattern and filamentous and non-filamentous bacteria; and Yamamoto *et al.* (1991) examined sulphate reduction and its relation to bulking sludge.

The performance of the SBR on full scale was examined in several studies. Ketchum *et al.* (1987) did a comparison of biological and chemical phosphorus removal; Melcer *et al.* (1987) described the conversion of small municipal wastewater treatment plants to the SBR; Irvine *et al.* (1987) analyzed the operation of treatment plants to develop plant operation procedures; Rusten and Eliassen (1993) studied operation optimization for nutrient removal; Sheker *et al.* (1993) conducted research on the effects of fill strategies under nitrogen deficiency; and Marklund (1993) monitored low temperature biological phosphorus removal. A common conclusion from these studies is that the SBR is a feasible alternative and in several situations is advantageous to continuous-flow systems.

Because an SBR is a typical time sequence system, it is easy to use it for calibration of a dynamic model. Use of the SBR for calibration of diverse models can be seen in the studies of Boero *et al.* (1991), Germirli *et al.* (1991) and Nakazama and Tanaka (1991). Oles and Wilderer (1991) presented a modified version of the IAWPRC Activated Sludge Model No.1 to describe the performance of laboratory and pilot-scale SBRs.

The versatility of the SBR for modelling has been demonstrated by several studies. Carucci *et al.* (1994) studied the dynamics of the anaerobic utilization of organic substrate during biological phosphorus removal; Wild *et al.* (1994) described the turnover of denitrification intermediates; Smolders *et al.* (1994) developed a metabolic model for the biological phosphorus removal process; and Mino *et al.* (1994) studied the hydrolysis rates of slowly biodegradable COD under anaerobic, anoxic and aerobic conditions.

1.3 MODELLING

To use models, it is important to understand how we can situate them inside the frame of systems analysis (Forrester, 1961). Within this frame, models have different meanings. In this study we restrict ourselves to the mathematical model.

According to de Wit (1993), a system is a limited part of reality that contains interrelated elements. A model is a simplified representation of a system. Simulation is the building of mathematical models and the study of their behaviour with respect to the functioning of the system.

Murthy *et al.* (1990) go into more detail about simulation and delineate two phases: modelling and simulation. Modelling is the mathematical model building process and simulation is the relationship between a mathematical model and its implementation on a computer.

Models can be static or dynamic. If the data collection and treatment are linked to time, the model is called dynamic. Models can also be classified by the method they use to show the relations inside the system as descriptive or explanatory.

As presented by de Wit (1993), a model is called descriptive when it shows the relation between the system's elements without an explanation of its functioning. Explanatory models are those that consider levels of integration in which the process occurs; the classification of these levels can be done according to the size of the system, such as cells, individuals, populations, and so on. The lower integration level is then the explanatory level and the upper

level is to be explained.

Leffellar (1993) stated that simulation of ecological systems with an explanatory model is based on the assumption that the state of each system at every moment can be quantitatively characterized and that changes in a system can be described by means of mathematical equations. This hypothesis leads to the formulation of state-determined dynamic models in which state, rate and driving variables can be distinguished.

State variables are the system's component that the model tries to quantify over time. Rate variables indicate the rate at which the state variables change. Driving variables characterize the influence of external factors on the system and are not influenced by the processes within the system. Parameters and constants are examples of driving variables.

Tanji (1981) presented the four consecutive stages in the development and application of system simulation models as:

- problem definition and study objectives;
- systems analysis;
- systems synthesis; and
- simulation analysis.

Problem definition, or recognizing a specific problem situation, is the starting point for the simulation modelling process. Next, the system of interest is isolated from the system environment. The following step is to establish study objectives. Aspects that should be considered include the purpose of the model and whether it is to be used for research or

practice.

Systems analysis, or mathematical modelling, is a technique for developing systems response functions (mathematical models) when both inputs and outputs are known. This technique goes through four general stages: i) evaluation of available information and data; ii) review of the state of the knowledge of the problem; iii) blockbuilding and conceptual filtering (simplification); and iv) mathematical model formulation.

Systems synthesis, or mathematical simulation, is a technique for determining the outputs based on given inputs and prior knowledge of the functional relations. It includes five general stages: i) computer modelling, programming and debugging; ii) calibration of models; iii) sensitivity analysis; iv) validation of models; and v) simulation runs.

At this time, a programming language or special programming package is needed. Before the computer model is used, it usually has to be calibrated. Calibration involves fine-tuning the coefficients or parameters in the models so that computed data fit more closely to observed data. Sensitivity analysis gives an appraisal of the relative importance of the variables and their net effect on outputs. The calibrated model may be further tested with observed data other than the set used for calibration. This validation step demonstrates the credibility of the model.

Simulation analysis is the final step in the process. Conclusively, computer simulation runs, comparable with study objectives, are carried out.

Penning de Vries (1982) defined the steps that the development of a model must go through as follows: i) preliminary models are those with structure and data that reflect current scientific knowledge, but the insight at the explanatory level is still vague and imprecise; ii) comprehensive models describe systems whose essential elements are thoroughly understood and in which much of this knowledge is incorporated; iii) summary models are simplifications of comprehensive models that keep their essential aspects in a less detailed fashion to make them more accessible for users.

The stages proposed by Penning de Vries (1982) lead to the conclusion that the summary models, or simplified ones, are an evolution of the comprehensive models in the direction of making them more applicable in practice.

In the area of modelling and simulation of wastewater treatment processes, Andrews (1993) presented some basic concepts of modelling and their relation to engineering research and practice: i) the use of models, ii) information for model development, iii) testing of models and iv) required accuracy. The main conclusions are: i) the differences in the uses and expectations of models by the different users makes important a clear statement of their intended use; ii) different sources of information have potential value for the development of models; iii) the amount of testing needed is highly dependent on the model's use; iv) models with or without feedback control have distinct required accuracy.

The use of models to predict wastewater treatment plant performance opens up a large horizon in the field of control (Patry and Chapman, 1989). Vassos (1993) stated that the need to optimize plant performance and meet increasingly stringent effluent standards are two key

factors that will influence the development of instrumentation, control and automation. He concluded that dynamic modelling and simulation software, as an integral component of instrumentation application, will play a significant role in developing control strategies and in optimizing plant performance.

In 1983, IAWPRC formed a task group to facilitate the application of practical models to the design and operation of biological wastewater treatment systems. As a result, the Activated Sludge Model No.1 was presented by Henze *et al.* (1987) for biological wastewater treatment including nitrification and denitrification. Basically, four processes are considered in this model: growth of biomass, decay of biomass, ammonification of organic nitrogen and 'hydrolysis' of particulate organics which are entrapped in the biofloc. The process kinetics and stoichiometry were defined, creating conditions for the mass balance of the different components. These components in the model are presented by symbols in conformity with IAWPRC's nomenclature (Grau *et al.*, 1987) in such a way that the symbols are used either for the component itself or for its concentration. The model presentation is based on the work of Petersen (1965) with a matrix format.

The Activated Sludge Model No. 2 (Henze *et al.*, 1994) was introduced as a further development of the Activated Sludge Model No. 1. It includes the presence of phosphorus accumulating organisms (PAOs) and it makes possible the simulation of the behaviour of biological phosphorus removal activated sludge systems. The phosphorus accumulating organisms are a new group of microorganisms in the activated sludge, representing all types which are able to accumulate phosphorus in the form of stored poly-phosphates. From a microbiological point of view, the description of the activity of PAOs must be based on

intracellular components such as stored poly-phosphates and poly-hydroxy-alkanoates, leading to models which include structured biomass.

Model No. 2, however, does not distinguish between the composition (structure) of individual cells but considers only average properties of the biomass. Since each cell has a different history, its composition will typically deviate from the population average (e.g., it may or may not contain storage products). This is of importance because kinetic expressions used in Model No. 2 are non-linear and therefore average behaviour can not be predicted from average properties. In view of the additional problems that population models would introduce, Model No. 2 was proposed as a so-called distributed parameter model.

1.4 RESPIROMETRY

During aerobic biological wastewater treatment, substrate removal and growth of biomass are related to oxygen consumption. This link gives the biological oxygen consumption measurement an important role in the activated sludge process assessment (Allsop *et al.*, 1990; Benefield *et al.*, 1974; Haas, 1979; Holmberg, 1982; Tur *et al.*, 1990). Analysis of the oxygen consumption by the microorganisms involved in the wastewater oxidation process is called respirometry (Rozich and Gaudy, Jr., 1992).

With respect to the relationship between substrate removal and biological oxygen uptake (respiration), important parameters, such as biological oxygen demand (BOD), substrate removal activity by the several types of microorganisms and related parameters, can be

determined by respirometry, as presented by Chudoba *et al.* (1989), Fleps (1975), Huang and Cheng (1984), Tebbutt and Berkun (1976), Therien *et al.* (1984), and Vernimmen *et al.* (1967).

The rate of oxygen consumption gives information about the process kinetics (D'Adamo *et al.*, 1984; Spanjers and Klapwijk, 1990). Therefore, the oxygen uptake rate, or respiration rate, is the key variable that characterizes the process and the associated removal and degradation of the biodegradable matter.

The equipment which measures the respiration rate is called a respiration meter or respirometer, which consists of a respiration chamber and a device to assess the dissolved oxygen variation. Respiration meters can be manometric or volumetric (Spanjers, 1993).

Manometric meters evaluate differences in pressure in a constant volume system as oxygen is consumed (Huang and Cheng, 1984; Jenkins, 1960; Montgomery, 1967; Tebbut and Berkun, 1976). With volumetric meters, the pressure is constant and the variation in oxygen concentration is directly measured with an oxygen probe (Blok, 1974; Chen *et al.*, 1980; Clarke *et al.*, 1978; Hisset *et al.*, 1982; Randal *et al.*, 1991; Ros *et al.*, 1988; Sollfrank and Gujer, 1990; Vanrolleghem *et al.*, 1990). The development of more reliable oxygen sensors has made the use of volumetric respirometers more attractive (Ros, 1993; Spanjers, 1993).

Respirometry has long been a useful tool in the field of water pollution control. Most respirometers were developed to determine biochemical oxygen demand (BOD). Later on, different respirometers were used for measuring and analysing activated sludge and the

kinetics of the biodegradation processes in activated sludge systems (Ros, 1993).

The possibility of using respirometry for monitoring and controlling activated sludge systems induced the development of respirometers that could be used on-line. One such respirometer was developed at the Department of Environmental Technology at the Wageningen Agricultural University (Figure 1). It consists of a closed, completely mixed respiration chamber through which the activated sludge is continuously pumped. The dissolved oxygen concentration is periodically measured by a probe placed at the inlet and the outlet of the respiration chamber. This is achieved by alternating the flow direction. Calculation of the respiration rate is based on the dissolved oxygen mass balance over the respiration chamber (Spanjers, 1993).

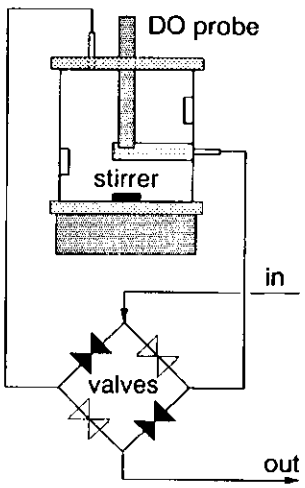


Figure 1. Schematic representation of the respiration meter developed at the Department of Environmental Technology, Wageningen Agricultural University (Spanjers, 1993).

1.5 SCOPE OF THIS THESIS

The main objectives of the present thesis can be summarized as:

- the development and validation of simplified mathematical models for activated sludge processes in an SBR treating real domestic wastewater;
- the application of these simplified models for analysing the respirometric response and for obtaining information about the oxygen uptake for the different processes;
- the application of the monitored respirometric values for model calibration and determination of parameter values, which are used to predict the processes in the next cycle;
- the use of models as theoretical background for the development of control strategies;
- relating the basic time scale for the models to the short term.

To accomplish the main objectives of this thesis, an SBR pilot plant was built to treat domestic wastewater. During the two and a half years of operation, the plant underwent three different technological phases. The first phase began with the removal of organics and nitrification. Denitrification was incorporated in the second phase. The last phase included biological phosphorus removal. In general, Chapters 2, 3 and 4 are related to these technological phases.

In Chapter 2, two simplified mathematical activated sludge models are presented. The first

model gives the response of the respiration rate in an SBR with nitrification, the oxidation of readily biodegradable matter, and endogenous respiration during one cycle. This model is used to predict the respiration rate during a complete SBR cycle. For this, it uses parameter values calibrated during the previous cycle, some default values and information about the ammonia concentration in the influent. The endogenous respiration rate is described with an exponential equation. The second model is used to predict the changes in nitrification capacity after a change in the loading rate and/or sludge wastage rate. For model calibration and validation, an SBR pilot plant receiving domestic wastewater was operated for nine weeks.

In Chapter 3, a mathematical model is presented for the behaviour of the respiration rate and nitrate removal in an activated sludge Sequencing Batch Reactor (SBR) with nitrification, denitrification and carbon oxidation. This model is based on the response of the respiration rate measured during nitrification and carbon oxidation and the nitrate removal rate during the post-denitrification period. For model calibration and validation, an SBR pilot plant receiving domestic wastewater was operated for three months. The respiration rate was used to calibrate several parameters of the model.

In Chapter 4, a mathematical model for an activated sludge SBR with nitrification, denitrification, carbon oxidation and phosphate removal is proposed. This model is based on the response of the respiration rate measured during nitrification, carbon oxidation and phosphate removal, together with the behaviour of phosphate and acetate as proposed by Gujer *et al.* (1994) for the Activated Sludge Model No. 2. For model calibration and validation, an SBR pilot plant receiving settled domestic wastewater plus acetic acid solution was operated for five months.

Chapter 5 summarizes the conclusions from the studies presented in Chapters 2, 3 and 4, and also gives some recommendations.

REFERENCES

Alleman, J.E. and Irvine, R.L. (1980a). Storage-induced denitrification using sequencing batch reactor operation. *Wat. Res.* **14**:1483-1488.

Alleman, J.E. and Irvine, R.L. (1980b). Nitrification in sequencing batch biological reactor. *J. Wat. Pollut. Control Fed.* **52**:2747-2754.

Allsop, P.J., Moo-Young, M. and Sullivan, G.R. (1990). The dynamics and control of substrate inhibition in activated sludge. *CRC Critical Reviews in Environm. Control.* **20**:115-167.

Andrews, J.F. (1993). Modelling and simulation of wastewater treatment processes. *Wat. Sci. Tech.* **28**:(11-12) 141-150.

Antoniou, P., Hamilton, J., Koopman, B., Jain, R., Holloway, B., Lyberatos, G. and Svoronos, S.A. (1990). Effect of temperature and pH on the effective maximum specific growth rate of nitrifying bacteria. *Wat. Res.* **24**:97-101.

Appeldoorn, K.J. (1993). Ecological aspects of the biological phosphate removal from

wastewaters. PhD. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Arvin, E. (1983). Observation supporting phosphate removal by biological mediate chemical precipitation. A review. *Water Sci. Technol.* **15**:43-63.

Barnard, J.L. (1975). Biological nutrient removal without the addition of chemicals. *Wat. Res.* **9**:485-490.

Beccari, M., Marani, D. and Ramadori, R. (1979). A critical analysis of nitrification alternatives. *Wat. Res.* **13**:185-192.

Benefield, L.D., Randal, C.W. and King, P.H. (1974). Process control by oxygen uptake and solid analysis. *J. Wat. Poll. Cont. Fed.* 47:2498-2507.

Blok, J. (1974). Respirometric measurements on activated sludge. *Wat. Res.* **8**:11-18.

Boero, V.J., Eckenfelder, W.W., Jr., and Bowers, A.R. (1991). Soluble microbial product formation in biological systems. *Wat. Sci. Tech.* **23**:(4-6) 1067-1076.

Carucci, A., Lindrea, K.C., Majone, M. and Ramadori, R. (1994). Dynamics of the anaerobic utilization of organic substrates in an anaerobic/aerobic sequencing batch reactor. *Proc. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes.* Copenhagen, Denmark. section 6.

Chen, C.Y., Roth, J.A. and Eckenfelder, W.W. (1980). Response of dissolved oxygen to changes in influent organic loading to activated sludge systems. *Wat. Res.* **14**:1449-1457.

Chiesa, S.C. and Irvine, R.L. (1985). Growth and control of filamentous microbes in activated sludge: an integrated hypothesis. *Wat. Res.* **19**:471-479.

Chiesa, S.C., Irvine, R.L. and Manning, J.F., Jr. (1985). Feast/famine growth requirements and activated sludge population selection. *Biotechnol. Bioeng.* **27**:562-569.

Chiesa, S.C., Postiglione, J.A. and Bjelland, M. (1987). Effect of variable influent loading on biological phosphorus removal. *J. Environm. Eng.* **113**:1058-1073.

Chudoba, J., Albokova, J., Cech, J. (1989). Determination of kinetic constant of activated sludge microorganisms responsible for degradation of xenobiotics. *Wat. Res.* **23**:1431-1438.

Clarke, A.N., Eckenfelder, W.W. and McMullen, E.D. (1978). Development of a continuous respirometer. *Wat. Res.* **12**:799-804.

Comeau, Y., Hall, K.J., Hancock, R.E.W. and Oldham, W.K. (1986). Biochemical model for enhanced biological phosphorus removal. *Wat. Res.* **20**:1511-1521.

Comeau, Y., Oldham, W.K. and Hall, K.J. (1987). Dynamics of carbon reserves in biological dephosphatation of wastewater. *Proc. IAWPRC Specialized Conference.* Rome, Italy. pp. 39-55.

D'Adamo, P.C., Rozich, A.F. and Gaudy, A.F. Jr. (1984). Analysis of growth data with inhibitory carbon sources. *Biotechnol. Bioeng.* **26**:397-402.

Dawson, R.N. and Murphy, K.L. (1972). The temperature dependency of biological denitrification. *Wat. Res.* **6**:71-82.

Dawson, R.N. and Murphy, K.L. (1973). Factors affecting biological denitrification in wastewater. In *Advances in water pollution research.* Jenkins, S.H. (ed.) Pergamon Press, Oxford, England.

Dennis, R.W. and Irvine, R.L. (1979). Effect of fill to react ratio on sequencing batch biological reactor. *J. Wat. Pollut. Control Fed.* **51**:255-263.

Dold, P.L., Ekama, G.A. and Marais, G.v.R. (1980). A general model for the activated sludge process. *Prog. Wat. Tech.* **12**:47-77.

Downing, A.L., Painters, H.A. and Knowles, G. (1964). Nitrification in the activated sludge process. *J. Proc. Inst. Sew. Purif.* **2**:130-158.

Fleps, W. (1975). An automatic, continuous flow respirometer, its description and use. *Prog. Wat. Tech.* 7:1-12.

Forrester, J.W. (1961). *Industrial dynamics.* John Wiley & Sons, New York, USA.

Gee, C.S., Suidan, M.T. and Pfeffer, J.T. (1990). Modelling of nitrification under substrate-inhibiting conditions. *J. of Envir. Engrg.,* ASCE. **116:**18-31.

Germirli, F., Orhon, D. and Artan, N. (1991). Assessment of the initial inert soluble COD in industrial wastewaters. *Wat. Sci. Tech.* **23:**(4-6) 1077-1086.

Grau, P., Sutton, P.M., Henze, M., Elmaleh, S., Grady, C.P., Gujer, W. and Koller, J. (1987). Notation for use in the description of wastewater treatment process. *Wat. Res.* **21**:135-139.

Gujer, W., Henze, M., Mino, T., Matsuo, T., Wentzel M.C. and Marais, G.v.R. (1994). The Activated Sludge Model No. 2: biological phosphorus removal. *Proc. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes.* Copenhagen, Denmark. section 1.

Haandel, A.C.v., Ekama, G.A. and Marais, G.v.R. (1981). The activated sludge process-3: single sludge denitrification. *Wat. Res.* **15**:1135-1152.

Haas, C.N. (1979). Oxygen uptake rate as an activated sludge control parameter. *J. Wat. Poll. Cont. Fed.* **51**:938-943.

Hascoet, M.C., Florentz, M. and Granger, P. (1984). Biochemical aspects of enhanced biological phosphorus removal from waste waters. *Water SA.* **11**:1-8.

Henze, M., Grady, C.P.L. Jr., Gujer, W., Marais, G.v.R. and Matsuo, T. (1987). *Activated*

Sludge Model No. 1. IAWPRC Scientific and Technical Report No. 1. IAWQ. London. ISSN 1010-707X.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel M.C. and Marais, G.v.R. (1994). Activated Sludge Model No. 2. *Proc. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes.* Copenhagen, Denmark. section 3.

Herzbrun, P.A., Irvine, R.L. and Malinowski, K.C. (1985). Biological treatment of hazardous waste in sequencing batch reactors. *J. Wat. Pollut. Control Fed.* **57**:1163-1167.

Hisset, E., Deans, A. and Evans, M.R. (1982). Oxygen consumption during batch aeration of piggery slurry at temperatures between 5 and 50 C. *Agricultural Wastes.* **4**:477-487.

Holmberg, A. (1982). Modelling of the activated sludge process for microprocessor-based state estimation and control. *Wat. Res.* **16**:1233-1246.

Huang, J.Y.C. and Cheng, M.D. (1984). Measurements and new applications of oxygen uptake rates in activated sludge processes. *J. Wat. Poll. Cont. Fed.* **56**:259-265.

Irvine, R.L. and Busch, A.W. (1979). Sequencing batch biological reactors - an overview. *J. Wat. Pollut. Control Fed.* **54**:235-243.

Irvine, R.L. and Ketchum, L.H., Jr. (1989). Sequencing batch reactors for biological wastewater treatment. *CRC Critical Reviews in Environm. Control.* **18**:255-294.

Irvine, R.L., Ketchum, L.H., Jr., Arora, M.L. and Barth, E.F. (1985). An organic loading study of full-scale sequencing batch reactors. *J. Wat. Pollut. Control Fed.* **57**:847-853.

Irvine, R.L., Ketchum, L.H., Jr., Breyfogle, R.E. and Barth, E.F. (1983). Municipal application of sequencing batch treatment at Culver, Indiana. *J. Wat. Pollut. Control Fed.* **55**:484-488.

Irvine, R.L., Miller, G. and Bhamrah, A.S. (1979). Sequencing batch treatment of wastewaters in rural areas. *J. Wat. Pollut. Control Fed.* **51**:244-254.

Irvine, R.L., Murthy, D.V.S., Arora, M.L., Copeman, J.L. and Heidman, J.A. (1987). Analysis of full-scale SBR operation at Grundy Center, Iowa. *J. Wat. Pollut. Control Fed.* **59**:132-138.

Irvine, R.L., Sojka, S.A. and Colaruotolo, J.F. (1984). Enhanced biological treatment of leachates from industrial landfills. *Hazardous Wastes* 1:123-131.

Iwema, A. and Meunier (1984). Influence of nitrate on acetic acid induced biological phosphate removal. *Proc. IAWPRC Post Conf. Seminar on Enhanced Biological Phosphorus Removal from Wastewaters*, vol. 2, Paris. pp. 21-28.

Jenkins, D. (1960). *The use of manometric methods in the study of sewage and trade waste waters treatment.* Pergamon Press, New York, USA.

Jones, W.L., Schroeder, E.D. and Wilderer, P.A. (1990). Denitrification in a batch wastewater treatment system using sequestered organic substances. *Res. J. Wat. Pollut. Control Fed.* **62**:259-267.

Ketchum, L.H., Jr., Irvine, R.L., Breyfogle, R.E. and Manning, J.F., Jr. (1987). A comparison of biological and chemical phosphorus removal in continuous and sequencing batch reactors. *J. Wat. Pollut. Control Fed.* **59**:13-19.

Klapwijk, A. (1978) Eliminatie van stikstof uit afvalwater door denitrificatie. PhD. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Koh, W.K., Ng, W.J. and Ong, S.L. (1989). A bio-oxidation study of methanol synthetic wastewater using the SBR. *Biological Wastes* **27**:101-113.

Lawrence, A.W. and Brown, C.G. (1976). Design and control of nitrifying activated sludge systems. *J. Wat. Poll. Cont. Fed.* **48**:1779-1803.

Leffelaar, P.A. (1993). Basic elements of dynamic simulation. In *On systems analysis and simulation of ecological processes.*Leffellar, P.A. (ed.) Kluwer Academic Publishers, Dordrecht, The Netherlands.

Manning, J.F., Jr. and Irvine, R.L. (1985). The biological removal of phosphorus in a sequencing batch reactor. *J. Wat. Pollut. Control Fed.* **57**:87-94.

Marklund, S. (1993). Cold climate sequencing batch reactor biological phosphorus removal-results 1991-1992. *Wat. Sci. Tech.* **28**:(10) 275-282.

Matsuzawa, Y. and Mino, T. (1991). Role of glycogen as an intracellular carbon reserve of activated sludge in the competitive growth of filamentous and non-filamentous bacteria. *Wat. Sci. Tech.* **23**:(4-6) 899-905.

McCartney, D.M. and Oleszkiewicz, J.A. (1990). Carbon and nutrient removal in a sequencing batch reactor at low temperatures. *Envir. Technol.* **11**:99-112.

Melcer, H., Bedford, W.K. Topnik, B.H. and Schmidtke, N.W. (1987). Conversion of small municipal wastewater treatment plants to sequencing batch reactors. *J. Wat. Pollut. Control Fed.* **59**:79-85.

Metcalf & Eddy, Inc. (1991). *Wastewater engineering: treatment, disposal and reuse.* 3rd ed. McGraw-Hill, New York, USA.

Mino, T. San Pedro, D.C. and Matsuo, T. (1994). Estimation of the rate of slowly biodegradable COD (SBCOD) hydrolysis under anaerobic, anoxic and aerobic conditions by experiments using starch as model substrate. *Proc. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes.* Copenhagen, Denmark. section 15.

Montgomery, H.A.C. (1967). The determination of biochemical oxygen demand by respirometric methods. *Wat. Res.* **1**:631-662.

Mostert, E.S., Gerber, A. and van Riet, C.J.J. (1988). Fatty acid utilization by sludge from full-scale nutrient removal plants, with special reference to the role of nitrate. *Water SA.* **14**:179-184.

Murthy, D.N.P., Page, N.W. and Rodin, E.Y. (1990). *Mathematical modelling: a tool for problem solving in engineering, physical, biological and social sciences.* Pergamon Press, Oxford, England.

Nakazawa, H. and Tanaka, K. (1991). Kinetic model of sequencing batch activated sludge process for municipal wastewater treatment. *Wat. Sci. Tech.* **23**:(4-6) 1097-1106.

Ng, W.J. and Tan, J.C. (1990). Some observation on organic removal in an SBR. *Biological Wastes* **33**:169-179.

Okada, M., Murakami, A., Lin, C.K., Ueno, Y. and Okubo, T. (1991). Population dynamics of bacteria for phosphorus removal in sequencing batch reactor (SBR) activated sludge processes. *Wat. Sci. Tech.* **23**:(4-6) 755-763.

Okada, M., Murakami, A. and Sudo, R. (1987). Ecological selection of phosphorus-accumulating bacteria in sequencing batch reactor activated sludge processes for simultaneous removal of phosphorus, nitrogen and organic substances. *Proc. IAWPRC Specialized Conference.* Rome, Italy. pp. 147-154.

Oles J. and Wilderer, P.A. (1991). Computer aided design of sequencing batch reactors based

on the IAWPRC activated sludge model. *Wat. Sci. Tech.* **23**:(4-6) 1087-1095.

Oleszkiewicz, J.A. and Berquist, S.A. (1988). Low temperature nitrogen removal in sequencing batch reactors. *Wat. Res.* **22**:1163-1171.

Painter, H.A. and Loveless, J.E. (1983). Effect of temperature and pH value on the growth-rate constants of nitrifying bacteria in the activated sludge process. *Wat. Res.* 7:237-248.

Patry, G.G. and Chapman, D. (eds.) (1989). *Dynamic modelling and expert-systems in wastewater engineering.* Lewis Publishers, Inc. Michigan, USA.

Payne, W.J. (1981). *Denitrification.* John Wiley & Sons, New York, USA.

Peirano, L.E., Henderson, D.B., Gonzales, J.G.M. and Davis, E.F. (1983). Full scale experiments with the Phostrip process. *Water Sci. Technol.* **15**:181-195.

Penning de Vries, F.W.T. (1982). Phases of development of models. In *Simulation of plant growth and crop production.* Penning de Vries, F.W.T. and van Laar, H.H. (eds.) Pudoc, Wageningen, The Netherlands.

Petersen, E.E. (1965). *Chemical reactions analysis.* Prentice-Hall, NJ, USA.

Randal, E.W., Wilkinson, A. and Ekama, G.A. (1991). An instrument for the direct determination of oxygen uptake rate. *Water SA.* **17**:11-18.

Ros, M. (1993). *Respirometry of activated sludge.* Technomic Publishing Co. Inc., Pennsylvania, USA.

Ros, M., Dular, M. and Farkas, P. (1988). Measurement of respiration of activated sludge. *Wat. Res.* **22**:1405-1411.

Rozich, A.F. and Gaudy, A.F. Jr. (1992). *Design and operation of activated sludge processes using respirometry.* Lewis Publishers, Inc., Michigan, USA.

Rusten, B. and Eliassen, H. (1993). Sequencing batch reactors for nutrient removal at small wastewater treatment plants. *Wat. Sci. Tech.* **28**:(10) 233-242.

Sheker, R.E., Aris, R.M. and Shieh, W.K. (1993). The effects of fill strategies on SBR performance under nitrogen deficiency and rich conditions. *Wat. Sci. Tech.* **28**:(10) 259-266.

Smolders, G.J.F., van Loosdrecht, M.C.M. and Heijnen, J.J. (1994). A metabolic model for the biological phosphorus removal process. *Proc. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes.* Copenhagen, Denmark. section 10.

Sollfrank, U. and Gujer, W. (1990). Simultaneous determination of oxygen uptake rate and oxygen transfer coefficient in activated sludge systems by an on-line method. *Wat. Res.* **24**:725-734.

Spanjers, H. (1993). Respirometry in activated sludge. PhD. thesis, Wageningen Agricultural

University, Wageningen, The Netherlands.

Spanjers, H. and Klapwijk, A. (1990). On-line meter for respiration rate and short-term biochemical oxygen demand in the control of the activated sludge process. In *Advances in Water Pollution Control*, Proc. 5th IAWPRC Workshop, 26 July-3 August, Yokohama and Kyoto, Japan.

Stensel, H.D. and Barnard, J.L. (1992). Principles of biological nutrient removal. In *Design and retrofit of wastewater treatment plants for biological nutrient removal.* Randal, C.W., Barnard, J.L. and Stensel, H.D. (eds.) Technomic Publishing Co. Inc., Pennsylvania, USA.

Stenstrom, M.K. and Poduska, R.A. (1980). The effect of dissolved oxygen concentration on nitrification. *Wat. Res.* **14**:643-649.

Tanji, K.K. (1981). Approaches and philosophy of modelling. In *Modelling wastewater renovation.* Iskandar, I.K. (ed.) John Wiley & Sons, New York, USA. pp. 20-41.

Tebbut, T.H.Y. and Berkun, M. (1976). Respirometric determination of BOD. *Wat.Res.* **10**:613-617.

Therien, N., Le Clave, P., Jones, P. (1984). A respirometric study of the influence of aliphatic alcohols on activated sludges. *Wat. Res.* **18**:905-910.

Tur, M., Tseng, L., Chou, M., Fang, H. and Hsia, J. (1990). Application of oxygen uptake

rate in managing an activated sludge process for treating refinery wastewater. *44th Purdue Ind. Waste Conf. Proc.* 695-701.

Vanrolleghem, P., Dries, D. and Verstraete, W. (1990). RODOX: biosensor for rapid determination of the biochemical oxygen demand and the on-line monitoring of the toxicity of wastewaters. In *Proc. Fifth European Congress on Biotechnology.* 8-13 July, Copenhagen, Denmark, vol. 1, pp. 161-164.

Vassos, T.D. (1993). Future directions in instrumentation, control and automation in the water and wastewater industry. *Wat. Sci. Tech.* **28**:(11-12) 9-14.

Vernimmen, A.P., Henken, E.R., Larub, J.C. (1967). A short-term biochemical oxygen demand test. *J. Wat. Poll. Control Fed. 39*:1006-1020.

Vinçonneau, J.C., Schaack, F., Boschet, A.F., Chevalier, D., Villesot, D., Jaubert, M., Laval, Ch. and Lambert, S. (1985). The problem of phosphorus in France - its presence in natural waters and biological phosphorus removal. *Wat. Sci. Tech.* **17**:1-9.

Vlekke, G.J.F.M., Comeau, Y. and Oldham, W.K. (1988). Biological phosphate removal from wastewater with oxygen of nitrate in sequencing batch reactors. *Envir. Technol. Lett.* **9**:791-796.

Wentzel, M.C., Dold, P.L., Ekama, G.A. and Marais, G.v.R. (1984). Kinetics of biological phosphorus release. *Proc. IAWPRC Post Conf. Seminar on Enhanced Biological*

Phosphorus Removal from Wastewaters, vol. 1, Paris. pp. 90-103.

Wild, D., von Schulthess, R. and Gujer, W. (1994). Structured modelling of denitrification intermediates. *Proc. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes.* Copenhagen, Denmark. section 7.

de Wit, C.T. (1993). Philosophy and terminology. In *On systems analysis and simulation of ecological processes.* Leffellar, P.A. (ed.) Kluwer Academic Publishers, Dordrecht, The Netherlands.

Yamamoto, R.I., Komori, T. and Matsui, S. (1991). Filamentous bulking and hindrance of phosphate removal due to sulphate reduction in activated sludge. *Wat. Sci. Tech.* **23**:(4-6) 927-935.

Yeoman, S., Stephenson, T., Lester, J.N. and Perry, R. (1988). The removal of phosphorus during wastewater treatment: a review. *Environ. Pollut.* **49**:183-233.

CHAPTER 2

MODELLING RESPIRATION RATES IN A NITRIFYING SBR TREATING DOMESTIC WASTEWATER

2 MODELLING RESPIRATION RATES IN A NITRIFYING SBR TREATING DOMESTIC WASTEWATER

SUMMARY

This paper aims to present two simplified mathematical activated sludge models. The first model gives the response of the respiration rate (r) in an SBR with nitrification, the oxidation of readily biodegradable matter, and endogenous respiration during one cycle. This model is used to predict the respiration rate (r) during a complete SBR cycle. This is achieved by using parameter values calibrated during the previous cycle, some default values, and information about the ammonia concentration in the influent. The endogenous respiration rate (r_{end}) is described with an exponential equation. The second model is used to predict the changes in nitrification capacity after a change in the loading rate and/or the sludge wastage rate.

An on-line monitoring procedure based on respirometry was used. The measurements were used to calibrate the parameters used in the model.

For model validation, an SBR pilot plant receiving domestic wastewater was operated for nine weeks and the results were compared with the model predictions. The proposed model matched well with the measured r. It is concluded that r has good potential as a variable for on-line monitoring and control of activated sludge in an SBR with nitrification.

KEY WORDS

Sequencing Batch Reactor (SBR); nitrification; respiration rate; endogenous respiration rate; modelling; domestic wastewater.

INTRODUCTION

Nitrification is accountable for a significant part of the total oxygen consumption in activated sludge treatment plants. Originally, nitrification was carried out in wastewater treatment plants to avoid depletion of dissolved oxygen in the receiving water. Later, it became an important step in biological nitrogen removal. Control of nitrification is required to achieve good nitrogen removal (van Haandel *et al.*, 1981).

The use of Sequencing Batch Reactors (SBRs) for wastewater treatment has been extensively reported on. It is a system that has flexibility in operation, and the capability to select specific microbial populations (Dennis and Irvine, 1979; Irvine and Busch, 1979; Jones *et al.*, 1990). An SBR can also be seen as a physical model for continuous plug-flow activated sludge plants. For kinetic studies, the use of an SBR, rather than a continuous plug-flow system, is advantageous.

Good process control is crucial for high performance of an activated sludge plant. Normally, several variables are monitored to evaluate process behaviour, most of which depend on laboratory analyses, although some, such as pH, temperature, dissolved oxygen and ammonia,

can be monitored on-line. The variables based on laboratory analyses are not appropriate for control purposes. Measurement of respiration rates in an activated sludge plant has been demonstrated by Spanjers and Klapwijk (1990) to be an important tool for monitoring process behaviour. They have also indicated that respirometry is useful for process control. Most of their respirometric research focused on monitoring continuous-flow activated sludge plants with completely mixed aeration tanks. The present work concerns the study of activated sludge plants with other hydraulic regimes, and a Sequencing Batch Reactor (SBR) with organic carbon removal and nitrification was used.

The performance of an activated sludge plant can be controlled by the manipulation of different variables: i) the air-flow rate into the aeration tank; ii) the sludge wastage-flow rate; iii) the influent-flow rate; or iv) the cycle time in an SBR.

In the time scale of hours, the air-flow rate and the cycle time are important manipulated variables. Because the activated sludge's respiration rate is changeable, to select an appropriate air-flow rate, information about the activated sludge's respiration rate is required. In an activated sludge system treating domestic wastewater with carbon oxidation and nitrification, the latter is the limiting step for an acceptable loading rate. The cycle time for a nitrifying SBR is determined by the ammonia concentration of the influent and the nitrification rate of the activated sludge. In a long-term scenario, sludge wastage is an important variable for nitrification because it can control the nitrifier's concentration and, consequently, the nitrification rate. Both short- and long-term scenarios are complex and a model can be effective for understanding the processes.

Mathematical models are an important tool for the design and control of treatment plants, and several have been developed for activated sludge processes. More elaborate models, such as the one developed by the IAWPRC Task Group, can lead to a rational selection between process variants (Dold *et al.*, 1980; Henze *et al.*, 1987; Padukone and Andrews, 1989). Oles and Wilderer (1991) presented a model to describe nitrification in an SBR treating domestic wastewater.

The question is whether activated sludge models can be simplified to such an extent that, in combination with a measuring system, good prediction of the behaviour of the relevant variables for short- and long-term operation can be given. In this study, we have focused on the SBR or reactors with plug-flow characteristics. The objective of this paper is to present two preliminary dynamic and explanatory models for nitrification and organic carbon oxidation in an SBR receiving domestic wastewater. They include: i) a model to simulate the respiration rate during one process cycle and ii) a model to simulate the nitrification capacity in an SBR during long-term operation.

The simplified model for one SBR cycle is used to analyse the respirometric response and to obtain information about the oxygen uptake for the different processes. In addition, the monitored respirometric values are used for calibration and determination of the parameter values. These values, together with measurements of the ammonia concentration of the added wastewater, are used as input for the next cycle's respirogram prediction. This prediction gives information about the total amount of oxygen to be used and its distribution during the cycle. It also predicts when the added ammonia will be completely nitrified.

The simplified model for long-term operation is used to predict the changes in nitrification capacity over the long term after changing the loading rate and/or the sludge wastage rate. The input for this model is the nitrification capacity, determined by analysing the respirogram using the model for one SBR cycle.

For model validation, an SBR was operated for nine weeks, achieving full nitrification during the process. During this period, the respiration rate was monitored on-line. An experiment was carried out with inhibited nitrification to survey the respiration rate of the organic carbon oxidation process. Measurements of the respiration rate during a cycle with low ammonia influent concentration also yielded information on the respiration rate during organic carbon oxidation.

THEORETICAL BACKGROUND FOR ORGANIC CARBON AND NITROGEN OXIDATION

The Activated Sludge Model No. 1 (Henze *et al.*, 1987) was the starting point for the development of the models in the present study. The symbols used (see Nomenclature) are according to the work of Henze *et al.* (1987). In the model of one SBR cycle:

i) we considered the removal of readily biodegradable matter (S_S) similar to Model No. 1;

ii) we did not consider the fraction of N incorporated into the biomass for the removal of ammonia nitrogen (S_{NH});

iii) we did not consider the particulate's removal;

iv) we considered the endogenous respiration, also including in our definition the oxidation of the particulate organics adsorbed by the activated sludge;

v) we did not consider the biomass growth in one SBR cycle.

Growth of autotrophic organisms was considered for the long-term operation model.

Organic matter can be: i) readily biodegradable, ii) slowly biodegradable and iii) non-biodegradable. Readily biodegradable organic matter (S_S) is directly available for oxidation by heterotrophic bacteria. Slowly biodegradable organic matter (X_S) is first adsorbed, then hydrolysed into S_S, and then oxidized. Non-biodegradable organic matter is not degraded during the process. The general equation for carbon oxidation can be written as:

$$Organic\ \ Carbon + O_2 \xrightarrow[bacteria]{} CO_2 + H_2O + energy \qquad (1)$$

The difference in the rate of oxygen consumption between S_S and X_S strongly varies. S_S passes directly through the cell wall and is metabolized at a high rate, and the biodegradation process can be modelled with a Monod-type equation. The oxidation rate of X_S is limited by the rate of extracellular enzymatic breakdown and is relatively slow (Ekama and Marais, 1980). In an activated sludge system treating wastewater with a relatively high concentration of X_S, biosorption is very strong. A few minutes after the addition of wastewater almost all the organic carbon is adsorbed and no longer in the solution. Information about the rate of organic carbon oxidation can, therefore, only be obtained from the rate of oxygen uptake (Gujer, 1980).

Organic nitrogen can be transformed into ammonia through bacterial decomposition of proteinaceous matter and hydrolysis of urea. Ammonia nitrogen can be oxidized by autotrophic bacteria in a two-step process to form nitrate. This process is called nitrification.

$$2\ NH_4^+ + 3\ O_2 \xrightarrow[Nitrosomonas]{} 2\ NO_2^- + 2\ H_2O + 4\ H^+ + energy \qquad (2)$$

$$2\ NO_2^- + O_2 \xrightarrow[Nitrobacter]{} 2\ NO_3^- + energy \qquad (3)$$

The stoichiometric quantities of oxygen required according to equations **2** and **3** are 3.43 g for oxidation of 1 g ammonia-N and 1.14 g for oxidation of 1 g nitrite-N. The total oxygen demand is 4.57 g per gram of ammonia oxidized.

In activated sludge models, nitrification is usually modelled as a one-step reaction. In the study of Ossenbruggen *et al.* (1991), as well as in this study, both steps are modelled with a Monod equation. Nitrite accumulation is reported, indicating distinct rates for the two steps in the overall nitrification (Gee *et al.*, 1990).

MODELLING THE RESPIRATION RATE (r) DURING ONE CYCLE

The aim of the simplified model is to predict the total amount of oxygen consumption and distribution during the cycle. The aim is also to predict when all the ammonia will be nitrified. This information is necessary for optimal control of an SBR. The model for the respiration rate during one process cycle is used to predict the r by using parameters estimated in the previous cycle, together with information about the ammonia concentration of the added wastewater.

The description of the respiration rate during one SBR cycle should consider the oxygen requirements for nitrification, oxidation of readily biodegradable matter and endogenous respiration. For aerobic microorganisms, the oxygen consumption is related to substrate utilization. In turn, substrate utilization is related to the growth of microorganisms. The development of these relationships follows.

The rate of microorganism growth (r_g) in a batch reactor can be defined by the following general relationship:

$$r_g = \mu X_B \qquad (4)$$

The effect of substrate concentration on specific growth rates (μ) can be described by the general expression proposed by Monod:

$$\mu = \hat{\mu} \frac{S}{K+S} \tag{5}$$

Combining equations 4 and 5 leads to:

$$r_g = \frac{\hat{\mu} X_B S}{K+S} \tag{6}$$

The general relationship between substrate utilization rate (r_{su}) and microorganism growth rate (r_g) can be expressed by:

$$r_g = -Y r_{su} \tag{7}$$

Combining equations 6 and 7 gives:

$$r_{su} = -\frac{\hat{\mu} X_B}{Y} \frac{S}{K+S} \tag{8}$$

The maximum substrate removal rate (r_m) can be easily measured, however it is more difficult to measure the parameters μ and Y and the variable X_B. The maximum substrate removal rate is related to μ, Y and X_B by the general equation:

$$r_m = -\frac{\hat{\mu} X_B}{Y} \tag{9}$$

During one SBR cycle, the biomass concentration is almost constant. Therefore, r_m is also constant. Using equations **8** and **9** for the removal of S during the aerobic activated sludge process, at limiting substrate concentration, we can write the general equation:

$$r_{su} = r_m \frac{S}{K + S} \tag{10}$$

For the removal of ammonia (S_{NH}), nitrite (S_{NO2}) and readily biodegradable matter (S_s), the following equations are used:

$$r_{NH} = r_{m,NH} \frac{S_{NH}}{K_{NH} + S_{NH}} \tag{11}$$

$$r_{NO2} = r_{m,NO2} \frac{S_{NO2}}{K_{NO2} + S_{NO2}} \tag{12}$$

$$r_S = r_{m,S} \frac{S_S}{K_S + S_S} \tag{13}$$

The oxidation rates of S_{NH}, S_{NO2} and S_S can be related to the rate of oxygen consumption, or the respiration rate, of microorganisms as follows:

$$r_{o,NH} = 3.43\ r_{NH} \tag{14}$$

$$r_{o,NO2} = 1.14\ r_{NO2} \quad (15)$$

$$r_{o,S} = (1 - Y_H)\ r_S \quad (16)$$

The last respiration rate to be included in the model is the endogenous respiration rate (r_{end}), which has several definitions. In microbiological literature, r_{end} is defined in terms of maintenance: endogenous respiration occurs when there is no observed substrate consumption and when maintenance ATP is obtained from biomass degradation (Herbert, 1958). Some definitions in the wastewater literature are: "metabolic respiration of a living cell using the contents of the cell as a substrate; occurs usually when there is an absence of any other substrate" (Patry and Chapman, 1989); "the amount of oxygen utilized per unit of MLVSS in the reactor in the absence of exogenous substrate" (Suschka and Ferreira, 1986).

In the present study, the operational definition of endogenous respiration rate (r_{end}) is used according to Spanjers (1993): "the oxygen uptake rate per unit of volume and unit of time in the absence of readily biodegradable matter in the solution". The cited work assumes that r_{end} is associated with the oxidation of readily biodegradable matter produced by (1) the hydrolysis of slowly biodegradable substances, (2) lysis of dead cells and, (3) the release of substrate for maintenance.

During one cycle in an SBR, r_{end} can be modelled by the following exponential equation:

$$r_{end} = K_1 \exp(-K_2\ t) \quad (17)$$

In this case, t is zero at the start of each SBR cycle.

The total respiration rate (r) is equal to the sum of all the partial respiration rates:

$$r = r_{o,S} + r_{o,NH} + r_{o,NO2} + r_{end} \quad (18)$$

First, model **17** is calibrated, followed by calibration of models 11 and 12. Then the resulted parameters K_1, K_2, $r_{m,NH}$ and $r_{m,NO2}$ are used for the validation of the model for the respiration rate during one cycle (equations **11-18**) by comparing the simulation results with the measured respiration rate.

MODELLING THE NITRIFICATION CAPACITY VARIATION IN AN SBR DURING LONG-TERM OPERATION

The model for nitrification capacity variation in an SBR during long-term operation is used to predict changes in nitrification capacity ($r_{m,NH}$) after changing the ammonia loading rate and/or the sludge wastage rate.

In a long-term operating SBR, the concentration of nitrifiers is not constant, as could be assumed during one SBR cycle. A net increase in the mass of nitrifiers and variation in the nitrification capacity ($r_{m,NH}$) of an SBR is determined by growth, decay and wastage of nitrifiers. The growth rate of nitrifiers ($r_{g,A}$) is normally modelled as:

$$r_{g,A} = \mu_A X_{B,A} \quad (19)$$

However, in an SBR with a constant ammonia loading rate and complete nitrification, the mass of nitrifiers produced is limited by the mass of substrate consumed. In this case, the mass of nitrifiers produced per unit of time is constant and can be modelled as:

$$r_{g,A} = Y_A \frac{Q_i}{V} (S_{NH,i} - S_{NH,e}) \qquad (20)$$

Long-term operation of an SBR can be seen as a continuous system. With this simplification, the mass balance for $X_{B,A}$, including growth, sludge wastage and decay is:

$$V \frac{dX_{B,A}}{dt} = Y_A Q_i(S_{NH,i} - S_{NH,e}) - Q_s X_{B,A} - b_A X_{B,A} V \qquad (21)$$

Since $\hat{\mu}_A$ and Y_A are constants, equation **21** can be rearranged as:

$$\frac{d(\frac{\hat{\mu}_A X_{B,A}}{Y_A})}{dt} = \frac{\hat{\mu}_A Q_i(S_{NH,i} - S_{NH,e})}{V} - Q_s \frac{\hat{\mu}_A X_{B,A}}{Y_A V} - \frac{b_A \hat{\mu}_A X_{B,A}}{Y_A} \qquad (22)$$

In an activated sludge system, it is almost impossible to measure the mass concentration of nitrifiers ($X_{B,A}$). However, the nitrification capacity, or maximum rate of S_{NH} oxidation ($r_{m,NH}$), can be measured quite easily, for example with a respiration meter, by taking a sample of mixed liquor and spiking it with an excess of ammonia.

Applying equation **9** to nitrifiers, the nitrification capacity ($r_{m,NH}$) can be defined as:

$$r_{m,NH} = \frac{\hat{\mu}_A X_{B,A}}{Y_A} \qquad (23)$$

Combining equations **22** and **23** gives:

$$\frac{dr_{m,NH}}{dt} = \frac{\hat{\mu}_A \, Q_i(S_{NH,i}-S_{NH,e})}{V} - Q_s \frac{r_{m,NH}}{V} - b_A \, r_{m,NH} \qquad (24)$$

By introducing the cellular detention time ($\Theta_c = V/Q_S$) and considering b_A equal to zero, equation **24** can be rewritten as:

$$\frac{dr_{m,NH}}{dt} = \frac{\hat{\mu}_A \, Q_i(S_{NH,i}-S_{NH,e})}{V} - \frac{r_{m,NH}}{\Theta_c} \qquad (25)$$

For the model (equation **25**) verification, the evolution of nitrification capacity from each SBR cycle was compared with the simulation response.

MATERIALS AND METHODS

EXPERIMENTAL APPARATUS

In this study, two parallel SBRs were used: a pilot-plant SBR and a laboratory-scale SBR.

The pilot-plant SBR (Figure 1) consisted of a cylindric polystyrene vessel with a total volume of 1.3 m^3. The main equipment connected to the reactor were: three pneumatic valves, controlled by an electromagnetic device (to regulate the flow of influent, effluent and air supply); three float-level switches, to control fill and draw activities in the reactor; and a unit

for pH control (pump to dose NaOH solution). Probes for measuring temperature, pH and dissolved oxygen were installed in the reactor. On the bottom of the reactor, two porous tube diffusers (60 mm x 600 mm) connected to the air supply line were installed, which were also responsible for the mixing.

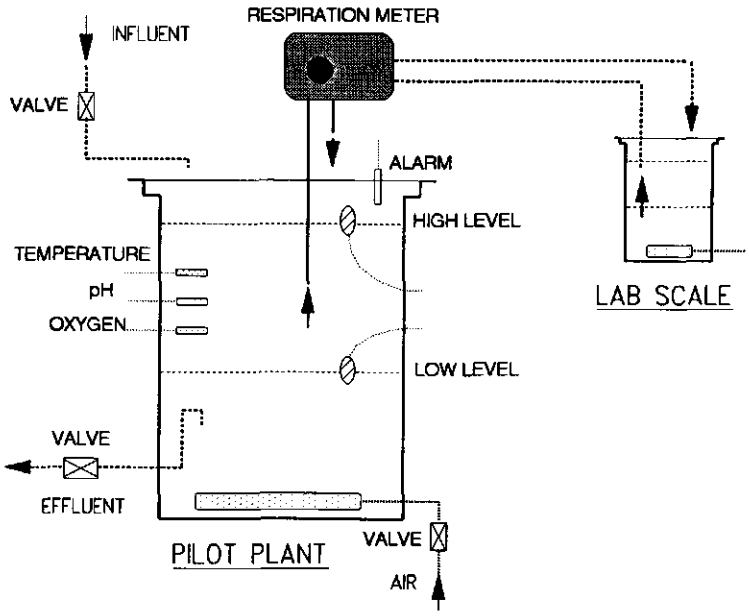


Figure 1. Schematic view of the pilot-plant and laboratory-scale SBRs used in the experiment.

The pilot-plant SBR was connected to a measuring and control system. The measuring system consisted of a respiration meter, an analog and digital input/output board (I/O board) and a personal computer. Data collection and reactor operation were carried out by the I/O system.

The respiration meter used was a continuous respiration meter (prototype of RA-1000, Manotherm, The Netherlands), which consisted of a closed respiration chamber through which activated sludge liquor was pumped. The inflow and outflow of dissolved oxygen concentration was measured using the same oxygen sensor, by periodically changing the flow direction through the chamber (Spanjers, 1993). The respiration rate was calculated from the mass balance of dissolved oxygen over the respiration chamber.

The laboratory-scale SBR (Figure 1) consisted of a reactor with a total volume of 10 l, which had probes similar to the pilot-plant SBR. This reactor was used for the experiment with nitrification inhibition with allylthiourea (ATU). In this way, the biomass in the pilot-plant SBR maintained its nitrification activity.

WASTEWATER

The influent used in the study was pre-settled domestic wastewater from Bennekom, The Netherlands. Average values of the concentrations are presented in Table I.

Table I. Wastewater characteristics. (March-May, 1991)

COMPONENT	CONCENTRATION	N# SAMPLES
COD (mg/l)	450 ± 142	22
COD_{vfa} (mg/l)	52 ± 17	10
TKN (mgN/l)	85 ± 20	12
S_{NH} (mgN/l)	65 ± 22	24

OPERATION OF THE PILOT-PLANT SBR

The pilot-plant SBR was in operation for nine weeks: the first two weeks with 8h cycles and the last seven weeks with 12h cycles. Each cycle had four periods: i) AERATED FILL; ii) AERATED REACT; iii) SETTLE of mixed liquor and iv) DRAW of effluent. These periods and the average timetable for the cycles are schematically presented in Figure 2. During the FILL period the reactor received 500 l of pre-settled domestic wastewater, and during the DRAW period, 500 l of effluent were drawn.

During the FILL and REACT periods, aerobic conditions were maintained and the pH was kept around 7.2. The temperature of the activated sludge fluctuated over the nine weeks of operation between 12 °C to 18 °C. The ratio between the sludge in the reactor at the end of the AERATED REACT period and the excess sludge discharged, is the cellular detention time (Θ_c). The average Θ_c during 8h cycles was 31 days and during 12h cycles, 76 days. Measurement of the respiration rate (r) started just after the reactor was fully filled.

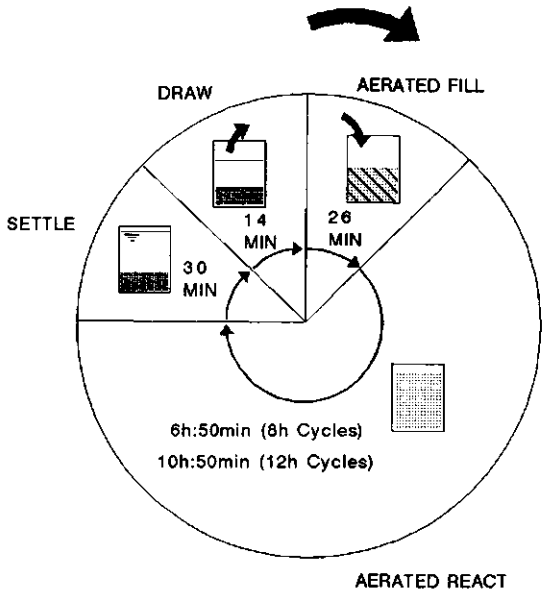


Figure 2. Timetable for the SBR cycle (8h and 12h).

EXPERIMENTS WITH THE LABORATORY-SCALE SBR

The experiments for nitrification inhibition were performed using the pilot-plant SBR and the laboratory-scale SBR. Using the same influent, biomass and operational procedure, r was measured in both reactors, starting at FILL. For nitrification inhibition, allylthiourea was used (Wood *et al.*, 1981).

The laboratory-scale reactor was manually operated. The reactor was filled with 8 l of mixed liquor at the end of the aeration period in the pilot-plant SBR. After settling, 4 l of effluent was drawn and 4 l of influent was added to the mixed liquor that remained in the reactor after settling. Allylthiourea (3 mg per litre) was added to the reactor.

Measurements from a cycle in the pilot-plant SBR with a low concentration of S_{NH} in the influent were also used to obtain information on carbon oxidation.

PARAMETER CALIBRATION

The parameters used in the models were either default values from the literature or calibrated by respirogram analysis. Using a simulation programme (Annex 1) written in SIMNON (Elmqvist *et al.*, 1990), the results from the differential equations system were compared with the measured respirogram. Parameters were calibrated by trial and error until the simulation came close to the measured values. The parameters used are presented in Table II, indicating where calibrated and default values were used.

Table II. Parameters

Parameter	Default value or calibration process	Reference
K_1	Respirogram analysis	Present study
K_2	Respirogram analysis	Present study
K_{NH}	0.7 mg N/l	Gee *et al.* (1990)
K_{NO2}	1.0 mg N/l	Gee *et al.* (1990)
K_S	20 mg COD/l	Henze *et al.* (1987)
$r_{m,NH}$	Respirogram analysis	Present study
$r_{m,NO2}$	Respirogram analysis	Present study
$r_{m,S}$	Respirogram analysis	Present study
Y_H	0.5	Henze *et al.* (1987)

ANALYSES

For monitoring the pilot-plant SBR operation and the experiment with the laboratory-scale SBR, some laboratory analyses were performed. During the cycles in which samples were taken, they were taken from the influent and the mixed liquor in the reactor, at different times. All the analyses were done according to APHA (1985).

Influent samples were analyzed for COD, nitrogen (S_{NH}, S_{NO2}, nitrate), suspended solids (MLSS) and volatile suspended solids (MLVSS), volatile fatty acids in the form of COD (COD_{VFA}) and Total Kjeldahl Nitrogen (TKN).

Mixed liquor samples were analyzed for suspended solids (MLSS), volatile suspended solids (MLVSS) and after filtration (Whatman glass microfibre 1 μm), for COD and nitrogen (S_{NH}, S_{NO2}, nitrate).

The data from the on-line surveillance of the reactor operation were stored, namely: real time, reactor temperature, dissolved oxygen in the reactor, dissolved oxygen in the respiration vessel, pH in the reactor and *r*.

RESULTS

CALIBRATION OF r_{end} MODEL

Calibration of r_{end} (equation **17**) is an important step in the calibration of the model for the respiration rate in one SBR cycle (equations **11-18**).

For calibration of equation **17**, the experiments with nitrification inhibition were used. In these experiments, the measurement of r started when the reactors were fed. In the graphs that are presented, time zero coincides with the beginning of FILL.

Since the experiments yielded similar results, only one experiment is presented. This experiment generated two respirograms: i) from the operation of the pilot-plant SBR (see Figure 3) and ii) from the operation of the laboratory-scale SBR with the addition of allylthiourea (see Figure 4).

For the interpretation of the respirograms shown in Figures 3 and 4, two assumptions were made. The first one is that because $S_{NH} >> K_{NH}$, ammonia oxidation can be modelled by a zero order equation, and as a result $r_{o,NH}$ and $r_{o,NO2}$ are constant. Therefore, according to equation **18**, the changes in respiration rate are due to a change in r_S and r_{end}. The second assumption is that after some time, when S_S is eliminated, the decrease in r is due to changes in r_{end}. To be able to interpret the respirogram it is essential to have information about the endogenous respiration rate. These considerations are schematically represented in Figure 3.

In Figure 3, it is assumed that the conditions $S_{NH} >> K_{NH}$ and S_S=0 are valid in the period between t=2 hours and t=6 hours. During this period, the measurements of r can be used to fit equation 17. As there are still constants $r_{o,NH}$ and $r_{o,NO2}$ in this period, we had to mathematically translate the equation to a lower position for it to also fit the final part of the respirogram. In this way, we were able to get r_{end}, as shown in Figure 3. It is also shown in Figure 3 that S_{NH} reached zero at the same time that a sharp drop in r was observed. This is a typical observation during pilot-plant SBR operation.

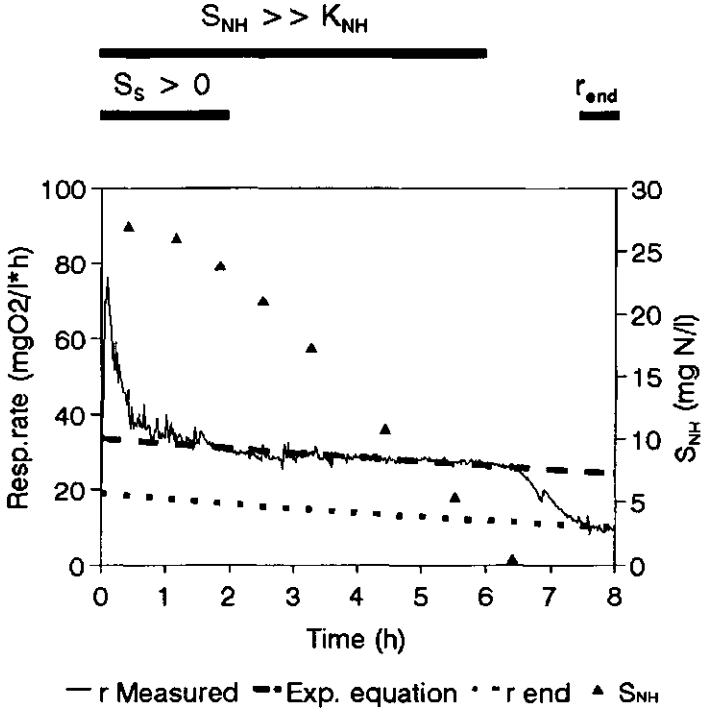


Figure 3. Respirogram from pilot-plant SBR during nitrification inhibition experiment, without nitrification inhibition.

Figure 4 shows r in the laboratory-scale reactor with nitrification inhibition, together with the

prediction of r_{end}, obtained from the model calibrated with the pilot-plant measurements (Figure 3). It can be seen that r_{end} better fits the curve after three hours, which is the time that nitrification inhibition was more effective.

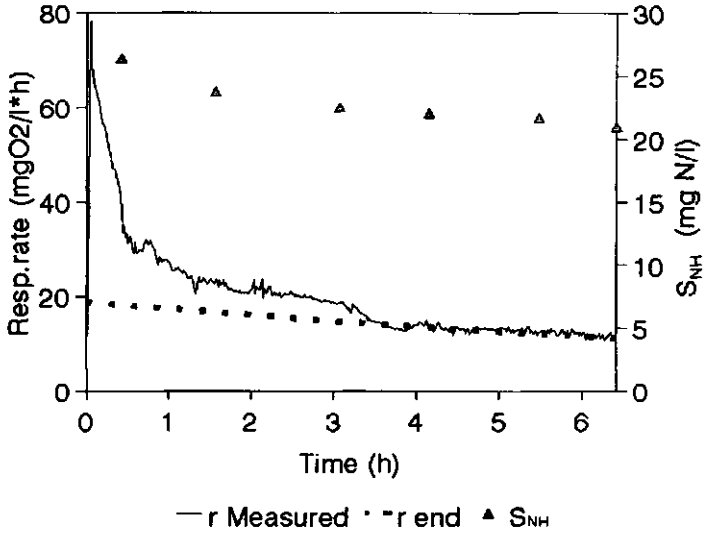


Figure 4. Respirogram from laboratory-scale SBR during nitrification inhibition experiment, with nitrification inhibition.

Figure 5 shows a respirogram from a cycle with low influent S_{NH}. Considering that after t=2 hours all S_{NH} and S_S had been oxidized, the model from equation **17** can be fit to the remaining part of the respirogram. Figure 4 also shows that the model fits the measurements well. In this case (Figure 5), a linear equation would also fit. However, based on all the results during the nine weeks of operation, we concluded that an exponential equation was better.

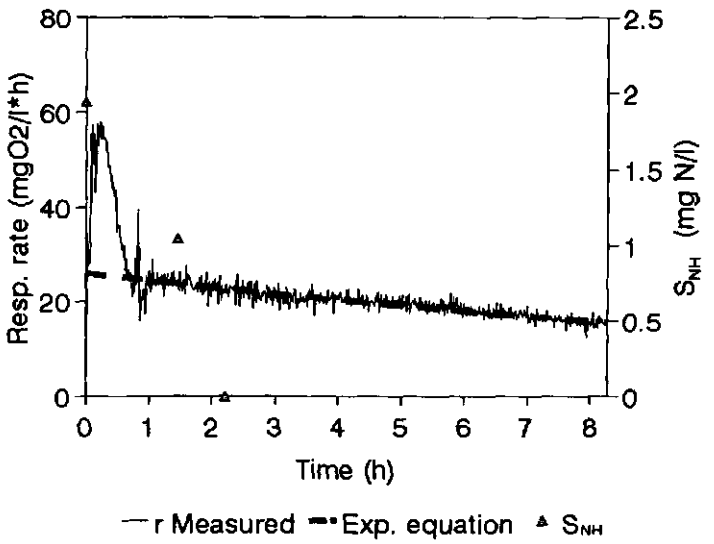


Figure 5. Respirogram from a cycle in the pilot-plant SBR with low S_{NH} influent.

Based on the experiments, we conclude that equation **17** can be used to model the endogenous respiration rate during a cycle of the SBR.

For determination of the parameters K_1 and K_2 in equation **17** for each cycle, the methodology is the same as that used in the nitrification inhibition experiment. The values for K_1 and K_2 were not constant during all the cycles. Though these parameters have no physical meaning, they seem to be fairly stable over a longer period. During the period with 8h cycles, the average value for K_1 was 25 ± 4 (mg l^{-1} h^{-1}) and for K_2 the average value was 0.13 ± 0.02 (h^{-1}). During the period with 12h cycles, the average value for K_1 was 30 ± 7 (mg l^{-1} h^{-1}) and for K_2 the average value was 0.12 ± 0.02 (h^{-1}).

VALIDATION OF THE MODEL FOR THE RESPIRATION RATE (r) DURING ONE CYCLE

By comparing the r measurements during one cycle with the model simulation from equations **11-18,** we determined the parameters ($r_{m,NH}$, $r_{m,NO2}$, $r_{m,S}$, K_1 and K_2) of the model. For the saturation values, K_{NH}=0.7, K_{NO2}=1.0 and K_S=20 were chosen. For the simulation, Y_H=0.5 was used. Determination of the parameter was done with all the respirograms produced during the whole period (8 and 12h cycles). Figure 6 shows a typical respirogram, along with the model response for r and r_{end}.

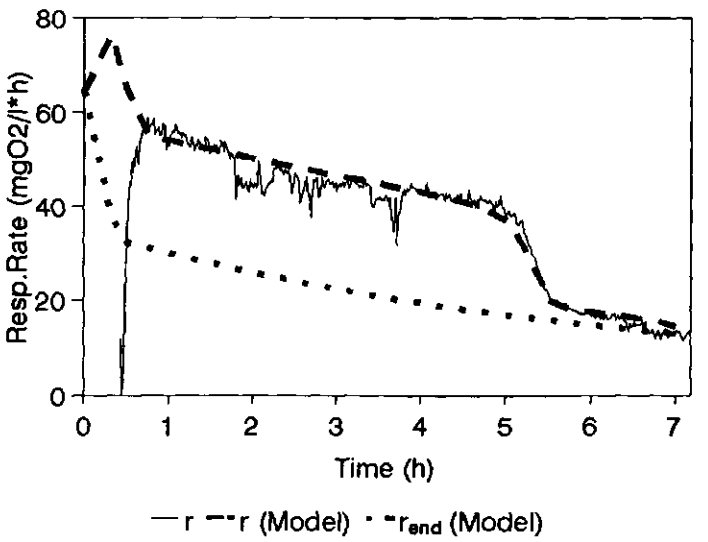


Figure 6. Measured respirogram from a cycle in the pilot-plant SBR together with the model response for r (equation **18**) and r_{end} (equation **17**).

To verify the model's prediction capability, the results from one cycle were compared with the model response with parameter values from the previous cycle. The variables to describe wastewater characteristics (S_S, S_{NH} and S_{NO2}) were taken from the cycle itself. Figure 7 shows an example of this prediction, with r predicted and measured, together with r_{end} prediction.

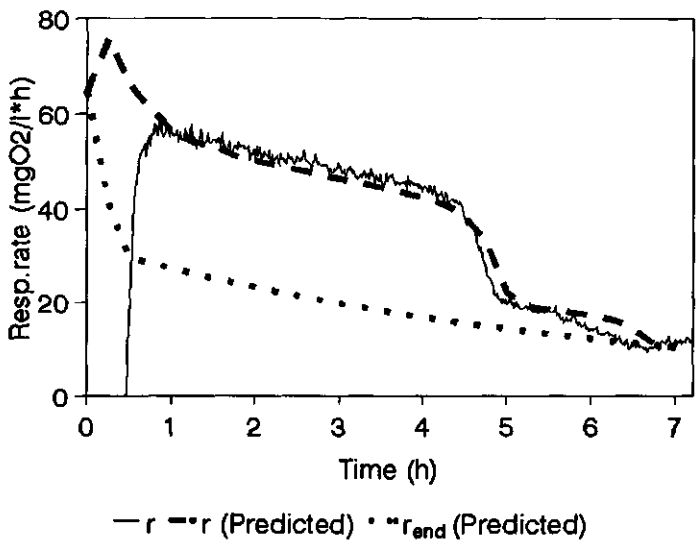


Figure 7. Measured respirogram from a cycle in the pilot-plant SBR together with model prediction for r (equation **18**) and r_{end} (equation **17**) with variables from a previous cycle.

By fitting the model equations **11-18** in each cycle, the maximum rate of S_{NH} oxidation ($r_{m,NH}$) that gave the best adjustment was determined. This rate gives the nitrification capacity of the system. The values found for each batch cycle are shown in Figure 8.

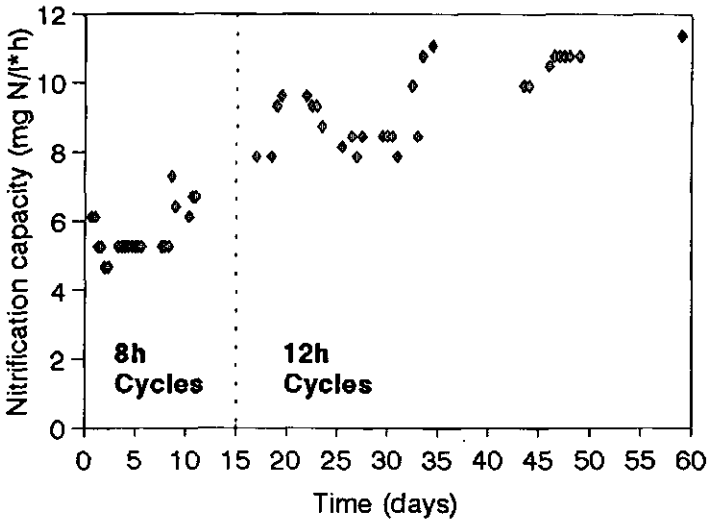


Figure 8. Values of nitrification capacity ($r_{m,NH}$) from each cycle, found by adjustment of equations **11-18** to r measurements.

VALIDATION OF THE MODEL FOR NITRIFICATION CAPACITY VARIATION IN AN SBR DURING LONG-TERM OPERATION

To apply equation **25**, some factors should be determined or assumed, viz. nitrogen load and $\hat{\mu}_A$. For nitrogen load determination, averaged values were used: $S_{NH,i}$ equal to 65 mg N/l and $S_{NH,e}$ equal to 0 mg N/l. For $\hat{\mu}_A$, the value of 0.10 d^{-1} was used, together with the values 0.06 and 0.14 d^{-1} as boundary. Dold *et al.* (1980) reported a value of 0.21 d^{-1} for settled wastewater. Using their equation for the effect of temperature on $\hat{\mu}_A$, we can calculate a value of 0.1 d^{-1} for the temperature, as was in our experiment. The Θ_c during the period with 8h cycles was 31 days and with 12h cycles, 76 days.

Figure 9 shows the results from the equation **25** model for $r_{m,NH}$ variation in an SBR during long-term operation, together with the values of $r_{m,NH}$ determined from each batch cycle, as presented in Figure 8.

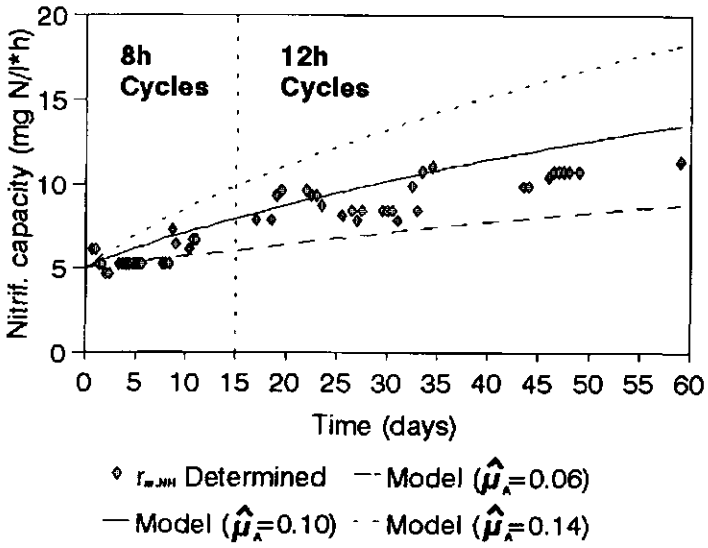


Figure 9. Values of nitrification capacity ($r_{m,NH}$) from each cycle (shown in Figure 8) together with the model for nitrification capacity variation in an SBR during long-term operation (equation **25**).

DISCUSSION

Two models have been validated: a model to simulate the respiration rate (r) during one SBR

cycle and a model to simulate the variation of the nitrification capacity ($r_{m,NH}$) during long-term operation.

In the model for the respiration during one cycle, the nitrification, the oxidation of readily biodegradable matter, and the endogenous respiration were considered. This study has shown that the oxygen consumption for the oxidation of readily biodegradable matter is small compared with the oxygen used for nitrification. Considering COD_{vfa} as the readily biodegradable matter, the respirograms have shown that only a small amount of oxygen is used for that oxidation process. The oxygen consumption during the cycle is mostly related to nitrification and endogenous respiration.

The results in Figure 6 indicate that after calibration the simulation is a suitable representation of the measured values. The results can thus be explained by the three modelled processes, viz. nitrification, oxidation of readily biodegradable matter and endogenous respiration.

The model for respiration rate during one SBR cycle has an important sub-model for the endogenous respiration rate (r_{end}), which has also been validated. For the system under study, the exponential equation describing the endogenous respiration rate during an SBR cycle matched well with the measurements, showing that this type of equation can be used for r_{end}. However, a better theoretical base is necessary for this equation. The idea that r_{end} is related to the oxidation of S_S produced by hydrolysis of X_S, lysis of dead cells and the release of substrate for maintenance should be further developed. With a model equation that incorporates the transformation of X_S and cell material into S_S, it is possible to have a full theoretical dynamic model to describe r in an SBR. In a nitrifying SBR, the sum of $r_{o,NH}$ and

$r_{o,N02}$ in equation **18** is much more significant then r_{end} in the total respirogram. Thus, considerable fluctuations in r_{end} do not result in great fluctuation of the total r. In this way, a good variable measurement, such as X_S in the influent and the decay rate, can give a good model response even in a system where the nitrification respiration rate is not as relevant as in the present system.

In general, the respiration rate model for an SBR during one cycle gives a good prediction response when the parameters from the previous cycle are fitted into the equations. This is because there is little deviation between successive cycles. The main difficulty is getting information about influent variables, such as S_S and S_{NH}. One way to solve this is to use the measurement of BOD_{st}, as described by Spanjers (1993), in order to have information on the influent characteristic. It is also possible to measure S_{NH} with an ammonia probe.

The model predictions are effective for control purposes, especially for controlling the air-flow rate. The model predictions are also useful for predicting when the ammonia will be completely oxidized. The model projection, therefore, can also be used to decide when a new cycle can start.

Monitoring combined with model prediction can also be practical for control purposes. For on-line nitrification control in an SBR during one cycle, model equation **18** can be a useful tool. By using monitored respiration rates, the end of the S_{NH} oxidation period can be assessed in two ways. The first way is related to the sharp decrease in r. The second way is by using r_{end}. With the K_1 and K_2 values from the previous cycle, we can predict r_{end} during the cycle. As soon as the prediction of r_{end} equals the measured r, we know that S_{NH} has become zero.

A typical respirogram first shows a stage with a high r value. The end of this period can be clearly seen by a sharp decrease in r values until they reach some stabilization in another stage. This drop is clearly associated with a low level of S_{NH} present in the solution. With this information, the end of S_{NH} oxidation can generally be predicted. However, in some situations, S_{NO2} can be present in the solution and require oxidizing to achieve full nitrification. To predict the end of this second step, r_{end} is an important variable. When the r values in the respirogram reach what is expected to be r_{end}, it means that the system has achieved full nitrification.

The model for the variation of the nitrification capacity during long-term operation is used to predict changes in nitrification capacity after loading changes. This model is useful in designing the sludge loading rate and/or the sludge wastage rate.

It can be seen from Figure 8 that the values for nitrification capacity ($r_{m,NH}$) increased with time during long-term operation. It can be concluded that the net production of nitrifiers was higher then the nitrifiers wasted. Looking to the average cellular detention time (Θ_c) (31 days for the 8h cycles and 76 days for the 12h cycles), an accumulation of nitrifiers can be expected. With model simulation we could calculate the steady-state nitrification capacity for these sludge detention times with μ_A=0.1 d^{-1}. It would be 12.5 mg N/l*h during the period with 8h cycles and 20.5 mg N/l*h during the period with 12h cycles.

The model for nitrification capacity variation in an SBR during long-term operation (equation **25**), as can be seen in Figure 9, gives a good response for the nitrification capacity variation trend, but cannot explain the sharp fluctuations observed over a short period of time. This

suggests that even when present, not all of the autotrophic biomass are active.

CONCLUSIONS

The model for the respiration rate (r) during one cycle, including nitrification, oxidation of readily biodegradable matter and endogenous respiration (equations **11-18**) gives a good simulation of the measured respiration rate.

A simulation with this model using parameters calculated from the previous cycle, together with the variables S_{NH}, S_{NO2} and S_S from the influent wastewater, gives a good prediction of the total oxygen consumption and distribution during one cycle.

The endogenous respiration rate (r_{end}) in a nitrifying SBR treating domestic wastewater can be modelled with the proposed exponential equation (equation **17**).

The model for long-term variation of nitrification capacity ($r_{m,NH}$) in an SBR (equation **25**) gives a good response for the nitrification capacity variation trend. However, it cannot explain the nitrification capacity fluctuation over a short period of time.

NOMENCLATURE

Θ_c	cellular detention time (time)
μ	specific growth rate (time^{-1})
$\hat{\mu}$	maximum specific growth rate (time^{-1})
μ_A	specific growth rate for autotrophic biomass (time^{-1})
$\hat{\mu}_A$	maximum specific growth rate for autotrophic biomass (time^{-1})
ATU	allylthiourea
b_A	decay coefficient for autotrophic biomass (time^{-1})
COD	chemical oxygen demand (mass volume^{-1})
COD_{vfa}	volatile fatty acids as COD (mass volume^{-1})
$dX_{B,A}/dt$	rate of autotrophic biomass growth (mass volume^{-1} time^{-1})
K	half-saturation coefficient, substrate concentration at one-half the maximum growth rate (mass volume^{-1})
K_1	empirical constant (mass volume^{-1} time^{-1})
K_2	empirical constant (time^{-1})
K_{NH}	half-saturation coefficient for S_{NH} oxidation (mass volume^{-1})
K_{NO2}	half-saturation coefficient for S_{NO2} oxidation (mass volume^{-1})
K_S	half-saturation coefficient for S_S degradation (mass volume^{-1})
MLSS	total suspended solids (mass volume^{-1})
MLVSS	total volatile suspended solids (mass volume^{-1})
OUR	oxygen uptake rate (mass volume^{-1} time^{-1})
Q_i	average influent flow in SBR cycle (volume time^{-1})

Q_s	average sludge discharge flow in SBR cycle (volume time^{-1})
r	respiration rate (mass volume^{-1} time^{-1})
r_{end}	endogenous respiration rate (mass volume^{-1} time^{-1})
r_g	rate of microorganism growth (mass volume^{-1} time^{-1})
$r_{g,A}$	growth rate of nitrifiers (mass volume^{-1} time^{-1})
r_m	maximum rate of substrate utilization (mass volume^{-1} time^{-1})
$r_{m,NH}$	maximum rate of S_{NH} oxidation or nitrification capacity (mass volume^{-1} time^{-1})
$r_{m,NO2}$	maximum rate of S_{NO2} oxidation (mass volume^{-1} time^{-1})
$r_{m,S}$	maximum rate of S_S consumption (mass volume^{-1} time^{-1})
r_{NH}	rate of S_{NH} oxidation (mass volume^{-1} time^{-1})
r_{NO2}	rate of S_{NO2} oxidation (mass volume^{-1} time^{-1})
$r_{o,NH}$	respiration rate for S_{NH} oxidation (mass volume^{-1} time^{-1})
$r_{o,NO2}$	respiration rate for S_{NO2} oxidation (mass volume^{-1} time^{-1})
$r_{o,S}$	respiration rate for S_S oxidation (mass volume^{-1} time^{-1})
r_S	rate of S_S consumption (mass volume^{-1} time^{-1})
r_{su}	rate of substrate utilization (mass volume^{-1} time^{-1})
S	concentration of growth-limiting substrate in solution (mass volume^{-1})
SBR	Sequencing Batch Reactor
S_{NH}	soluble ammonia nitrogen concentration (mass volume^{-1})
$S_{NH,e}$	effluent S_{NH} from SBR (mass volume^{-1})
$S_{NH,i}$	influent S_{NH} into the SBR (mass volume^{-1})
S_{NO2}	soluble nitrite nitrogen concentration (mass volume^{-1})
S_S	readily biodegradable matter concentration (mass volume^{-1})

t	time of reaction (time)
TKN	Total Kjeldahl Nitrogen (mass volume^{-1})
V	reactor volume (volume)
X_B	concentration of microorganisms (mass volume^{-1})
$X_{B,A}$	concentration of autotrophic microorganisms (mass volume^{-1})
X_S	slowly biodegradable matter (mass volume^{-1})
Y	yield (mass mass^{-1})
Y_A	yield for autotrophic biomass (mass mass^{-1})
Y_H	yield for heterotrophic biomass (mass mass^{-1})

REFERENCES

APHA (1985). *Standard methods for the examination of water and wastewater.* 16th edition. American Public Health Association, Washington, DC.

Dennis, W.W. and Irvine, R.L. (1979). Effect of fill: reactor ratio on sequencing batch biological reactors. *J. Water Pollut. Control Fed.* **51**:255-263.

Dold, P.L., Ekama, G.A. and Marais, G.v.R. (1980). A general model for the activated sludge process. *Prog. Wat. Tech.* **12**:47-77.

Ekama, G.A. and Marais, G.v.R. (1979). Dynamic behaviour of the activated sludge process. *J. Water Pollut. Control Fed.* **51**:534-556.

Elmqvist, H., Åström, K.J., Schönthal, T. and Wittenmark, B. (1990). *Simnon - User's guide for MS DOS computers, V. 3.0.* SSPA Systems, Box 24001, S-400 22 Göteborg, Sweden.

Gee, C.S., Suidan, M.T. and Pfeffer, J.T. (1990). Modelling of nitrification under substrate-inhibiting conditions. *J. of Envir. Engrg.*, ASCE, **116**:18-31.

Gujer, W. (1980). The effect of particulate organic material on activated sludge yield and oxygen requirement. *Prog. Wat. Tech.* **12**:79-95.

Haandel, A.C. v., Ekama, G.A. and Marais, G.v.R. (1981). The activated sludge process-3. Single-sludge denitrification. *Wat. Res.* **15**:1135-1152.

Henze, M., Grady, C.P.L. Jr., Gujer, W., Marais, G.v.R. and Matsuo T. (1987). A general model for single-sludge wastewater treatment systems. *Wat. Res.* **21**:505-515.

Herbert, D. (1958). Some principles of continuous culture. In *Recent Progress in Microbiology* **3**:381-396. G. Tunevall (ed.) (Almquist and Winksell, Stockholm) VII Intern. Congr. for Microbiology.

Irvine, R.L. and Busch, A.W. (1979). Sequencing batch biological reactors - an overview. *J. Water Pollut. Control Fed.* **51**:235-243.

Jones, W.L., Wilderer, P.A. and Schroeder, E.D. (1990). Operation of a three-stage SBR system for nitrogen removal from wastewater. *Res. J. Water Pollut. Control Fed.* **62**:268-

274.

Oles, J. and Wilderer, P.A. (1991). Computer aided design of sequencing batch reactors based on the IAWPRC activated sludge model. *Wat. Sci. Tech.* **23**:1087-1095.

Ossenbruggen, P.J., Spanjers, H., Aspergren, H. and Klapwijk, A. (1991). Designing experiments for model identification of the nitrification process. *Wat. Sci. Tech.* **24**:9-16.

Padukone, N. and Andrews, G.F. (1989). A simple, conceptual mathematical model for the activated sludge process and its variants. *Wat. Res.* **23**:1535-1543.

Patry, G.G. and Chapman, D. (eds.) (1989). *Dynamic modelling and expert-systems in wastewater engineering.* Lewis Publishers, Inc., Michigan, USA.

Spanjers, H. (1993). Respirometry in activated sludge. PhD. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Spanjers, H. and Klapwijk, A. (1990). On-line meter for respiration rate and short-term biochemical oxygen demand in the control of the activated sludge process. *Advances in Water Pollution Control*, Proc. 5th IAWPRC Workshop on Instrumentation, Control and Automation of Water and Wastewater Treatment and Transport Systems, 26 July - 3 August, Yokohama and Kyoto, Japan, pp. 67-77.

Suschka, J. and Ferreira, E. (1986). Activated sludge respirometric measurements. *Wat. Res.*

20:137-144.

Wood, L.B., Hurley, B.J.E. and Matthews, P.J. (1981). Some observations on the biochemistry and inhibition of nitrification. *Wat. Res.* **20**:137-144.

CHAPTER 3

MODELLING RESPIRATION RATE AND NITRATE REMOVAL IN A NITRIFYING/DENITRIFYING SBR TREATING DOMESTIC WASTEWATER

3 MODELLING RESPIRATION RATE AND NITRATE REMOVAL IN A NITRIFYING/DENITRIFYING SBR TREATING DOMESTIC WASTEWATER

SUMMARY

This investigation aims to present a mathematical model for the behaviour of respiration rate and nitrate removal in an activated sludge Sequencing Batch Reactor (SBR) with nitrification, denitrification and carbon oxidation. This model is based on the response of the respiration rate (r) measured during nitrification and carbon oxidation, and the nitrate removal rate during the post-denitrification period.

For model validation, an SBR pilot plant (1 m^3) receiving domestic wastewater was operated for three months, and the results were compared with the model. The respiration rate was used to calibrate several parameters of the model. The simulation values matched well with the measured respiration rate and nitrate removal. The model was able to predict the respiration rate and denitrification in one cycle with parameters taken from the previous cycle. Parameter changes were followed during long-term operation, and significant variations were observed, too complex to be predicted. It can be concluded that r is a good parameter for on-line monitoring of an activated sludge SBR with nitrification/denitrification processes.

KEY WORDS

Sequencing Batch Reactor (SBR); nitrification; denitrification; respiration rate; modelling; domestic wastewater.

INTRODUCTION

Nitrification followed by denitrification is a widespread process for biological nitrogen removal from wastewaters. One of the reasons for implementing nitrogen elimination in wastewater treatment is to control eutrophication, as excess nitrate promotes the formation of algal blooms in the receiving water bodies.While nitrification occurs in an aerobic environment, denitrification is carried out by facultative heterotrophic bacteria in an anoxic environment. Denitrifying microorganisms in activated sludge are part of the heterotrophic biomass that normally use oxygen as an electron acceptor for the oxidation of organic substrates (Henze, 1991). However, as the dissolved oxygen concentration decreases, denitrifiers can use nitrate, if it is available, as an alternative electron acceptor (Klapwijk, 1978). There is evidence that the pathway for the transfer of electrons from the organic substrate to the final electron acceptor is similar for oxygen and nitrate (Christensen and Harremöes, 1977). And McClintock *et al.* (1988) showed that COD removal efficiencies were nearly equal.

The recent requirements for low concentrations of nitrogen and phosphate in the effluent of

wastewater treatment plants has given further importance to denitrification processes. In systems for biological P and N removal, Siebritz *et al.*(1983) showed that the presence of nitrate in the influent for a subsequent anaerobic step can limit or even stop the biological P removal.

On-line control of wastewater treatment plants is important not only from an economic standpoint but also for achieving good effluent characteristics. The complexity of the most recently developed biological treatment systems, along with the new effluent standards, requires better and faster response control systems. With respect to denitrification, the oxidation reduction potential (ORP) was used as an on-line control variable. However, it must be combined with other control systems for the complete treatment system (Charpentier *et al.*, 1987; Koch and Oldham, 1985).

Models allow for the development of strategies for on-line control. There are presently models to describe nitrification-denitrification in activated sludge processes (Di Pinto *et al.*, 1990; Clayton *et al.*, 1991). One general model that includes nitrification-denitrification is the model proposed by the IAWPRC Task Group (Henze *et al.*, 1987), however, it is based on variables that are difficult to be monitored on-line. The respiration rate was recognized as a useful variable for testing the behaviour of activated sludge models (Spanjers, 1993). The use of a mathematical model with respiration rate as an important variable to describe nitrification and carbon oxidation in a Sequencing Batch Reactor is presented in Chapter 2 of this thesis.

Based on the idea that the pathways for oxygen and nitrate utilization are similar for denitrifiers, the model for respiration rate with aerobic carbon oxidation, presented in Chapter

2, can also be used for the denitrification process. Regarding the kinetics involved, it was demonstrated by van Haandel *et al.* (1981) that in a single sludge denitrification system, with the anoxic volume fraction less than 40%, the mass production of sludge per mass COD removed does not appear to be significantly different than that generated in a completely aerobic system. Klapwijk (1978) showed that the kinetics for denitrifying activated sludge is similar to the kinetics for aerobic activated sludge. It can be inferred that the yield and decay coefficients are not significantly affected and, therefore, a model for organic oxidation in an aerobic environment can be used in an anoxic environment with the same parameters.

However, not all heterotrophic microorganisms are able to carry out denitrification. Denitrifiers are a fraction of the total heterotrophic biomass. Some studies give information about the fraction of denitrifiers in the heterotrophic biomass in activated sludge systems. Henze (1987) presented theories for estimating the fraction of denitrifiers. In installations without special measures to promote denitrification, Klapwijk (1978) concluded that denitrifiers represent 20-40% of the heterotrophic bacteria. Kristensen *et al.* (1992) estimated that this fraction was 15-20%. Wilderer *et al.* (1987) used a fraction of denitrifiers of 20% in a model to describe denitrification. In sludges from nitrogen removal plants, Kristensen *et al.* (1992) estimated that the fraction of denitrifiers to heterotrophs was in the range of 41-73%.

The symbols used in the text and equations of this thesis are employed in the same way as in the Activated Sludge Model No. 1 (Henze *et al.*, 1987) to describe either the compound or its concentration (see Nomenclature).

In the Activated Sludge Model No. 1 (Henze *et al.*, 1987), the parameters η_g and η_h are used to differentiate the processes of denitrification during oxidation of readily biodegradable matter (S_S) and during oxidation of the products of slowly biodegradable matter's hydrolysis. The parameter η_g is a correction factor which adjusts for either the change in the maximum specific growth rate for heterotrophic biomass associated with anoxic conditions, or for the fact that only part of the biomass can denitrify. The parameter η_h is a correction factor which adjusts for the difference in the rate of the hydrolysis of slowly biodegradable organic matter under aerobic and anoxic conditions. It has been observed that under anoxic conditions, the hydrolysis is slower then under aerobic conditions.

In the present study, we have assumed that only a portion of the heterotrophic biomass (F_{den}) can denitrify. It has also been assumed that the fraction of denitrifiers has a similar influence on the nitrate removal rate with or without S_S. The fraction of denitrifiers (F_{den}) is determined as the ratio between the anoxic equivalent endogenous respiration rate ($r_{end,den}$) and the endogenous respiration rate (r_{end}). The anoxic equivalent endogenous respiration rate ($r_{end,den}$) is the removal rate of nitrate expressed in oxygen equivalent (1 mg NO_3-N is 2.86 mg O_2 equivalent) under anoxic conditions. According to our assumptions, the ratio of the anoxic equivalent rate of S_S oxidation ($r_{o,S,den}$) to the respiration rate for S_S oxidation ($r_{o,S}$) is equal to F_{den}.

The model for the respiration rate during nitrification and carbon oxidation in an SBR, presented in Chapter 2 of this thesis, was also used for the nitrifying/denitrifying SBR. During the anoxic periods, when no oxygen is available and nitrate is present, $r_{o,S,den}$ and $r_{end,den}$ occur, rather than $r_{o,S}$ and r_{end}. Figure 1 shows a schematic representation of these considerations for

an SBR with aerobic and aerobic/anoxic cycles.

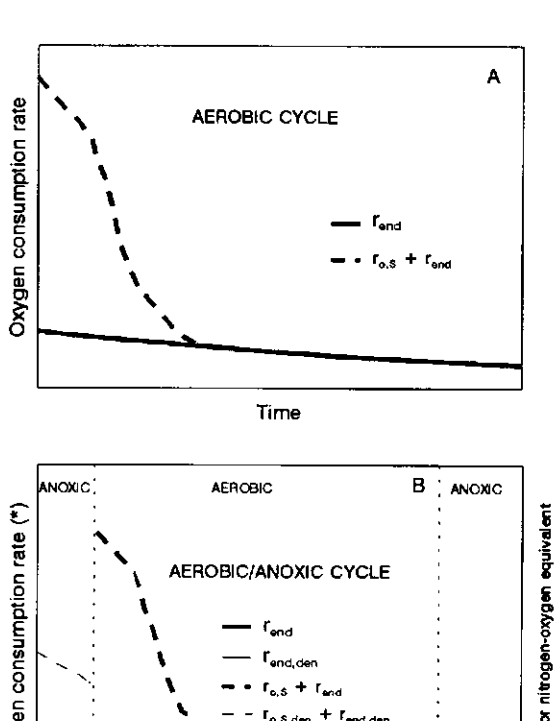


Figure 1. Schematic representation of oxygen consumption rate in an SBR for S_S oxidation and endogenous respiration versus time. (A) Totally aerobic cycle. (B) Anoxic+aerobic+anoxic cycle, with the nitrogen-oxygen equivalent consumption during the anoxic segments.

The objectives of this study are: i) to present a dynamic model for respiration rate and nitrate removal in a nitrifying/denitrifying SBR, ii) to predict the behaviour of respiration rate and nitrate concentration in a cycle using model parameters calibrated in the previous run, iii) to follow parameter changes during long-term operation.

As was proposed in Chapter 2, for the nitrification capacity ($r_{m,NH}$), the parameter change, as a result of growth and sludge wastage, was compared with the model for variation during long-term operation:

$$\frac{dr_{m,NH}}{dt} = \frac{\hat{\mu}_A \, Q_i(S_{NH,i}-S_{NH,e})}{V} - Q_S \frac{r_{m,NH}}{V} \qquad (1)$$

To validate the model, a pilot-plant SBR was operated continuously for three months in such a way as to achieve the processes of carbon oxidation, nitrification, and both pre- and post-denitrification. During this period, measurements of respiration rate were performed on-line for process assessment.

The model for respiration rate and nitrate removal describes the respiration rate during the aerobic period and the nitrate variation during the anoxic periods. Based on the ammonia and nitrate load to the SBR, parameters are calibrated from the measured respiration rate during the aerobic period in the cycle itself and from the post-denitrification rate from a previous cycle. For some parameters, default values are used.

Using the models to predict the SBR processes, the respiration rate during the aerobic period and the nitrate removal during the anoxic periods were simulated, using all parameters from

the previous cycle and the actual ammonia and nitrate load rates.

During operation of an SBR, when there is an anoxic period just after feeding, it is very difficult to get a good measurement of the respiration rate for S_S oxidation ($r_{o,S}$) during the aerobic period, due to the almost complete S_S consumption during the anoxic period. Therefore, an experiment was performed using a laboratory-scale batch reactor parallel to the pilot plant, to verify the acceptability of the value adopted for the maximum rate of S_S consumption ($r_{m,S}$). By adding acetate to the parallel reactor during post-denitrification, the nitrate removal model response was assessed.

The calibrated values in each cycle for the empirical constants K_1 and K_2, the nitrification capacity ($r_{m,NH}$) and the fraction of denitrifiers in the heterotrophic biomass (F_{den}) were plotted versus time. This made it possible to follow the parameter changes during long-term operation.

BACKGROUND FOR MODELLING RESPIRATION RATE AND NITRATE REMOVAL RATE

Depending on the electron acceptor present in a nitrifying/denitrifying SBR, two different environmental conditions can be defined. Therefore, the model for a nitrifying/denitrifying SBR has two different and complementary sub-models: i) for aerobic conditions and ii) for anoxic conditions.

RESPIRATION RATE (r) DURING THE AEROBIC PERIOD

According to the model presented in Chapter 2, the removal rates for S_{NH} and S_S are:

$$r_{NH} = r_{m,NH} \frac{S_{NH}}{K_{NH} + S_{NH}} \quad (2)$$

$$r_S = r_{m,S} \frac{S_S}{K_S + S_S} \quad (3)$$

The oxidation rates of S_{NH} and S_S can be related to the rate of oxygen consumption as:

$$r_{o,NH} = 4.57\ r_{NH} \quad (4)$$

$$r_{o,S} = (1 - Y_H)\ r_S \quad (5)$$

As shown in Chapter 2, during one cycle in an aerobic SBR, r_{end} can be represented well by:

$$r_{end} = K_1 \exp(-K_2\ t) \quad (6)$$

Here, t is zero at the start of each SBR cycle.

The model proposed in Chapter 2 to represent r in an aerobic SBR with nitrification and carbon oxidation is:

$$r = r_{o,S} + r_{end} + r_{o,NH} \quad (7)$$

This model is also used for the aerobic period of an aerobic/anoxic SBR.

RATE OF NITRATE REDUCTION (r_{NO3}) DURING THE ANOXIC PERIOD

Denitrification can be defined as a biological redox reaction, where nitrate is converted to nitrite and then reduced to nitrogen gas. Most of the denitrifying microorganisms involved are heterotrophic bacteria. The electron donor is biodegradable organic material and the redox reaction takes place in an anoxic environment.

In an SBR under aerobic conditions, the use of oxygen by the heterotrophic microorganisms can be modelled by the following equation:

$$r = r_{o,S} + r_{end} \quad (8)$$

As mentioned before, previous studies have suggested that the facultative biomass responsible for the denitrification process uses oxygen or oxidized nitrogen as alternatives for the same path (Christensen and Harremöes, 1977; Klapwijk, 1978; van Haandel *et al.*, 1981). This leads to the conclusion that the kinetics for organic carbon oxidation, for this group of organisms, are similar in aerobic and anoxic environments.

Based on the previous assumptions for F_{den}, as the fraction of denitrifiers in the heterotrophic

biomass, $r_{o,S,den}$ and $r_{end,den}$ can be defined as:

$$r_{o,S,den} = F_{den}\, r_{o,S} \tag{9}$$

$$r_{end,den} = F_{den}\, r_{end} \tag{10}$$

The anoxic equivalent respiration rate (r_{den}), the nitrate removal expressed in oxygen equivalent (1 mg NO_3-N is 2.86 mg O_2 equivalent), can be defined as the respiration rate the denitrifiers would have if they had used oxygen. Using equations **8**, **9** and **10,** it can be written as:

$$r_{den} = F_{den}\,(r_{o,S} + r_{end}) \tag{11}$$

Using the equivalent factor of 2.86 mg O_2 per mg nitrate reduced to nitrogen gas, r_{den} can be expressed as a function of the rates of nitrate reduction (r_{NO3}):

$$r_{den} = 2.86\, r_{NO3} \tag{12}$$

Combining equations **11** and **12** gives:

$$r_{NO3} = \frac{1}{2.86} F_{den}\,(r_{o,S} + r_{end}) \tag{13}$$

In an SBR with the following conditions: i) readily biodegradable matter unavailable, ii) no nitrification and iii) nitrite not present, equation **13** can be rewritten as:

$$F_{den} = \frac{2.86\ r_{NO3}}{r_{end}} \qquad (14)$$

Hence, F_{den} can be determined by the relationship between r_{NO3} and r_{end}. The first rate can be determined by laboratory analyses and the second by respirometry.

Equation **13** can predict r_{NO3} using F_{den} and information from respirometry. Therefore, in this study, equations **2-7** were applied during the aerobic period and equation **13** applied during the anoxic period, to describe the oxygen respiration rate (or anoxic equivalent respiration rate) during one cycle in an SBR with activated sludge under conditions of nitrification, carbon oxidation and denitrification. The variation in the nitrification capacity was modelled by equation **1**.

MATERIALS AND METHODS

PILOT-PLANT SBR

The pilot-plant SBR (Figure 2) consisted of a cylindrical polystyrene vessel with a total volume of 1.3 m^3. The main equipment connected to the reactor were: three pneumatic valves, controlled by an electromagnetic device (for influent, effluent and air supply commands); three float-level contactors, used to control fill and draw activities in the reactor; and a unit

for pH control (pump to dose NaOH solution). Probes for measuring temperature, pH and dissolved oxygen were installed in the reactor. On the bottom of the reactor, two porous tube diffusers (60 mm x 600 mm) connected to the air supply line were installed (also responsible for mixing during aeration). A propeller was connected to a stirring motor, to mix when the reactor had no aeration.

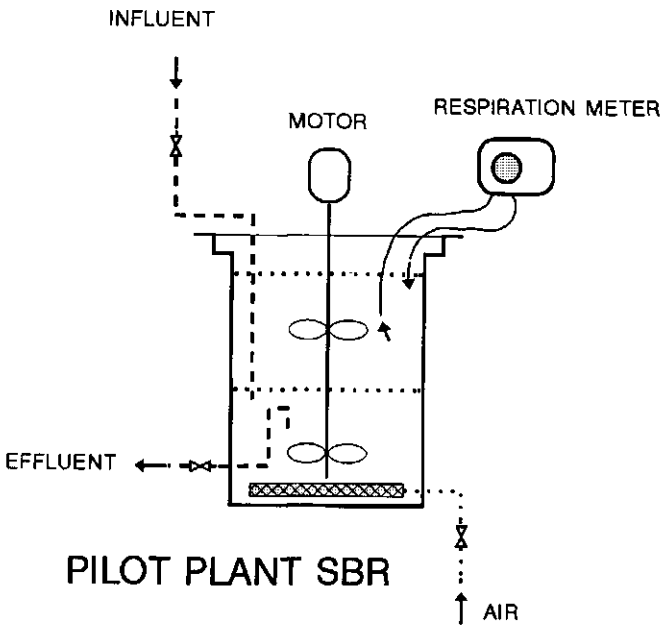


Figure 2. Schematic view of the SBR pilot plant used in the experiment.

The pilot-plant SBR was connected to a measuring and control system which consisted of a respiration meter, an analog and digital input/output board (I/O board) and a personal computer.

The continuous respiration meter (prototype of the RA-1000, Manotherm, The Netherlands) consisted of a closed respiration vessel through which activated sludge liquor was pumped. The inflow and outflow dissolved oxygen concentration was measured by the same oxygen sensor, by periodically changing the flow direction (Spanjers, 1993).

OPERATION

The pilot-plant SBR was operated for three months, with cycles of 12 hours, each cycle with seven periods. Figure 3 schematically shows the timetable for these periods. The periods are: i) MIXED FILL; ii) MIXED REACT I; iii) AERATED REACT I; iv) MIXED REACT II; v) AERATED REACT II; vi) SETTLE; and vii) DRAW. At the beginning of the cycle, the reactor received 500 l pre-settled domestic wastewater and at the end 500 l of effluent was drawn. The influent used was pre-settled domestic wastewater (Bennekom Municipal Treatment Plant, The Netherlands; Table I).

During the cycles, the pH was maintained at around 7.2 by dosing NaOH solution. Excess sludge was discharged during the AERATED REACT period at a rate corresponding to 1/15 of the total reactor volume per day (66.7 l per day). During the AERATED REACT periods, aerobic conditions were maintained in the reactor, with dissolved oxygen concentrations above 2 mg/l. The temperature of the activated sludge varied during the three months of operation from 10.5° C to 15° C, due to variation in the influent and air temperature. The average MLSS and MLVSS were 2.10 ± 0.40 g/l and 1.79 ± 0.32 g/l, respectively.

Table I. Wastewater characteristics (averaged values).

COMPONENT	CONCENTRATION	N# SAMPLES
COD (mg/l)	389 ± 102	39
COD_{vfa} (mg/l)	46 ± 15	22
TKN (mgN/l)	82 ± 21	36
S_{NH} (mgN/l)	62 ± 18	39

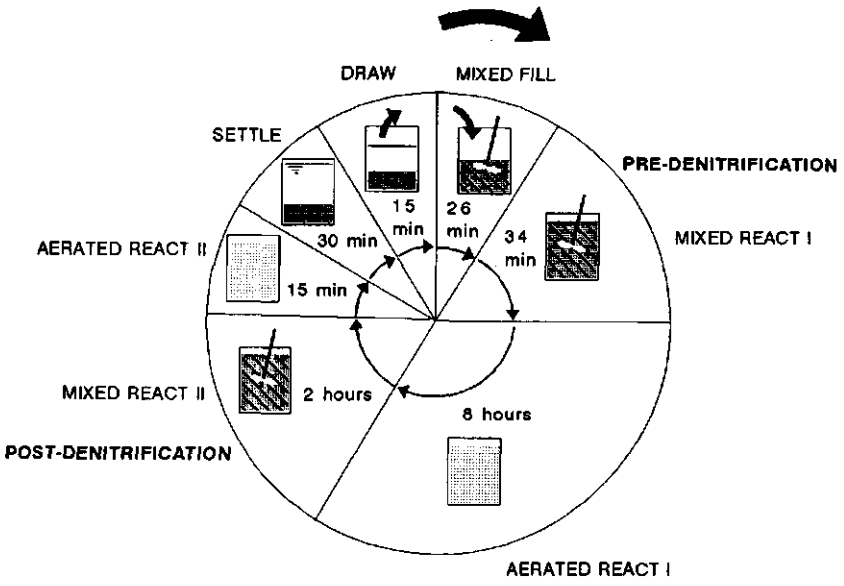


Figure 3. Timetable for the SBR cycle (12 h).

The data from the on-line surveillance of the reactor operation were stored, namely real time,

reactor temperature, dissolved oxygen in the reactor, dissolved oxygen in the respiration vessel, pH in the reactor and r.

PARAMETER CALIBRATION FOR r AND r_{NO3} MODELS DURING ONE CYCLE

The parameters used in the models were either default values from the literature, or calibrated by respirogram analysis. Using a simulation programme (see Annex 2) written in SIMNON (Elmqvist *et al.*, 1990), the results from the differential equations system were compared with the measured respirogram. Parameters were calibrated by trial and error until the simulation came close to the measured values. The parameters used are presented in Table II, indicating where calibrated and default values were used.

Measurement of r was done during the AERATED REACT I period. The r value, based on the average for the last 15 minutes of the period, was used for comparison with the post-denitrification rate. Considering that at this point no readily biodegradable matter was present and no nitrification was taking place, r was equal to r_{end} (equation 7). The post-denitrification rate (r_{NO3}) was determined by the decrease in the nitrate concentration during the MIXED REACT II period, assuming a zero-order reaction. The relationship between the denitrification rate (r_{NO3}) and r_{end} (equation 14) was used to calculate F_{den}.

Table II. Parameters

Parameter	Default value or calibration process	Reference
F_{den}	Respirogram + nitrate analysis	Present study
K_1	Respirogram analysis	Chapter 2 - This thesis
K_2	Respirogram analysis	Chapter 2 - This thesis
K_{NH}	1.0 mg N/l	Henze *et al.* (1987)
K_S	20 mg COD/l	Henze *et al.* (1987)
$r_{m,NH}$	Respirogram analysis	Chapter 2 - This thesis
$r_{m,S}$	Respirogram analysis	Chapter 2 - This thesis
Y_H	0.5	Henze *et al.* (1987)

PARAMETER FOR THE $r_{m,NH}$ VARIATION MODEL DURING LONG-TERM OPERATION

The $\hat{\mu}_A$ value is needed for equation **1**. Dold *et al.* (1980) reported a value of 0.21 d^{-1} for $\hat{\mu}_{A,20}$, for settled wastewater from Cape Town (South Africa). To correct $\hat{\mu}_A$ for the temperature effect, the equation $\hat{\mu}_{A,T} = \hat{\mu}_{A,20}\ (1.123)^{(T-20)}$ was proposed (temperature range from 12° C to 20° C). Using this equation, the value of 0.09 d^{-1} can be calculated for the average temperature during operation (12.7 °C). The corrected $\hat{\mu}_A$ value was used in equation **1** to predict the nitrification capacity variation during long-term operation.

LABORATORY-SCALE BATCH

The $r_{m,S}$ parameter was difficult to obtain from the respirograms, because in almost all the experiments S_S was already oxidized during the MIXED FILL and MIXED REACT periods. Therefore, to evaluate the accuracy of the estimated $r_{m,S}$, an experiment was carried out using both the pilot-plant SBR and the laboratory-scale batch reactor. The laboratory-scale batch reactor consisted of a reactor with a volume capacity of 10 l, and probes similar to the pilot-plant SBR. The air was supplied via a porous tube diffuser on the bottom of the reactor. The experiment compared nitrate removal during post-denitrification with and without the addition of an external carbon source. At the end of the AERATED REACT I period, 8 l of mixed liquor from the pilot-plant SBR was transferred to the laboratory-scale batch reactor and after achieving anoxic conditions, 1 g sodium acetate ($CH_3COONa \cdot 3H_2O$) was added. The batch reactor's temperature and pH were similar to the pilot-plant SBR. The parameters ($r_{m,S}$, K_S, K_1, K_2 and F_{den}) were calibrated from the respirogram during the aerobic period in the pilot-plant SBR. By using these values in equation **13**, the nitrate decrease in both reactors was simulated. During the MIXED REACT II period in the pilot-plant SBR, S_S was not present. The pilot-plant SBR and the laboratory-scale batch reactor were sampled simultaneously.

ANALYSES

All the analyses were done according to APHA (1985). Samples were taken from the influent and from the mixed liquor at different times. Samples from the mixed liquor were filtrated (Whatman glass microfibre 1 μm). All samples were analyzed for COD, nitrogen (S_{NH}, S_{NO2},

nitrate), suspended solids (MLSS) and volatile suspended solids (MLVSS). The influent was also analyzed for volatile fatty acids as COD (COD_{VFA}) and Total Kjeldahl Nitrogen (TKN).

RESULTS

For parameter calibration from the model of equations **2-7** ($r_{m,NH}$, $r_{m,S}$, K_1 and K_2), model response during the aerobic period was compared with the r measurements. The methodology for K_1 and K_2 determination used in equation **6** was the same as that used in Chapter 2 in the model to describe nitrification and carbon oxidation in an SBR. In the present study, t=0 is the beginning of the MIXED FILL period. Default values were used for the other parameters (K_{NH}, K_S, and Y_H). Table II shows the default values used and the parameters that were calibrated.

The respirographic information about r_{end} was used for F_{den} determination according to equation **14**. The determined F_{den} value, together with the other parameters obtained from the respirogram in the aerobic period, were used to simulate the respiration rate and nitrate removal during the whole cycle (equations **2-7** and **13**). Figure 4 shows the results of one of these simulations, together with the measured r and nitrate removal.

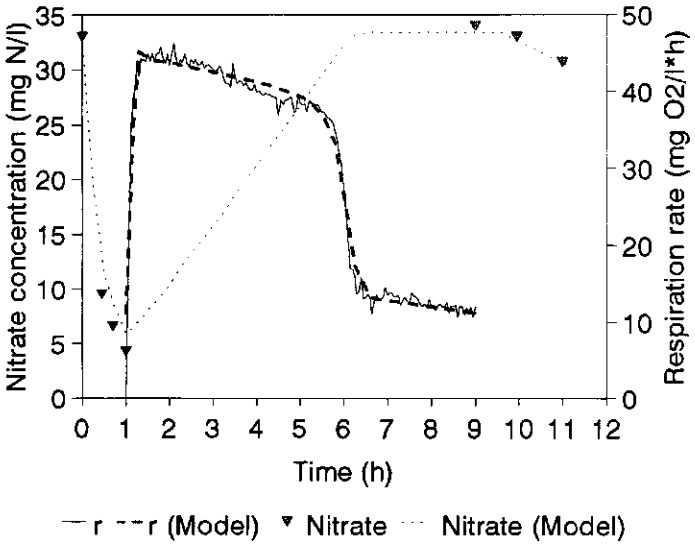


Figure 4. Measured respirogram and nitrate variation from a cycle, together with model response for r and nitrate. Parameters: K_1 = 21, K_2 = 0.07, $r_{m,NH}$ = 5.8 mg N/l*h, $r_{m,S}$ = 240 mg COD/l*h, F_{den} = 0.55 (average r_{end} before post-denitrification = 11.5 mg O_2/l*h and r_{NO3} during post-denitrification = 2.2 mg N/l*h). Initial variables in the influent: S_{NH} = 55 mg N/l and COD_{vfa} = 44 mg COD/l. Initial variable in the reactor: nitrate concentration = 33 mg N/l.

To evaluate the predictability of the model (equations **7** and **13**), parameters from a previous cycle ($r_{m,NH}$, $r_{m,S}$, K_1, K_2 and F_{end}) were used. Variables that give the initial condition about the substrate were from the studied cycle. Figure 5 shows an example of these predictions.

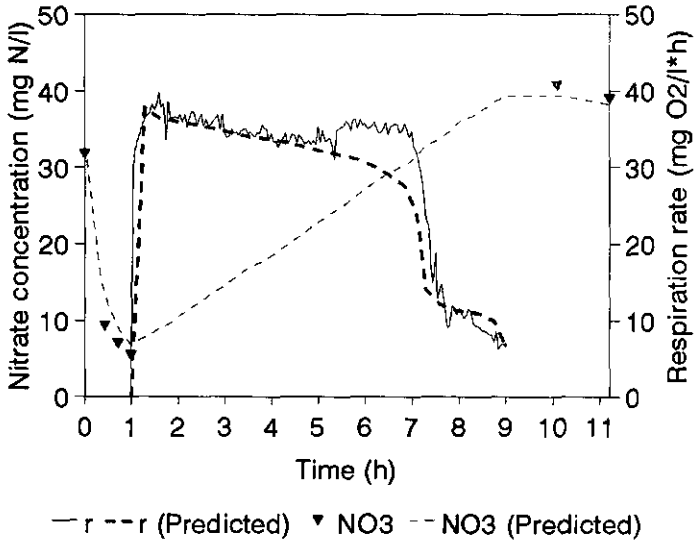


Figure 5. Measured respirogram and nitrate variation from a complete cycle, together with model prediction for respiration rate (r) and nitrate concentration with parameters from a previous cycle. Parameters: $K_1 = 15$, $K_2 = 0.11$, $r_{m,NH} = 6.0$ mg N/l*h, $r_{m,S} = 240$ mg COD/l*h, $F_{den} = 0.5$. Initial variables in the influent: $S_{NH} = 65$ mg N/l and $COD_{vfa} = 51$ mg COD/l. Initial variable in the reactor: nitrate concentration = 32 mg N/l.

Figure 6 presents the results from the post-denitrification experiment with acetate addition in the laboratory batch reactor. The measured nitrate concentration over time from the pilot-plant SBR (without external carbon source) and from the laboratory-scale batch reactor (with external acetate addition) were compared with the response from the model of equation **13** with only r_{end} and with r_{end} plus $r_{o,S}$. The model parameters were from the studied cycle.

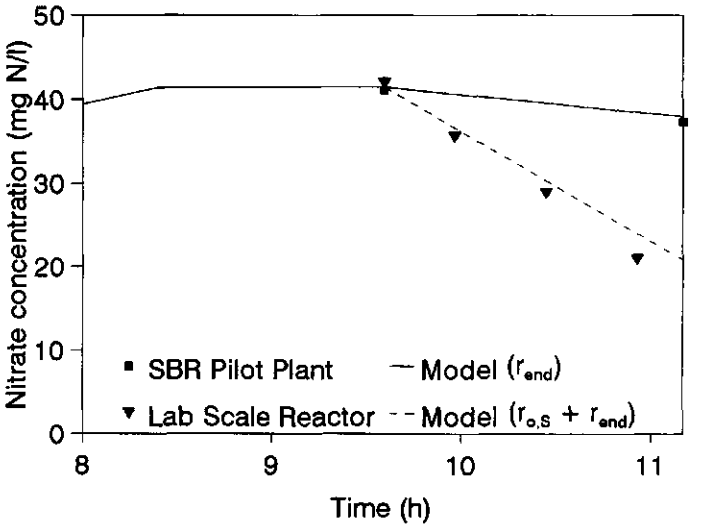


Figure 6. Nitrate variation during post-denitrification from pilot-plant SBR (without external carbon addition) and from laboratory-scale batch reactor (with acetate addition). Measured and model from equation **12** response.

The measured amount of nitrate denitrified during pre-denitrification was compared with the model results (equation **13**). Table III shows this comparison for several cycles. The model response is presented with two fractions: denitrification due to oxidation of S_S and due to endogenous respiration.

Table III. Nitrate removal during pre-denitrification (measured and modelled).

Cycles evaluated	F_{den}	Nitrate removed (mg N/l)			
		Modelled			Measured Total
		S_S oxidation	Endogenous resp.	Total[a]	
1	0.37	4.3	2.7	7.0	11.0
2	0.55	5.6	3.9	9.5	12.2
3	0.59	4.6	4.2	8.8	10.3
4	0.40	4.7	2.9	7.6	11.6
5	0.50	6.6	3.6	10.2	13.3
6	0.47	5.6	3.5	9.1	13.6
7	0.31	4.0	2.3	6.3	13.9
8	0.52	6.9	3.8	10.7	13.5
9	0.51	3.8	3.6	7.4	7.8
10	0.40	3.7	2.9	6.6	9.5
11	0.24	3.6	1.8	5.4	3.0
12	0.41	2.5	3.0	5.5	4.0
13	0.40	4.4	2.9	7.3	6.6
14	0.44	4.6	3.2	7.8	9.4
15	0.48	5.2	3.5	8.7	10.2
16	0.53	5.5	3.8	9.3	13.9
17	0.49	5.6	3.1	8.7	11.3

[a] Total = S_S oxidation + endogenous respiration

Figure 7 shows the measured S_{NH} and COD from influent wastewater. The average values for $S_{NH,i}$ also presented in Figure 7, are used for the following simulation of the nitrification capacity variation during long-term operation (equation **1**). To calculate the average values, the operation period was arbitrarily divided into small intervals in which the $S_{NH,i}$ was more or less constant. The average values in these intervals were calculated and used in the model simulation.

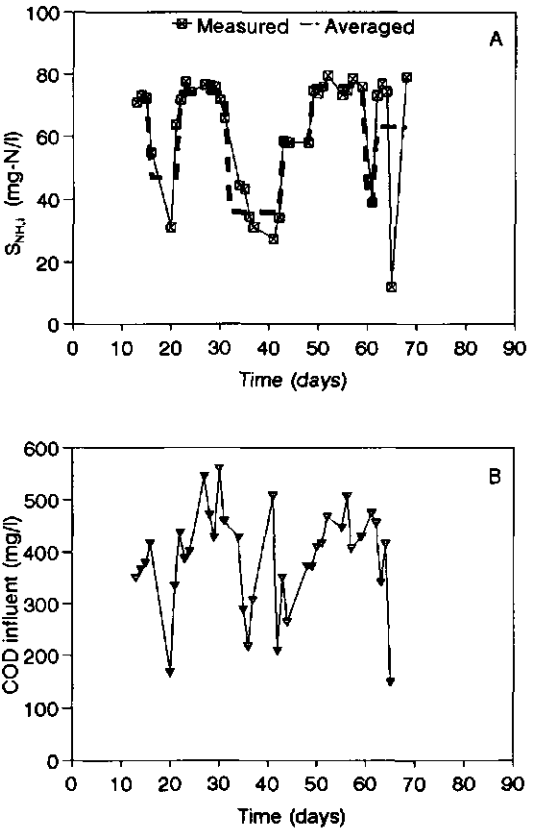


Figure 7. Measured S_{NH} and COD influent to the SBR. (A) Measured $S_{NH,i}$ together with the averaged values used for equation 1 simulation. (B) Measured COD.

To use the model for nitrification capacity variation in an SBR during long-term operation (equation 1), some parameters and variables should be determined or assumed. The averaged values of $S_{NH,i}$ are presented in Figure 7. The averaged value of $S_{NH,e}$ is equal to 0 mg N/l. The averaged volume of sludge discharged per day, 66.7 l/day, is used for Q_S. For $\hat{\mu}_A$, the value of 0.09 d^{-1} is used. The simulation of equation 1 for nitrification capacity variation during long-term operation is shown in Figure 8.

The SBR pilot plant was operated for three months. Seventeen cycles were analyzed and the parameters F_{den}, K_1, K_2 and $r_{m,NH}$ were calibrated according to the procedures presented in this chapter. These parameters are shown in Figure 8.

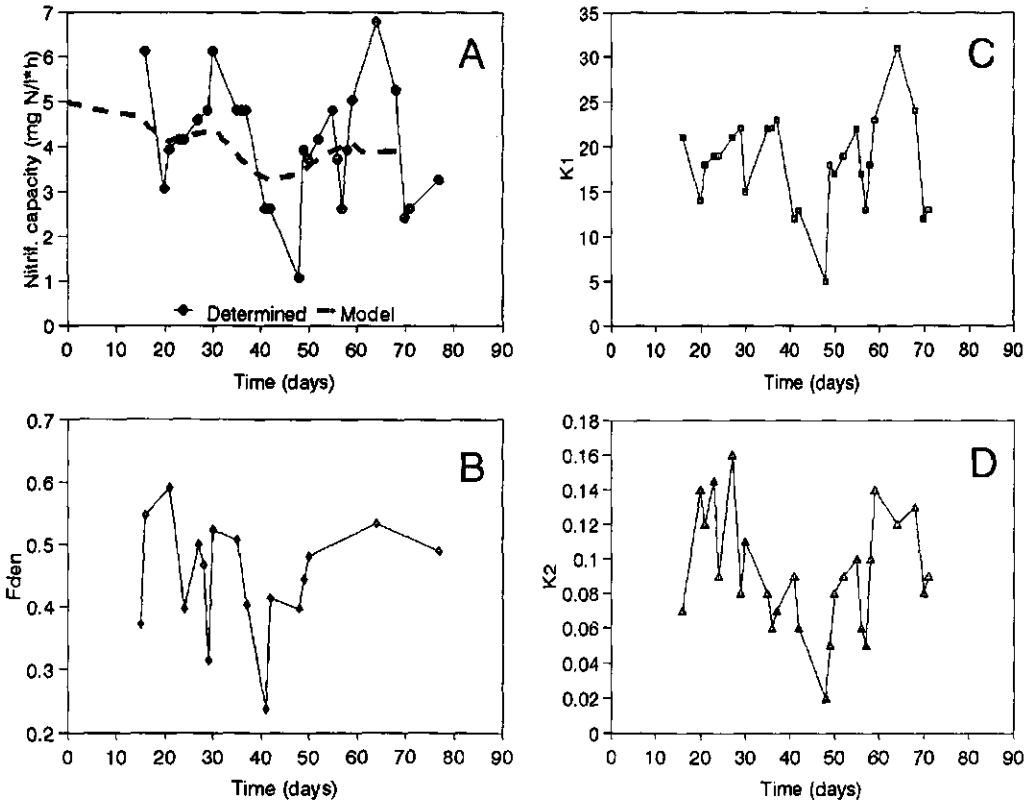


Figure 8. Variation of parameters ($r_{m,NH}$, F_{den}, K_1 and K_2) over time. (A) Estimated $r_{m,NH}$ together with model response (equation **1**). (B) Determined F_{den}. (C) Estimated K_1. (D) Estimated K_2.

DISCUSSION

As can be seen from the results presented in Figure 5, the model's capability for describing respiration rate (r) and nitrate concentrations during an SBR cycle can be considered satisfactory. The model for nitrate variation during post-denitrification fits the measured points with good approximation. This response can be expected, as the factor F_{den} used in the model was derived from the relationship between the observed denitrification rate and the measured r_{end}. However, from Table III we can see that the measured nitrate removal was always higher than the simulated. To explain this, F_{den}, $r_{m,S}$ and Y_H should be further evaluated.

Based on the idea that the denitrifiers use oxygen and nitrate in the same way (Christensen and Harremöes, 1977; Klapwijk, 1978; van Haandel *et al.*, 1981), F_{den} is considered to represent the fraction of denitrifiers in the heterotrophic biomass. The value of the parameter F_{den} was used to describe denitrification during all of the SBR cycles. In the present study, F_{den} was determined during the post-denitrification step, when S_S was not present. Then, F_{den} was extrapolated and used by the model to describe the pre-denitrification step, when S_S was present.

In the Activated Sludge Model No. 1 (Henze *et al.*, 1987), the parameter η_g adjusts for either the change in the maximum specific growth rate for heterotrophic biomass associated with anoxic conditions or because only part of the biomass can denitrify. The parameter η_h adjusts for the difference in the rate of the hydrolysis of slowly biodegradable organic matter under aerobic and anoxic conditions. In this model it is assumed that during anoxic conditions hydrolysis is slower than during aerobic conditions. Therefore, η_g and η_h are used to

differentiate the processes of denitrification during oxidation of S_S and during oxidation of the products of slowly biodegradable matter's hydrolysis.

The above evaluation of η_g and η_h leads to the conclusion that using F_{den}, determined during the post-denitrification period, to predict nitrate removal during the pre-denitrification period, would underestimate $r_{o,S,den}$. In addition, due to the small amount of S_S present in the domestic wastewater, the resulting underestimation would not be so high. However, the results presented in Figure 6 indicate that the F_{den} value can be used to predict nitrate removal.

In a nitrifying/denitrifying SBR operated with the pre-denitrification step, the estimation of $r_{m,S}$ is very difficult. After the first anoxic period, almost no S_S is left for the following aerobic period. In this case, the respirogram does not show enough information for a good $r_{m,S}$ estimation.

The parameter Y_H has a strong influence on the total amount of nitrate to be used for S_S oxidation in the pre-denitrification period. Consequently, we can assume that the underestimation of the nitrate removal simulation (Table III) is caused by overestimation of Y_H. By using Y_H=0.25, the simulated nitrate removal comes closer to the measured values.

All these considerations lead to the conclusion that it is very important to carry out additional experiments to improve the Y_H and $r_{o,S}$ calibration. Also, it is important to validate the use of F_{den} during the pre-denitrification process.

The model capability for prediction is reasonable if parameters from a previous cycle are

used. Figure 5 shows that the trend in r and nitrate concentration behaviour during the cycle can be described by the models from equations **2-7** and **13** with good agreement. Therefore, the model from equation **13** can be used for on-line control of denitrification in an SBR. By using respirogram information together with nitrate analyses, it is possible to predict denitrification rates in a future cycle and, consequently, the needed anoxic time.

Figure 6 clearly shows that F_{den} gives slower denitrification rates when it is used with $r_{o,S}$. The model response also indicates a trend towards nitrate concentration, although the measured nitrate concentrations are below the model description. This can also be explained by the imprecision in $r_{o,S,den}$ determination as was discussed above.

Figure 8 shows that parameter ($r_{m,NH}$, F_{den}, K_1 and K_2) variation over time is high. The most important aspect related to this is the difficulty in simulating long-term operation in an SBR system with fixed parameter values. Some correlation between change in the influent wastewater characteristics and change in the parameters indicates that a model with feedback would be an important stage. This is particularly important for $r_{m,NH}$ and F_{den}.

In Figure 8, the comparison between the model response of equation **1** and the estimated $r_{m,NH}$ value shows that the model can predict a trend for nitrification capacity variation over time. It can also be seen that the model has a close relation between $S_{NH,i}$ in the influent shown in Figure 7 and the system nitrification capacity. Considering that $S_{NH,e}$ was consistently zero, it is evident from equation **1** that an increase in the nitrogen load would mean an increase in the nitrification capacity. However, the model cannot predict the sudden variations observed in the estimated values.

The determined values of F_{den} fluctuated around the mean of 0.45 ± 0.09. However, Figure 8 shows that these changes could be quite sharp. Considering the assumption that F_{den} can be associated with the fraction of denitrifiers in the heterotrophic biomass, the changes in the determined F_{den} means changes in the biomass composition and/or biomass activity. An explanation for this variation can be the change in the organic load that goes into the system. Comparing the F_{den} values' evolution in Figure 8 with the influent COD values' evolution in Figure 7, some association between the change in the organic load and the change in the F_{den} can be seen. Considering that the first environment in the SBR cycle is anoxic, when most of the readily biodegradable substrate is available, it can be expected that the growth of denitrifiers is greater than the aerobic fraction of the heterotrophic biomass. However, some fluctuation cannot be explained by these considerations, which means that some further explanation is needed.

An important conclusion from long-term operation is that other environmental factors, such as floc size and mixing energy, and perhaps more importantly, the combination of environmental factors, should be studied to have a better understanding of parameter variations.

CONCLUSIONS

The model for the rate of nitrate reduction (equation **13**) can be used to represent the

denitrification process in an SBR treating domestic wastewater and is able to predict denitrification in one cycle with parameters taken from the previous cycle.

The model for respiration rate (equations 2-7) can be used for the nitrification and carbon oxidation processes during the aerobic period in an SBR treating domestic wastewater.

During long-term operation, parameter variation is significant and, therefore, too complex to be predicted. In the particular case of $r_{m,NH}$, the model for nitrification capacity variation in an SBR during long-term operation (equation 1) can explain the variation trend, but it cannot explain the abrupt changes. Regular parameter calibration is necessary.

NOMENCLATURE

$\hat{\mu}_A$	maximum specific growth rate for autotrophic biomass ($time^{-1}$)
$\hat{\mu}_{A,20}$	$\hat{\mu}_A$ at 20 °C ($time^{-1}$)
$\hat{\mu}_{A,T}$	$\hat{\mu}_A$ at temperature T ($time^{-1}$)
COD	chemical oxygen demand ($mass\ volume^{-1}$)
COD_{vfa}	volatile fatty acids as COD ($mass\ volume^{-1}$)
F_{den}	ratio between anoxic equivalent respiration rate and aerobic respiration rate or fraction of denitrifiers
K_1	empirical constant ($mass\ volume^{-1}\ time^{-1}$)
K_2	empirical constant ($time^{-1}$)

K_{NH}	ammonia half-saturation coefficient for S_{NH} oxidation (mass volume^{-1})
K_S	half-velocity constant for S_S oxidation by heterotrophic biomass (mass volume^{-1})
MLSS	total suspended solids (mass volume^{-1})
MLVSS	total volatile suspended solids (mass volume^{-1})
Q_i	average influent flow in SBR cycle (volume time^{-1})
Q_S	average sludge discharge flow in SBR cycle (volume time^{-1})
r	respiration rate (mass volume^{-1} time^{-1})
r_{den}	anoxic equivalent respiration rate (mass volume^{-1} time^{-1})
r_{end}	endogenous respiration rate (mass volume^{-1} time^{-1})
$r_{end,den}$	anoxic equivalent endogenous respiration rate (mass volume^{-1} time^{-1})
$r_{m,NH}$	maximum rate of S_{NH} oxidation or nitrification capacity (mass volume^{-1} time^{-1})
$r_{m,S}$	maximum rate of S_S consumption (mass volume^{-1} time^{-1})
r_{NH}	rate of S_{NH} oxidation (mass volume^{-1} time^{-1})
r_{NO3}	rate of nitrate reduction (mass volume^{-1} time^{-1})
$r_{o,NH}$	respiration rate for S_{NH} oxidation (mass volume^{-1} time^{-1})
$r_{o,S}$	respiration rate for S_S oxidation (mass volume^{-1} time^{-1})
$r_{o,S,den}$	anoxic equivalent rate of S_S oxidation (mass volume^{-1} time^{-1})
r_S	rate of S_S consumption (mass volume^{-1} time^{-1})
SBR	Sequencing Batch Reactor
S_{NH}	soluble ammonia nitrogen concentration (mass volume^{-1})
$S_{NH,e}$	effluent S_{NH} from SBR (mass volume^{-1})

$S_{NH,i}$	influent S_{NH} into SBR (mass volume^{-1})
S_S	readily biodegradable substrate concentration (mass volume^{-1})
t	time of reaction (time)
T	temperature (°C)
TKN	Total Kjeldahl Nitrogen (mass volume^{-1})
V	reactor volume (volume)
Y_H	yield for heterotrophic biomass (mass mass^{-1})

REFERENCES

APHA (1985). *Standard methods for the examination of water and wastewater.* 16th edition. American Public Health Association, Washington, DC.

Charpentier, J., Florentz, M. and David, G. (1987). Oxidation-reduction potential (ORP) regulation: a way to optimize pollution removal and energy savings in the low load activated sludge process. *Wat. Sci. Tech.* **19**:645-655.

Christensen, M.H. and Harremöes, P. (1977). Biological denitrification of sewage: a literature review. *Prog. Wat. Tech.* **8**:509-555.

Clayton, J.A., Ekama, G.A., Wentzel, M.C. and Marais, G.v.R. (1991). Denitrification kinetics in biological nitrogen and phosphorus removal activated sludge systems treating municipal waste waters. *Wat. Sci. Tech.* **23**:1025-1035.

Di Pinto, A.C., Passino, R., Ramadori, R. and Tomei, M.C. (1990). Modelling of two stage-single systems for nitrogen removal. *Environm. Technol.* **11**:509-520.

Dold, P.L., Ekama, G.A. and Marais, G.v.R. (1980). A general model for the activated sludge process. *Prog. Wat. Tech.* **12**:47-77.

Elmqvist, H., Åström, K.J., Schönthal, T. and Wittenmark, B. (1990). *Simnon - User's guide for MS DOS computers, V. 3.0.* SSPA Systems, Box 24001, S-400 22 Göteborg, Sweden.

Haandel, A.C.v., Ekama, G.A. and Marais, G.v.R. (1981). The activated sludge process-3. Single-sludge denitrification. *Wat. Res.* **15**:1135-1152.

Henze, M. (1987). Theories for estimation of the fraction of denitrifiers in combined nitrifying-denitrifying treatment plants. *Wat. Res.* **12**:1521-1524.

Henze, M. (1991). Capabilities of biological nitrogen removal processes from wastewater. *Wat. Sci. Tech.* **23**:669-679.

Henze, M., Grady, C.P.L. Jr., Gujer, W., Marais, G.v.R. and Matsuo T. (1987). A general model for single-sludge wastewater treatment systems. *Wat. Res.* **21**:505-515.

Klapwijk, A. (1978). Eliminatie van stikstof uit afvalwater door denitrificatie. PhD. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Koch, F.A. and Oldham, W.K. (1985). Oxidation-reduction potential - a tool for monitoring, control and optimization of biological nutrient removal systems. *Wat. Sci. Tech.* **17**:259-281.

Kristensen, G.H., Jørgensen, P.E. and Henze, M. (1992). Characterization of functional microorganism groups and substrate in activated sludge and wastewater by AUR, NUR and OUR. *Wat. Sci. Tech.* **25**:43-57.

McClintock, S.A., Sherrard, J.H., Novak, J.T. and Randall, C.W. (1988). Nitrate versus oxygen respiration in the activated sludge process. *J. Wat. Pol. Control Fed.* ***60***:342-350.

Siebritz, I.P., Ekama, G.A. and Marais, G.v.R. (1983). A parametric model for biological excess phosphorus removal. *Wat. Sci. Tech.* **15**:127-152.

Spanjers, H. (1993). Respirometry in activated sludge. PhD. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Stensel, H.D. and Barnard, J.L. (1992). Principles of biological nutrient removal. In *Design and retrofit of wastewater treatment plants for biological nutrient removal.* Randal, C.W., Barnard, J.L. and Stensel, H.D. (eds.) Technomic Publishing Co. Inc., Pennsylvania, USA.

Wilderer, P.A., Jones, W.L. and Dau, U. (1987). Competition in denitrification systems affecting reduction rate and accumulation of nitrite. *Wat. Res.* **21**:239-245.

CHAPTER 4

MODELLING NITRIFICATION, DENITRIFICATION AND BIOLOGICAL PHOSPHORUS REMOVAL IN AN SBR TREATING DOMESTIC WASTEWATER BASED ON RESPIROMETRY

4 MODELLING NITRIFICATION, DENITRIFICATION AND BIOLOGICAL PHOSPHORUS REMOVAL IN AN SBR TREATING DOMESTIC WASTEWATER BASED ON RESPIROMETRY

SUMMARY

This investigation aims to develop an on-line monitoring procedure for biological phosphorus removal in a Sequencing Batch Reactor (SBR). For this, a mathematical model for an activated sludge SBR with nitrification, denitrification, carbon oxidation and phosphorus removal was proposed. This model is based on the response of respiration rate (r) measured during nitrification, carbon oxidation and phosphorus removal, together with the behaviour of phosphate and acetate as proposed by Gujer *et al.* (1994) for the Activated Sludge Model No. 2.

For model validation, an SBR pilot plant (1 m^3) receiving settled domestic wastewater plus acetic acid solution was operated for five months and the results were compared with the model. The simulation values for phosphate, acetate, ammonia, nitrate and respiration rate were in good agreement with the measured ones. However, in activated sludge plants treating domestic wastewater with biological phosphorus removal, the respiration related to the phosphate uptake process was low in comparison with the other oxygen consumption processes. Therefore, the respiration rate due to phosphate uptake was in the range of the measuring uncertainty of the equipment. With these results, it can be concluded that r is a

good variable for on-line monitoring of an activated sludge SBR with nitrification/denitrification processes, but its use is limited to the phosphorus removal process.

KEY WORDS

Sequencing Batch Reactor (SBR); nitrification; denitrification; biological phosphorus removal; respiration rate; modelling; domestic wastewater.

INTRODUCTION

Because phosphate is a key factor in the eutrophication of receiving water, phosphorus removal during wastewater treatment is an important process (Vinçonneau *et al.*, 1985; Yeoman *et al.*, 1988).

Biological phosphorus removal is basically achieved through modification of the activated sludge process. A combination of anaerobic and aerobic environments is implemented in order for the excess phosphorus to be taken up by a group of heterotrophic organisms called phosphorus accumulating organisms (PAOs). These organisms are strongly affected by the competition with denitrifier organisms for organic carbon compounds. For this reason, denitrification is always part of the biological phosphorus removal process in nitrifying activated sludge plants. (Appeldoorn, 1993; Marais *et al.*, 1983).

Studies have shown the capability of activated sludge Sequencing Batch Reactors (SBR) to remove nutrients. With respect to biological phosphorus removal, the SBR is described as a very efficient alternative to conventional activated sludge systems (Manning and Irvine, 1985; Shin and Park, 1991; Vlekke *et al.*, 1988). The results from van Niel (1993) show that the SBR system can have a population of PAOs in the range of 37-85% of the total population.

Since the early seventies, mathematical models for the conventional activated sludge process have been strongly developed, with a tendency towards explanatory dynamic models. These models, like the one developed by the IAWPRC Task Group (Henze *et al.*, 1987), are limited in that the parameters used can not be monitored on-line. Spanjers (1993) showed the potential for respirometry to monitor the conventional activated sludge process. A model for a nitrifier/denitrifier SBR, using respiration rate as an important parameter, is presented in Chapter 2. Gujer *et al.* (1994) incorporated biological phosphorus removal into the Activated Sludge Model No. 1 and presented the Activated Sludge Model No. 2. Calibration and verification of their model has been indicated as a priority in their paper.

The present study intends to: i) monitor the biological phosphorus removal process in an SBR during long-term operation; ii) incorporate the biological phosphorus removal equations presented by Gujer *et al.* (1994) into the model presented in Chapter 3. In this research, an SBR pilot plant was operated for five months.

The pilot-plant SBR used in this study consisted of two reactors: i) a 300 l reactor with an anaerobic/anoxic environment and ii) a 1000 l reactor with an anoxic/aerobic environment. Laboratory analysis and respirometry were used to monitor the plant.

THEORETICAL ASPECTS OF C, N AND P REMOVAL IN AN SBR

MODEL FOR CARBON OXIDATION, NITRIFICATION AND DENITRIFICATION DURING ONE SBR CYCLE

In Chapter 3 of this thesis, the removal of S_{NH} and S_S during the aerobic period in an SBR with nitrification and carbon oxidation is described by:

$$r_{NH} = r_{m,NH} \frac{S_{NH}}{K_{NH} + S_{NH}} \quad (1)$$

$$r_S = r_{m,S} \frac{S_S}{K_S + S_S} \quad (2)$$

The oxidation rates of S_{NH} and S_S can be related to the rate of oxygen consumption as:

$$r_{o,NH} = 4.57\ r_{NH} \quad (3)$$

$$r_{o,S} = (1 - Y_H)\ r_S \quad (4)$$

It is shown in Chapter 2 of this thesis that during one cycle in an aerobic SBR, r_{end} can be well represented with the exponential equation:

$$r_{end} = K_1 \exp(-K_2 t) \quad (5)$$

In this case, t is zero at the start of each SBR cycle.

The model proposed in Chapter 3 to represent r in the aerobic period of an aerobic/anoxic SBR with nitrification, denitrification and carbon oxidation is:

$$r = r_{o,NH} + r_{o,S} + r_{end} \quad (6)$$

In an SBR under anoxic conditions, the following model is proposed to describe denitrification (Chapter 3):

$$r_{NO3} = \frac{1}{2.86} F_{den} (r_{o,S} + r_{end}) \quad (7)$$

BIOLOGICAL PHOSPHORUS REMOVAL

Biological phosphorus removal is a process carried out by aerobic microorganisms called phosphorus accumulating organisms (PAOs) which are able to accumulate excess phosphates in their cells. To accumulate PAOs in an activated sludge plant, the following conditions are necessary: i) the activated sludge has to pass through an anaerobic environment followed by

an aerobic environment, ii) there is no nitrate present during the anaerobic period.

During the anaerobic period, PAOs selectively take up acetates into their cells, using stored poly-phosphates as energy source, and release phosphates into the liquid phase. The acetates taken up are stored as poly-ß-hydroxyalkanoates (*PHA*) in the cells. During the aerobic period, *PHA* is metabolized, providing energy for the excess uptake of available orthophosphate and the growth of biomass.

An activated sludge SBR receiving domestic wastewater can perform carbon oxidation, nitrification, denitrification and biological P removal. To achieve this, a succession of anaerobic, anoxic and aerobic conditions has to be arranged. Several SBR plant configurations are possible. One of these configurations, using two batch reactors, is shown in Figure 1, together with the comparable conventional, continuous plug-flow system.

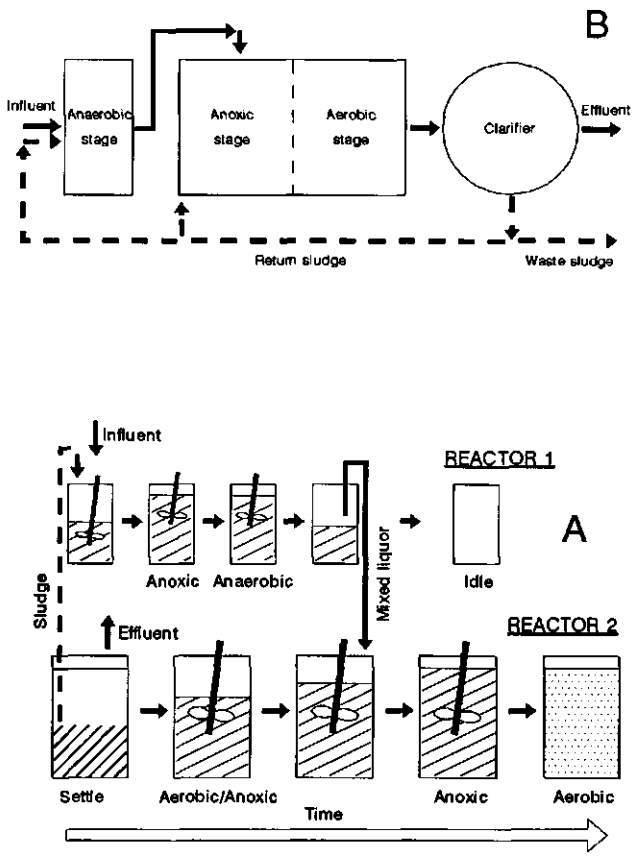


Figure 1. Scheme for the SBR combination in order to achieve carbon oxidation, nitrification, denitrification and biological P removal (A), together with the comparable conventional, continuous plug-flow system (B).

The different environmental conditions in Reactors 1 and 2 induce the different processes for nitrogen and phosphate. In the anaerobic/anoxic Reactor 1, some denitrification takes place and phosphate is released. In the anoxic/aerobic Reactor 2, denitrification takes place, followed by nitrification and phosphate uptake.

For nitrogen, Reactor 2 can be considered a nitrifying/denitrifying SBR and the model developed in Chapter 3, represented by the set of equations **1-6,** can be applied, with an extension to describe phosphate uptake.

For the anoxic period in Reactor 1, the denitrification model (equation **7**) can be applied. For the subsequent anaerobic period, an extra model to describe phosphate release is needed.

MODELLING PHOSPHATE RELEASE

Gujer *et al.* (1994) proposed the following equation for the rate of X_{PHA} storage during the anaerobic period:

$$r_{PHA} = q_{PHA} \frac{S_A}{K_A + S_A} \frac{X_{PP}/X_{PAO}}{K_{PP} + X_{PP}/X_{PAO}} X_{PAO} \qquad \textbf{(8)}$$

Equation **8** describes the organic storage of X_{PHA} in the cells. If fermentation products S_A are available, PAOs are presumed to store these organics in the form of poly-hydroxy-alkanoates under all environmental conditions. The energy for this process is derived from the hydrolysis of poly-phosphates (X_{PP}) and leads to the release of soluble phosphorus (S_{PO4}).

The rate of S_A uptake from the liquid phase of a batch reactor is then:

$$r_{SA} = - r_{PHA} \qquad \textbf{(9)}$$

The phosphate released can be related to the acetate used by a stoichiometric factor (Y_{PO4}). Then, the rate of phosphate release is:

$$r_{PO4} = Y_{PO4}\, r_{PHA} \qquad (10)$$

MODELLING PHOSPHATE UPTAKE

During the aerobic period, *PHA* is metabolized and the resulting energy is used for phosphate uptake and biomass production. Gujer *et al.* (1994) proposed the following equation to describe the rate of X_{PP} storage:

$$r_{PP} = q_{PP} \frac{S_{O2}}{K_{O2} + S_{O2}} \frac{S_{PO4}}{K_P + S_{PO4}} \frac{X_{PHA}/X_{PAO}}{K_{PHA} + X_{PHA}/X_{PAO}} \frac{K_{MAX} - X_{PP}/X_{PAO}}{K_{IPP} + X_{PP}/X_{PAO}} X_{PAO} \qquad (11)$$

Under aerobic conditions, it is assumed that PAOs store soluble phosphorus (S_{PO4}) in the form of intracellular poly-phosphates (X_{PP}). The required energy for this process stems from organic storage products (X_{PHA}) in the cell. When $S_{O2} >> K_{O2}$, the fraction due to the oxygen in equation **11** can be ignored.

During phosphate uptake in the aerobic period, *PHA* is oxidized resulting in oxygen uptake. According to Smolders *et al.* (1994), the ratio for the consumed O_2 is 0.31 mol O_2 per mol P, or the ratio oxygen consumed for P uptake ($f_{O/P}$) is equal to 0.35 g O_2 per g phosphate-P. The equivalent respiration rate for P uptake is:

$$r_{o,P} = f_{O/P}\, r_{PP} \qquad (12)$$

Considering the rate for P uptake, the model for respiration rate during the aerobic period in an SBR (equation **6**) can be expressed as:

$$(13) \quad r = r_{o,NH} + r_{o,S} + r_{end} + r_{o,P}$$

Therefore, in this study, equations **1-5** and **13** were used to describe r from nitrogen and carbon oxidation plus phosphate uptake, during the aerobic period. Equation **7** was applied during the anoxic period to describe denitrification. For model calibration of the P release process, equations **8-10** were applied during the anaerobic period of the pilot-plant SBR operation. For model calibration on P uptake, equations **11** and **12** were used during the aerobic period.

MATERIALS AND METHODS

EXPERIMENTAL APPARATUS

In this study, a pilot-plant SBR was operated in order to have: i) a mixed culture able to perform carbon oxidation, nitrification, denitrification and biological phosphorus removal; ii) long-term respirometric measurements during the aerated period; and iii) long-term assessment of the biological phosphorus removal process.

The pilot-plant SBR (Figure 2) consisted of two cylindric polystyrene vessels, the first with a total volume of 0.35 m^3 (Reactor 1) and the second with a total volume of 1.3 m^3 (Reactor 2).

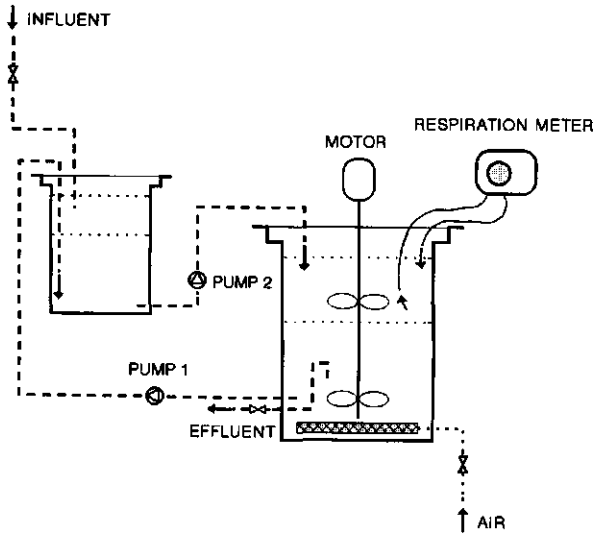


Figure 2. Schematic view of the SBR pilot plant used in the experiment.

The main equipment connected to Reactor 1 included: one pneumatic valve, controlled by an electromagnetic device (influent control); three float-level switches, used to control fill and draw activities in the reactor; one bottom-level switch (to control the end of draw); a propeller connected to a stirring motor, for mixing without aeration; a pump to discharge activated sludge from Reactor 1 into Reactor 2 (Pump 1); and a unit to dose acetic acid. Probes for measuring temperature, pH and dissolved oxygen were installed in the reactor.

The main equipment connected to Reactor 2 included: two pneumatic valves, controlled by an electromagnetic device (effluent and air supply control); three float-level switches, used

to control fill and draw activities in the reactor; a unit for pH control (pump to dose NaOH solution); a propeller connected to a stirring motor for mixing without aeration; a pump to discharge mixed liquor from Reactor 2 into Reactor 1 (Pump 2); and a pump to discharge excess sludge. Probes for measuring temperature, pH and dissolved oxygen were installed in the reactor. On the bottom of the reactor, two porous tube diffusers (60 mm x 600 mm) connected to the air supply line were installed (also responsible for mixing during aeration).

The pilot-plant SBR was connected with a measuring and control system. The system consisted of a respiration meter, an analog and digital input/output board (I/O board) and a personal computer.

A continuous respiration meter (prototype of the RA-1000) was used, which consisted of a closed respiration vessel through which activated sludge could be pumped. The inflow and outflow dissolved oxygen concentration was measured using the same oxygen sensor, by periodically changing the flow direction (Spanjers, 1993).

INFLUENT

The influent used during this study was pre-settled domestic wastewater from the Bennekom Municipal Treatment Plant (The Netherlands). Acetic acid was added to this influent from a feed solution (500 ml of 80% acetic acid solution diluted in 30 l tap water). The COD of the acetic acid feed solution was periodically checked and the amount of solution dosed to the pilot plant was enough to supply an extra 100 mg COD/l to the influent wastewater. Average

values of the analyzed variables are presented in Table I.

Table I. Influent characteristics, after addition of acetic acid.

COMPONENT	CONCENTRATION	N# SAMPLES
COD (mg/l)	443 ± 106	37
COD_{vfa} (mg COD/l)	142 ± 22	20
S_A (mg COD/l)	132 ± 18	20
TKN (mg N/l)	71 ± 31	34
S_{NH} (mg N/l)	53 ± 22	37
S_{PO4} (mg P/l)	7 ± 3	37

SLUDGE FOR THE PILOT PLANT

To start operation of the pilot-plant SBR, seed sludge was taken from the sewage treatment plant in Bennekom (RWZI Bennekom), The Netherlands. The treatment plant's capacity was 22,000 population equivalent and it was a former oxidation ditch with alterations to achieve biological phosphorus removal.

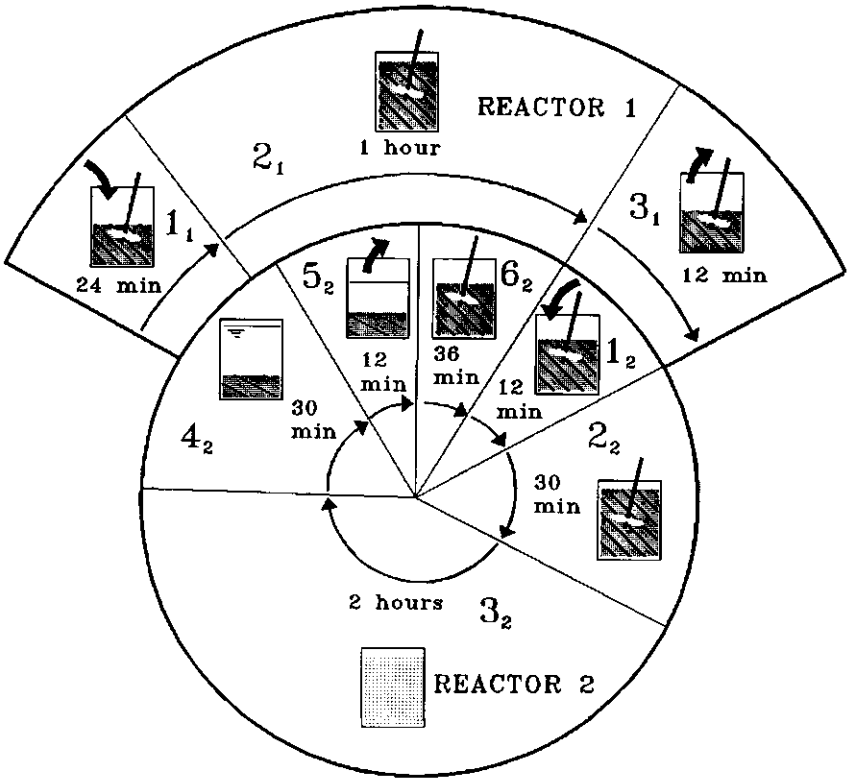
OPERATION OF THE PILOT-PLANT SBR

The pilot-plant SBR was operated for five months, with cycles of four hours. Data were collected during three months of operation. In Reactor 1, each cycle had three periods and in Reactor 2 each cycle had seven periods (see Figure 3). The periods in Reactor 1 were: i) MIXED FILL; ii) MIXED REACT; and iii) DRAW. The periods in Reactor 2 were: i) MIXED FILL; ii) MIXED REACT I; iii) AERATED REACT; iv) SETTLE; v) DRAW; and vi) MIXED REACT II. Figure 3 also schematically shows the timetable for these periods.

During the MIXED FILL period in Reactor 1, the reactor received 250 l pre-settled domestic wastewater plus the solution of acetic acid, an operation that lasted for 22 minutes. Then, for two minutes, 50 l of settled sludge from Reactor 2 was pumped by Pump 2 into Reactor 1. In Reactor 1, the MIXED REACT period lasted for one hour. During a DRAW period of 12 minutes, all the 300 l was pumped by Pump 1 into Reactor 2. During these periods, the reactor was stirred with the propeller.

The MIXED FILL period in Reactor 2 coincided with the DRAW period in Reactor 1. Reactor 2 received the 300 l contents from Reactor 1 within 12 minutes. After MIXED FILL, the MIXED REACT I period lasted for 30 minutes. During these periods, Reactor 2 was stirred with the propeller. The AERATED REACT period lasted for two hours, with the mixing done by the aeration system. The SETTLE period lasted for 30 minutes and in the middle of this period, Pump 2 pumped 50 l of thickened sludge from the bottom of Reactor 2 into Reactor 1 (at the end of MIXED FILL in Reactor 1). During the DRAW period in Reactor 2, 250 l of effluent was discharged for 12 minutes. After that, MIXED REACT II

started, in which the remaining 700 l of activated sludge in Reactor 2 was stirred by the propeller for 36 minutes.



STEPS

REACTOR 1

1_1 – MIXED FILL

2_1 – MIXED REACT

3_1 – DRAW

REACTOR 2

1_2 – MIXED FILL

2_2 – MIXED REACT I

3_2 – AERATED REACT

4_2 – SETTLE

5_2 – DRAW

6_2 – MIXED REACT II

Figure 3. Timetable for the SBR cycle (4h).

The discharge of excess sludge was done at a rate corresponding to 1/20 of the total volume per day. Once a day, 50 l of mixed liquor was discharged during AERATED REACT in Reactor 2. During this specific cycle, 200 l of effluent was discharged, instead of the 250 l during the other cycles.

The pH in Reactor 1 was not controlled during the cycles and was in the range of 7.1 to 8.3. In Reactor 2, the pH was kept around 7.2 by dosing NaOH solution. During the operation of the pilot-plant SBR, the average biomass concentration in Reactor 1 during the MIXED REACT period was: i) MLSS = 3.03 ± 0.28 g/l, ii) MLVSS = 2.53 ± 0.35 g/l. The average biomass concentration in Reactor 2 during the AERATED REACT period was: i) MLSS = 5.24 ± 0.81 g/l, ii) MLVSS = 4.04 ± 0.65 g/l. During the AERATED REACT period, aerobic conditions were maintained. The temperature of the activated sludge varied during the five months of operation between 14° C and 18° C, due to variation in the influent and air temperature.

Measurement of r was performed during the AERATED REACT period. The r values, based on the average for the last 15 minutes of the period, were used to compare with the denitrification rate in the MIXED REACT II period in Reactor 2. At this point, no readily biodegradable matter was present and no nitrification was taking place. According to equation **6**, r is equal to r_{end}. The relationship between denitrification rate (r_{NO3}) and r_{end} was used to determine F_{den}, according to equation **7**. The average r values for the last 15 minutes in the AERATED REACT period fluctuated in the range of 15 to 22 mg O_2/l*h. The calculated F_{den} was in the range of 0.2 to 0.6.

PARAMETER CALIBRATION

The parameters used in the models were either default values from the literature, or were calibrated by model simulation. The calibrations were based on respirogram analysis or laboratory analyses. Using a simulation programme (see Annex 3) written in SIMNON (Elmqvist *et al.*, 1990), the results for the differential equations system were compared with the measured respirogram or the measured S_A, S_{PO4} and nitrate concentration. Parameters were calibrated by trial and error until the simulation came close to the measured values. The parameters used are presented in Table II, indicating which ones were calibrated and which ones were default values.

ANALYSES

For monitoring the pilot-plant SBR operation and the experiment with the laboratory-scale SBR, laboratory analyses were performed, according to APHA (1992). Samples were taken from the influent and from the mixed liquor in the reactor at different times. Samples from the mixed liquor were filtrated using filter paper (Whatman glass microfibre 1 μm). All samples were analyzed for COD, nitrogen (S_{NH} and nitrate), phosphate (orthophosphate - Automated Ascorbic Acid Reduction Method), suspended solids (MLSS) and volatile suspended solids (MLVSS). During MIXED REACT in Reactor 1, samples were also analyzed for acetate as COD (S_A). The influent was also analyzed for volatile fatty acids as COD (COD_{VFA}), acetate as COD (S_A) and Total Kjeldahl Nitrogen (TKN).

Table II. Parameters

Parameter	Default value or calibration process	Reference
F_{den}	Respirogram + nitrate analysis	Chapter 3 - This thesis
K_1	Respirogram analysis	Chapter 3 - This thesis
K_2	Respirogram analysis	Chapter 3 - This thesis
K_{NH}	1.0 mg N/l	Henze *et al.* (1987)
K_S	20 mg COD/l	Henze *et al.* (1987)
$r_{m,NH}$	Respirogram analysis	Chapter 3 - This thesis
$r_{m,S}$	Respirogram analysis	Chapter 3 - This thesis
Y_H	0.5	Henze *et al.* (1987)
$f_{O/P}$	0.35 g O_2/g P	Smolders *et al.* (1994)
K_A	4 mg COD/l	Gujer *et al.* (1994)
K_{IPP}	20 mg PP/g PAO	Gujer *et al.* (1994)
K_{MAX}	340 mg PP/g PAO	Gujer *et al.* (1994)
K_P	0.01 mg P/l	Gujer *et al.* (1994)
K_{PHA}	10 mg PHA/g PAO	Gujer *et al.* (1994)
K_{PP}	10 mg PP/g PAO	Gujer *et al.* (1994)
q_{PHA}	104 mg COD/g PAO * h	Gujer *et al.* (1994)
q_{PP}	52 mgPP/g PAO * h	Gujer *et al.* (1994)
X_{PAO}	Simulation of equations **8-11** plus S_A and S_{PO4} analysis	Present study
Y_{PHA}	0.20 mg COD/mg P	Gujer *et al.* (1994)
Y_{PO4}	Simulation of equations **8-10** plus S_A and S_{PO4} analysis	Present study

To determine the total P contents in the sludge, the Persulfate Digestion Method was used. Sludge was sampled at the end of AERATED REACT in Reactor 2. The results are given in % P per g MLSS.

During the anaerobic period (MIXED REACT), the increase in phosphate in the liquid phase in the Reactor 1 was linear with time. Thus, the maximum rate of phosphate release (r_{PO4}) can be calculated by the increase in phosphate concentration. The results are given in mg P/l per hour.

RESULTS

Figure 4 (A) shows the evolution in time of the total P contents in the activated sludge in Reactor 2 at the end of the aerobic period (AERATED REACT). The value of the PAOs concentration (X_{PAO}) in Reactor 1 (Figure 4 [B]) was reached by calibrating the model for phosphorus release (equations **8-10**). In Figure 4 (C) the measured rate of P release in Reactor 1 (r_{PO4}) is also given.

For parameter calibration (X_{PAO} and Y_{PO4}), P release model response (equations **8-10**) during the anaerobic period was compared with the S_A and S_{PO4} measurements. The initial value for X_{PP} was assumed to be the total P contents in the sludge. The parameters used are shown in Table II. The calibration yielded X_{PAO} in Reactor 1 in the range of 0.4 to 0.7 g PAO/l and Y_{PO4} in the range of 0.54 to 0.59 mg P/mg COD. Figure 5 shows the results of one of these comparisons.

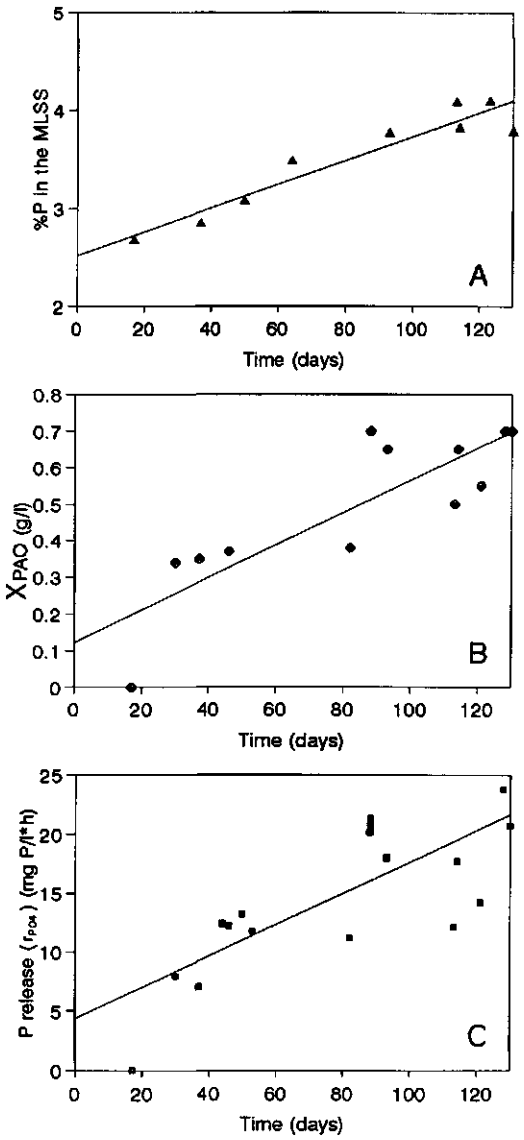


Figure 4. Values for: A) measured P contents in the sludge at the end of AERATED REACT in Reactor 2; B) X_{PAO} from model calibration (equations **8-10**); and C) calculated rate of phosphate release (r_{PO4}) during the anaerobic step (MIXED REACT) in Reactor 1, versus time.

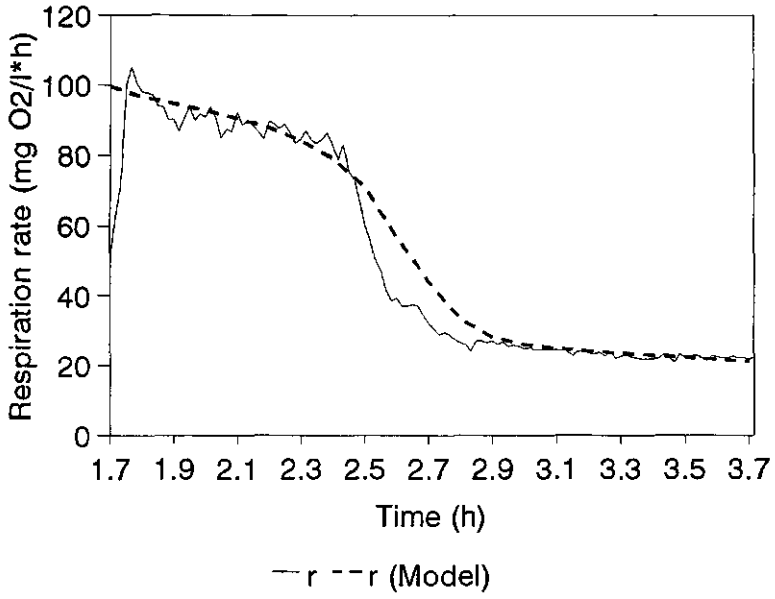


Figure 7. Measured respirogram from a cycle together with model response, for parameter calibration. Example from one SBR cycle.

A qualitative overview of the results shows that the parameters K_1, K_2, F_{den} and $r_{m,NH}$ varied over time analogous to that verified in Chapter 3 during long-term parameter evaluation in a nitrifying/denitrifying SBR.

To evaluate the predictability of the model (equations **1-5**, **7** and **8-13**), parameters from a previous cycle were used. Variables giving the initial condition of the substrate were from the cycle itself. Particularly for phosphate uptake, two situations were considered: a) only the X_{PAO} going to the anaerobic period are able to take up phosphate; b) all X_{PAO} (Reactors 1 and 2) are able to take up phosphate. Figure 8 shows an example of these predictions.

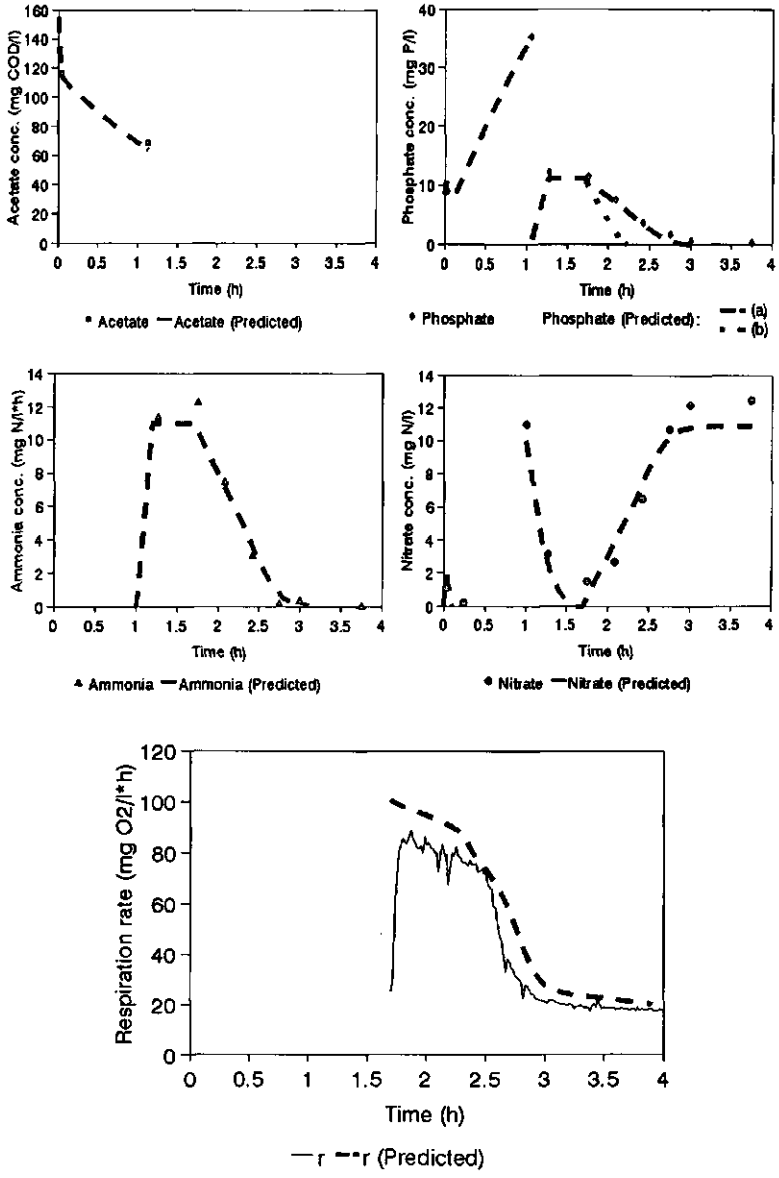


Figure 8. Measurements and predictions for acetate, phosphate, ammonia, nitrate and respiration rate, during a complete SBR cycle. Parameters used in the model are from the previous cycle. Variables representing the initial condition are from the cycle in the study. Example from one SBR cycle.

DISCUSSION

The increase in P removal activity can be associated with the P release rate. Appeldoorn *et al.* (1992) showed that this is an important condition for P uptake and that it can be associated with the presence of P-accumulating organisms.The evolution of P contents in the sludge, together with the rate of P release, shows that even for sludge from a biological P removal plant, the adopted acetate addition procedure can improve the P removal activity. Figure 4 shows that the values for X_{PAO} originated from the model for P release, and that they follow the same trend as P contents in the sludge and the rate for P release. It indicates that a combination of these measurements can help to estimate X_{PAO}. The quantification of X_{PAO} is very important for better quantification of the biological P removal process.

The simulation of the P release model (equations **8-10**) showed that it is a good representation of the process itself. However, some considerations about X_{PAO} and Y_{PO4} are important. In equation **8**, the rate of *PHA* storage is strongly related to X_{PAO}. To use the model as a tool for process control, therefore, a good estimation or determination of X_{PAO} is crucial. The range of 0.4 to 0.7 g PAO/l found in the simulations seems to be reasonable, compared with the results from similar installations (van Niel, 1993). The values for the stoichiometric factor Y_{PO4} (0.54 to 0.59 g P/g COD) differed from the 0.4 g P/G COD proposed by Gujer *et al.* (1994). Smolders *et al.* (1994) showed the influence of pH on this factor. Using the range of pH during the experiment (7.1 to 8.3) the results from Smolders *et al.* (1994) gave Y_{PO4} in the range of 0.49 to 0.72, which is closer to the values found in the simulations.

Calibration of the model during X_{PP} storage (equations **11** and **12**) showed that the model fit the measurements well. The same considerations about the influence of X_{PAO} in the model, as during the X_{PHA} storage step, are now valid. The X_{PAO} range of 0.1 to 0.25 g PAO/l out of simulations differs from the values during X_{PHA} storage. One explanation for this can be the system operation procedure. Because only a part of the total biomass goes through the anaerobic step, where *PHA* storage takes place, only this part can later perform *PP* storage. The determined X_{PAO} in Reactor 1 with 300 l (0.4 to 0.7 g PAO/l), when transferred to Reactor 2 with 1000 l became 0.12 to 0.21 g PAO/l, similar to the range from the calibration. This indicates that PAOs are only important to the model if they have been through the anaerobic step.

The inclusion of $r_{o,P}$ in the equation for r (equation **13**) shows that the model for one SBR cycle, presented in Chapter 3, can incorporate the biological phosphorus removal equations proposed by Gujer *et al.* (1994), in order to describe nutrient removal in an SBR. However, due to the low phosphate concentration at the beginning of AERATED REACT in Reactor 2, the contribution of $r_{o,P}$ to r in equation **13** is not very big. When nitrification takes place, it can not be measured well due to insufficient sensitivity of the measuring equipment (Spanjers and Klapwijk, 1990). Therefore, under the present experimental conditions, respirometry is a limited tool for monitoring biological phosphate removal in an SBR. However, for high phosphate concentrations, as reported by Smolders *et al.* (1994), respirometry can give relevant information about the process.

CONCLUSIONS

Measurement of P release rate and P contents in the sludge can be an indirect evaluation of X_{PAO}.

The model for *PHA* storage proposed by Gujer *et al.* (1994) (equations **8-10**), can be used to describe the anaerobic step of P release in an SBR treating domestic wastewater. The influence of pH on the stoichiometric factor Y_{PO4} should be considered. The results from the model calibration are in accordance with the values proposed by Smolders *et al.* (1994).

The model for X_{PP} storage proposed by Gujer *et al.* (1994) (equation **11**) can be used to describe the aerobic step of P uptake in an SBR treating domestic wastewater.

The incorporation of a fraction $r_{o,P}$ in the equation to describe r in an SBR (equation **13**), allows the use of the model proposed in chapter 3 in an SBR receiving domestic wastewater, with carbon oxidation, nitrification, denitrification and biological P removal.

NOMENCLATURE

COD	chemical oxygen demand (mass volume^{-1})
COD_{vfa}	volatile fatty acids as COD (mass volume^{-1})

F_{den}	ratio between anoxic equivalent respiration rate and aerobic respiration rate
$f_{O/P}$	ratio oxygen consumed by P uptake (mass mass^{-1})
K_1	empirical constant (mass volume^{-1} time^{-1})
K_2	empirical constant (time^{-1})
K_A	saturation coefficient for acetate, S_A (mass volume^{-1})
K_{IPP}	inhibition coefficient for X_{PP} storage (mass mass^{-1})
K_{MAX}	maximum ratio of X_{PP}/X_{PAO} (mass mass^{-1})
K_{NH}	saturation coefficient for S_{NH} oxidation (mass volume^{-1})
K_{O2}	saturation coefficient for S_{O2} (mass volume^{-1})
K_P	saturation coefficient for S_{PO4} in PP storage (mass volume^{-1})
K_{PHA}	saturation coefficient for X_{PHA} (mass mass^{-1})
K_{PP}	saturation coefficient for poly-phosphate, X_{PP} (mass mass^{-1})
K_S	saturation coefficient for S_S oxidation (mass volume^{-1})
MLSS	total suspended solids (mass volume^{-1})
MLVSS	total volatile suspended solids (mass volume^{-1})
P	phosphorus
PHA	poly-ß-hydroxyalkanoates
PP	poly-phosphate
q_{PHA}	rate constant for storage of PHA (mass mass^{-1} time^{-1})
q_{PP}	rate constant for storage of PP (mass mass^{-1} time^{-1})
r	respiration rate (mass volume^{-1} time^{-1})
r_{end}	endogenous respiration rate (mass volume^{-1} time^{-1})
$r_{m,NH}$	maximum rate of S_{NH} oxidation or nitrification capacity (mass volume^{-1} time^{-1})

$r_{m,S}$	maximum rate of S_S consumption (mass volume^{-1} time^{-1})
r_{NH}	rate of S_{NH} oxidation (mass volume^{-1} time^{-1})
r_{NO3}	rate of nitrate reduction (mass volume^{-1} time^{-1})
$r_{o,NH}$	respiration rate for S_{NH} oxidation (mass volume^{-1} time^{-1})
$r_{o,P}$	respiration rate for P uptake (mass volume^{-1} time^{-1})
$r_{o,S}$	respiration rate for S_S oxidation (mass volume^{-1} time^{-1})
r_{PHA}	rate of X_{PHA} storage (mass volume^{-1} time^{-1})
r_{PO4}	rate of S_{PO4} release (mass volume^{-1} time^{-1})
r_{PP}	rate of X_{PP} storage (mass volume^{-1} time^{-1})
r_S	rate of S_S consumption (mass volume^{-1} time^{-1})
r_{SA}	rate of S_A uptake (mass volume^{-1} time^{-1})
SBR	Sequencing Batch Ractor
S_A	acetate concentration (mass volume^{-1})
S_{NH}	soluble ammonia nitrogen concentration (mass volume^{-1})
S_{O2}	dissolved oxygen concentration (mass volume^{-1})
S_{PO4}	soluble ortho phosphate concentration (mass volume^{-1})
S_S	readily biodegradable substrate concentration (mass volume^{-1})
t	time of reaction (time)
TKN	Total Kjeldahl Nitrogen (mass volume^{-1})
X_{PAO}	phosphorus accumulating organisms concentration (mass volume^{-1})
X_{PHA}	cell internal storage product of phosphorus accumulating organisms concentration (mass volume^{-1})
X_{PP}	poly-phosphate concentration (mass volume^{-1})
Y_H	yield for heterotrophic biomass (mass mass^{-1})

Y_{PO4} *PP* requirement (S_{PO4} release) for *PHA* storage (mass mass^{-1})

REFERENCES

APHA (1992). *Standard methods for the examination of water and wastewater.* 18th edition. American Public Health Association, Washington, DC.

Appeldoorn, K.J. (1993). Ecological aspects of the biological phosphate removal from wastewaters. PhD. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Appeldoorn, K.J., Kortstee, G.J.J. and Zehnder, A.J.B. (1992). The fill and draw system as method to study the enhanced biological phosphate removal by activated sludge under defined conditions. *Wat. Res.* ***26***:453-460.

Elmqvist, H., Åström, K.J., Schönthal, T. and Wittenmark, B. (1990). *Simnon - User's guide for MS DOS computers, V. 3.0.* SSPA Systems, Box 24001, S-400 22 Göteborg, Sweden.

Gujer, W., Henze, M., Mino, T., Matsuo T., Wentzel, M.C. and Marais, G.v.R. (1994). The Activated Sludge Model No. 2: biological phosphorus removal. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes. 22-24 August, Copenhagen, Denmark.

Henze, M., Grady, C.P.L. Jr., Gujer, W., Marais, G.v.R. and Matsuo T. (1987). Activated Sludge Model No. 1. IAWPRC *Scientific and Technical Report No. 1*, IAWPRC, London, ISSN 1010-707X.

Manning, J.F., Jr. and Irvine, R.L. (1985). The biological removal of phosphorus in a sequencing batch reactor. *J. Water Pollut. Control Fed.* **57**:87-94.

Marais, G.v.R., Loewenthal, R.E. and Siebritz, I.P. (1983). Observations supporting phosphate removal by biological excess uptake - a review. *Wat. Sci. Tech.* **15**:15-41.

van Niel, E.W.J. (1993). Modelling and optimalization of biological phosphate removal from wastewater (in Dutch). STW and RIZA, The Netherlands.

Shin, H.-S. and Park, H.-S. (1991). Enhanced nutrient removal in porous biomass carrier sequencing batch reactor (PBCSBR). *Wat. Sci. Tech.* **23**:719-728.

Smolders, G.J.F., van Loosdrecht, M.C.M. and Heijnen, J.J. (1994). A metabolic model for the biological phosphorus removal process. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes. 22-24 August, Copenhagen, Denmark.

Spanjers, H. (1993). Respirometry in activated sludge. PhD. thesis, Wageningen Agricultural University, Wageningen, The Netherlands.

Spanjers, H. and Klapwijk, A. (1990). On-line meter for respiration rate and short-term biochemical oxygen demand in the control of the activated sludge process. In *Advances in Water Pollution Control,* Proc. 5th IAWPRC Workshop, 26 July-3 August, Yokohama and Kyoto, Japan.

Stensel, H.D. and Barnard, J.L. (1992). Principles of biological nutrient removal. In *Design and retrofit of wastewater treatment plants for biological nutrient removal.* Randal, C.W., Barnard, J.L. and Stensel, H.D. (eds.) Technomic Publishing Co. Inc., Pennsylvania, USA.

Vinçonneau, J.C., Schaack, F., Boschet, A.F., Chevalier, D., Villesot, D., Jaubert, M., Laval, Ch. and Lambert, S. (1985). The problem of phosphorus in France - its presence in natural waters and biological phosphorus removal. *Wat. Sci. Tech.* **17**:1-9.

Vlekke, G.J.F.M., Comeau, Y. and Oldham, W.K. (1988). Biological phosphate removal from wastewater with oxygen or nitrate in sequencing batch reactors. *Environ. Tech. Letters.* **9**:791-796.

Yeoman, S., Stephenson, T., Lester, J.N. and Perry, R. (1988). The removal of phosphorus during wastewater treatment: a review. *Environ. Pollut.* **49**:183-233.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5 SUMMARY AND CONCLUSIONS

The essence of this thesis is the development and validation of mathematical models for the activated sludge process in an SBR treating real domestic wastewater. A simple model was developed to be used for on-line monitoring. The models, however, have adequate conceptual basis for use as theoretical background for the development of control strategies. The starting points for the model development and simplification were: i) the Activated Sludge Model No. 1, for carbon oxidation, nitrification and denitrification (Henze *et al.*, 1987); and ii) the Activated Sludge Model No. 2, for biological phosphorus removal (Gujer *et al.*, 1994; Henze *et al.*, 1994).

In every situation, the model construction and its validations were strongly directed by the main objectives of the whole study, which can be summarized as:

- the development and validation of simplified mathematical models for activated sludge processes in an SBR treating real domestic wastewater;
- the application of these simplified models for analysing the respirometric response and for obtaining information about the oxygen uptake for the different processes;
- the application of the monitored respirometric values for model calibration and determination of parameter values, used to predict the processes in the following cycle;
- the use of models as theoretical background for the development of control

strategies;

- relating the basic time scale for the models to the short term;
- for variation of nitrification capacity, relating the basic time scale to the long term.

The research was performed with a Sequencing Batch Reactor (SBR) activated sludge pilot plant of 1 m^3. In the first period, an SBR pilot plant receiving domestic wastewater was operated to perform carbon oxidation and nitrification. In the second period, the SBR pilot plant operation included denitrification. In the third period, the system achieved biological phosphorus removal. During the two and a half years of operation of the SBR pilot plant, monitored results were compared with the model predictions.

For the nitrifying SBR (first period), two simplified mathematical activated sludge models were developed. The first model gives the response of the respiration rate in an SBR with nitrification, the oxidation of readily biodegradable matter, and endogenous respiration during one cycle. This model is used to predict the respiration rate during a complete SBR cycle, achieved by using parameter values calibrated during the previous cycle, some default values, and information about the ammonia concentration in the influent. The endogenous respiration rate is described with an exponential equation. An on-line monitoring procedure based on respirometry was used and the measurements were used to calibrate the parameters used in the model. The proposed model was in accordance with the measured respiration rates. It can therefore be concluded that the respiration rate has good potential as a variable for on-line monitoring and control of an SBR with nitrification.

The second model is used to predict the changes in nitrification capacity after a change in the loading rate and/or the sludge wastage rate. During long-term operation, nitrification capacity variation was significant and too complex to be predicted. This model can explain the variation trend, but it cannot explain the abrupt changes.

For the nitrifying/denitrifying SBR (second period) a mathematical model for the behaviour of respiration rate and nitrate removal in an activated sludge SBR with nitrification, denitrification and carbon oxidation is presented. This model is based on the response of the respiration rate measured during nitrification and carbon oxidation and the nitrate removal rate during the post-denitrification period. For model validation, an SBR pilot plant receiving domestic wastewater was operated and the results were compared with the model. The respiration rate was used to calibrate several parameters of the model. The simulation values were in good agreement with the measured respiration rate and nitrate removal. This model is able to predict respiration rate and denitrification in one cycle with parameters taken from the previous cycle. Parameter changes followed during long-term operation showed significant variation, too complex to be predicted. It can be concluded that the respiration rate is a good variable for on-line monitoring of an activated sludge SBR with nitrification/denitrification processes.

For an SBR with biological phosphorus removal (third period) a mathematical model for an activated sludge SBR with nitrification, denitrification, carbon oxidation and phosphorus removal is proposed. This model is based on the response of the respiration rate measured during nitrification, carbon oxidation and phosphorus removal, together with the behaviour of phosphate and acetate as proposed by Gujer *et al.* (1994) for the Activated Sludge Model

No. 2.

For model validation, an SBR pilot plant receiving settled domestic wastewater plus acetic acid solution was operated, and the results were compared with the model. The simulation values for phosphate, acetate, ammonia, nitrate and respiration rate were in good agreement with the measured ones. However, in activated sludge plants treating domestic wastewater with biological phosphorus removal, the respiration related to the phosphate uptake process was low compared with the other oxygen consumption processes, too low to be accurately measured. It can be concluded from these results that the respiration rate is a good variable for on-line monitoring of an activated sludge SBR with nitrification/denitrification processes, but its use is limited to the phosphorus removal process.

Within the above framework, as well as that of the studies for each technological phase (nitrification, denitrification and biological phosphorus removal), the following conclusions are presented.

The model for the respiration rate (r) during one cycle, including nitrification, oxidation of readily biodegradable matter and endogenous respiration, gives a good simulation of the measured respiration rate.

A simulation with this model, using parameters calculated from the previous cycle together with the variables for ammonia, nitrite and readily biodegradable matter from the influent wastewater, gives a good prediction of the total oxygen consumption and distribution during one cycle.

The endogenous respiration rate in a nitrifying SBR treating domestic wastewater can be modelled by an empirical exponential equation with a negative exponent.

During long-term operation, parameter variation is significant and too complex to be predicted. In the particular case of nitrification capacity variation in an SBR during long-term operation, the model can explain the variation trend but cannot explain the abrupt changes. Regular parameter calibration is necessary.

The model for the rate of nitrate reduction can be used to represent the denitrification process in an SBR treating domestic wastewater, and is able to predict denitrification in one cycle with parameters taken from the previous cycle.

The model for the respiration rate (r) can be used for the nitrification and carbon oxidation processes during the aerobic period in a denitrifying SBR treating domestic wastewater.

Measurement of the P release rate and P contents in the sludge can be an indirect evaluation of the phosphorus accumulating organism concentration.

The model for the internal cell storage products of phosphorus accumulating organisms proposed by Gujer *et al.* (1994) can be used to describe the anaerobic step of phosphorus release in an SBR treating domestic wastewater. The influence of pH on the stoichiometric factor Y_{PO4} should be considered. The results from the model's calibration are in accordance with the values proposed by Smolders *et al.* (1994).

The model for poly-phosphate storage proposed by Gujer *et al.* (1994) can be used to describe the aerobic step of phosphorus uptake in an SBR treating domestic wastewater.

The incorporation of a fraction for the respiration rate for phosphorus uptake in the equation to describe the respiration rate (r) in an SBR, allows use of the model in an SBR receiving domestic wastewater with carbon oxidation, nitrification, denitrification and biological P removal.

Several important points for discussion arose out of this study which could lead to further research on the subject. A set of propositions follows.

Denitrification plays an important role in the activated sludge process. In addition to nitrogen removal, it is also important for biological phosphorus removal, and it can be a good alternative to oxygen for organics stabilization. It can, therefore, be a good direction to pursue for research.

Readily biodegradable substrate plays an important role in the denitrification and biological phosphorus removal processes. A large part of the carbon removed by pre-sedimentation can be converted into readily biodegradable substrate. This particular conversion process should be further researched.

A reliable procedure for the estimation of phosphate accumulating organism concentration in the activated sludge is an important step for the biological phosphorus removal modelling.

Although the respirometer used in the present study (Spanjers, 1993) is a strong tool for monitoring the activated sludge process, the oxygen sensor is a weak but essential component. For long-term operation, a stronger sensor should be developed.

REFERENCES

Gujer, W., Henze, M., Mino, T., Matsuo, T., Wentzel, M.C. and Marais, G.v.R. (1994) The Activated Sludge Model No. 2: biological phosphorus removal. *Proc. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes.* Copenhagen, Denmark. section 1.

Henze, M., Grady, C.P.L. Jr., Gujer, W., Marais, G.v.R. and Matsuo, T. (1987). *Activated Sludge Model No.1.* IAWPRC Sci. and Technical Reports No.1. IAWQ. London. ISSN 1010-707X.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M.C. and Marais, G.v.R. (1994). Activated Sludge Model No. 2. *Proc. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes.* Copenhagen, Denmark. section 3.

Smolders, G.J.F., van Loosdrecht, M.C.M. and Heijnen, J.J. (1994). A metabolic model for the biological phosphorus removal process. *Proc. IAWQ Specialized Seminar: Modelling and Control of Activated Sludge Processes.* Copenhagen, Denmark. section 10.

Spanjers, H. (1993). *Respirometry in activated sludge.* PhD. thesis. Wageningen Agricultural University, Wageningen, The Netherlands.

ANNEX 1

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CONTINUOUS SYSTEM SBRNIT


"MODEL FOR THE RESPONSE OF RESPIRATION RATES IN A SBR THAT
"RECEIVES PRE-SETTLED DOMESTIC WASTEWATER, WITH NITRIFICATION
"AND CARBON OXIDATION BIOMASS POPULATION.


TIME t
STATE SS SNH SNO2 NO3 DOr V X
DER dSS dSNH dSNO2 dNO3 dDOr dV dX



"CONSTANTS


Qi : 1000       "influent wastewater flow (l/h)
SNHi : 65       "influent SNH into the SBR (mgN/l)
SSi : 52        "influent SS into the SBR (mgCOD/l)

K1 : 25         "empirical constant (mgO2/l*h)
K2 : 0.13       "empirical constant (1/h)
KNH : 0.7       "half-saturation coefficient for SNH (mgN/l)
KNO2 : 1.0      "half-saturation coefficient for SNO2 (mgN/l)
KS : 20         "half-saturation coefficient for SS (mgCOD/l)

rmNH : 9        "maximum rate of SNH oxidation (mgN/l*h)
rmNO2 : 8       "maximum rate of SNO2 oxidation (mgN/l*h)
rmS : 240       "maximum rate of SS consumption (mgCOD/l*h)

Yh : 0.5        "yield for heterotrophic biomass

DOs : 8         "oxygen saturation concentration (mgO2/l)
Kla : 11        "overall mass-transfer coefficient (1/h)
Vm : 1000       "maximum volume of mixed liquor in SBR (l)


"INITIAL VALUES

SS : 0          "SS in SBR (mgCOD/l)
SNH : 0         "SNH in SBR (mgN/l)
SNO2 : 0        "SNO2 in SBR (mgN/l)
NO3 : 37        "NO3 concentration in SBR (mgN/l)
DOr : 5         "DO in the SBR (mgO2/l)
V : 500         "volume of mixed liquor in the SBR (l)
X : 4           "biomass concentration in the SBR (g MLVSS/l)
```

```
"MODEL EQUATIONS


dSS = - rS + A
dSNH = - rNH + B
dSNO2 = - rNO2t + C
dNO3 = - rNO3 + D

dDOr = OT-r
OT = Kla*(DOs-DOr)
"OT : net input in the aerated period

dV = IF V<Vm THEN Qi ELSE 0
dX = IF V<Vm THEN -Qi/V*X ELSE 0



"AUXILIARY VARIABLES


A = IF V<Vm THEN Qi/V*(SSi-SS) ELSE 0
B = IF V<Vm THEN Qi/V*(SNHi-SNH) ELSE 0
C = IF V<Vm THEN -Qi/V*SNO2 ELSE 0
D = IF V<Vm THEN -Qi/V*NO3 ELSE 0
E = Vm/V



"RATES


rS = IF SS>0 THEN (rmS*SS/(KS+SS))*E ELSE 0
roS = (1-Yh)*rS

rNH = IF SNH>0 THEN (rmNH*SNH/(KNH+SNH))*E ELSE 0
roNH = 3.43*rNH

rNO2t = -rNH + rNO2
rNO2 = IF SNO2>0 THEN (rmNO2*SNO2/(KNO2+SNO2))*E ELSE 0
roNO2 = 1.14*rNO2

rNO3 = -rNO2

rend = E*K1*exp(-K2*t)


r = roS + roNH + roNO2 + rend



"SPECIFIC RESPIRATION RATE

Sr = r/X

END
```

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CONTINUOUS SYSTEM NITRCAP

"MODEL FOR SIMULATE THE NITRIFICATION CAPACITY ADAPTATION DURING
"LONG-TERM OPERATION IN AN ACTIVATED SLUDGE SBR, OPERATED WITH
"DIFFERENT CYCLE TIME.



TIME t
STATE rmNH
DER drmNH


"CONSTANTS

bA : 0          " decay coefficient for autotrophic biomass (d-1)
mumax : 0.1     "maximum specific growth rate for autotrophic
                "biomass (d-1)
Qi3 : 1500      "average flow during 8h Cyc. (3 X per day) (l/d)
Qi2 : 1000      "average flow during 12h Cyc. (2 X per day) (l/d)
SNHi : 65       "influent SNH into the SBR  (mgN/l)
SNHe : 0        "effluent SNH from the SBR  (mgN/l)
t1 : 15         "starting time for Cycle 12  (d)
theta3 : 31     "sludge retention time 8h cycle  (d)
theta2 : 76     "sludge retention time 12 h cycle  (d)
V : 1000        "reactor volume  (l)


"INITIAL VALUES


rmNH : 120      "nitrification capacity (mgN/l.d)


"MODEL EQUATIONS


theta = IF t<t1 THEN theta3 ELSE theta2
Qi = IF t<t1 then Qi3 ELSE Qi2

drmNH = mumax*Qi*(SNHi-SNHe)/V - rmNH/theta - bA*rmNH
rmNHh = rmNh/24
romNH = rmNHh*4.57

"romNH = respiration rate for nitrification (mgO2/l*h)

END
```

ANNEX 2

```
CONTINUOUS SYSTEM SBRDEN


"MODEL FOR THE RESPONSE OF RESPIRATION RATES IN A SBR THAT
"RECEIVES PRE-SETTLED DOMESTIC WASTEWATER, WITH NITRIFICATION,
"CARBON OXIDATION AND DENITRIFICATION BIOMASS POPULATION.


TIME t
STATE SS SNH NO3 DOr V X
DER dSS dSNH dNO3 dDOr dV dX


"CONSTANTS

Qi : 1200       "influent wastewater flow (l/h)
SNHi : 55       "influent SNH into the SBR (mgN/l)
SSi : 45        "influent SS into the SBR (mgCOD/l)

Fden : 0.55     "denitrifier fraction of heterotrophic biomass
K1 : 21         "empirical constant (mgO2/l*h)
K2 : 0.07       "empirical constant (1/h)
KNH : 1.0       "half-saturation coefficient for SNH (mgN/l)
KS : 20         "half-saturation coefficient for SS (mgCOD/l)

rmNH : 5.8      "maximum rate of SNH oxidation (mg N/l*h)
rmS : 240       "maximum rate of SS consumption (mgCOD/l*h)

Yh : 0.5        "yield for heterotrophic biomass

t1 : 1          "start aeration (h)
t2 : 9          "end of aeration (h)
Vm : 1000       "maximum volume of mixed liquor in the SBR (l)

Dl : 0          "limiting oxygen concentration (mgO2/l)
Nl : 0          "limiting NO3 concentration (mgNO3-n/l)

DOs : 8         "oxygen saturation concentration (mgO2/l)
Kla : 11        "overall mass-transfer coefficient (1/h)


"INITIAL VALUES
SS : 0          "SS in the SBR (mgCOD/l)
SNH : 0         "SNH in the SBR (mgN/l)
NO3 : 33        "NO3 concentration in the SBR (mgN/l)
DOr : 5         "initial DO in the SBR (mgO2/l)
V : 500         "volume of mixed liquor in the SBR (l)
X : 4           "biomass concentration in the SBR (g MLVSS/l)
```

```
"MODEL EQUATIONS

dSS = - rS + A
dSNH = - rNH + B
dNO3 = - rNO3 + C

dDOr = OT-ra
OT = IF t>t1 AND t<t2 THEN Kla*(DOs-DOr) ELSE 0
"OT : net input in the aerated period
ra = IF DOr>Dl then r ELSE 0
"ra : aerobic respiration

dV = IF V<Vm THEN Qi ELSE 0
dX = IF V<Vm THEN -Qi/V*X ELSE 0


"AUXILIARY VARIABLES


A = IF V<Vm THEN Qi/V*(SSi-SS) ELSE 0
B = IF V<Vm THEN Qi/V*(SNHi-SNH) ELSE 0
C = IF V<Vm THEN -Qi/V*NO3 ELSE 0
D = Vm/V
E = IF DOr>Dl THEN 1 ELSE IF NO3>Nl THEN Fden ELSE 0


"RATES


rS = IF SS>0 THEN (rmS*SS/(KS+SS))*E*D ELSE 0
roS = (1-Yh)*rS

rNH = IF SNH>0 AND DOr>Dl THEN rmNH*SNH/(KNH+SNH)*D ELSE 0
roNH = 4.57*rNH

rNO3 = IF DOr>Dl THEN -rNH ELSE raNO3
raNO3 = IF NO3>Nl THEN (roS + rend) / 2.86 ELSE 0

rend = K1*exp(-K2*t)*E*D


r = roS + roNH + rend


"SPECIFIC RESPIRATION RATE


Sr = r/X

END
```

```
CONTINUOUS SYSTEM NITRCAP

"MODEL FOR SIMULATE THE NITRIFICATION CAPACITY ADAPTATION DURING
"LONG-TERM OPERATION IN AN ACTIVATED SLUDGE SBR.

TIME t
STATE rmNH
DER drmNH

"CONSTANTS

bA : 0          "decay coefficient for autotrophic biomass (d-1)
mumax : 0.1     "maximum specific growth rate for autotrophic
                "biomass (d-1)
Qi : 1500       "average flow during 8h Cyc. (3 X per day) (l/d)

SNHe : 0        "effluent SNH from the SBR  (mgN/l)
Qs : 66.67      "average sludge discharge flow (l/d)
V : 1000        "reactor volume  (l)

t1 : 15         "limit between period 1 and 2  (d)
t2 : 25         "limit between period 2 and 3  (d)

A : 70          "influent SNH into SBR during period 1 (mgN/l)
B : 50          "influent SNH into SBR during period 2 (mgN/l)
C : 75          "influent SNH into SBR during period 3 (mgN/l)

"INITIAL VALUES

rmNH : 120      "nitrification rate at the beginning  (mgN/l.d)

"MODEL EQUATIONS

SNHi=IF t<t1 THEN A ELSE IF t<t2 THEN B ELSE C

drmNH = mumax*Qi*(SNHi-SNHe)/V - Qs*rmNH/V - bA*rmNH
rmNHh = rmNh/24
romNH = rmNHh*4.57

"romNH = respiration rate for nitrification (mgO2/l*h)

END
```

ANNEX 3

```
CONTINUOUS SYSTEM PHASTO

"MODEL FOR THE VARIATION OF ACETATE, PO4, NITROGEN AND OXYGEN IN
"A SBR THAT RECEIVES PRE-SETTLED DOMESTIC WASTEWATER PLUS ACETATE
"AND THEN NITRIFICATION, CARBON OXIDATION, DENITRIFICATION AND
"POLY-P BIOMASS POPULATION. EQUATIONS FROM BERNARDES et al. PLUS
"ACTIVATED SLUDGE MODEL No 2.


TIME t
STATE SS SA SNH NO3 SPO4 PO4r DOr X V
DER dSS dSA dSNH dNO3 dSPO4 dPO4r dDOr dX dV


"CONSTANTS


DOi : 7          "DO concentration in the returned sludge (mg O2/l)
fAS : 0.9         "initial ratio SA/SS
Qi : 1500         "return sludge flow (l/h)
NO3i : 15        "NO3 concentration in the returned sludge (mgN/l)
SPO4i : 1        "PO4 concentration in the returned sludge (mgP/l)
Xi : 15           "inflow biomass concentration (g MLVSS/l)
Xppin : 30        "initital available Xpp in the sludge (mgP/gX)

qPHA : 104        "rate for PHA storage (mgCOD/gPAO*h)
rmS : 120         "maximum rate of Ss consumption (mgCOD/gX*h)
rmNH : 3.2        "maximum rate of SNH oxidation (mgN/gX*h)

K1 : 7            "constant affecting rend (mgO2/gX*h)
K2 : 0.07         "constant affecting rend (1/h)
KA : 4            "half-saturation coefficient for SA (mgCOD/l)
kNH : 1.0         "half-saturation coefficient for SNH (mgN/l)
KS : 20           "half-saturation coefficient for SS (mgCOD/l)
Kpp : 0.01       "half-saturation coefficient for Xpp (gPP/gPAO)

Fden : 0.55      "denitrifier fraction of heterotrophic biomass
fpao : 0.2        "fraction of PAO in sludge

Yh : 0.5          "yield for heterotrophic biomass (gCOD/gCOD)
YPO4 : 0.55       "PO4 released for PHA storage (gP/gCOD)

Dl : 0.1          "limiting oxygen concentration (mgO2/l)
Nl : 0.1          "limiting NO3 concentration (mgN/l)
Vm : 300          "maximum volume of mixed liquor in SBR (l)


"INITIAL VALUES


SS : 160          "SS in SBR (wastewater+Acetate) (mgCOD/l)
SA : 145          "SA in SBR (wastewater+Acetate) (mgCOD/l)
SNH : 50          "SNH in SBR (wastewater) (mgN/l)
SPO4 : 8.5        "PO4 concentration in SBR (wastewater) (mgP/l)
V : 250           "initial volume of wastewater in SBR (l)
```

```
"MODEL EQUATIONS

dSS = - rS + A - rPHA
dSA = - rPHA + B - rS*fAS
dSNH = - rNH + C
dNO3 = - rNO3 + D
dSPO4 = IF NO3>Nl OR DOr>Dl THEN E ELSE YPO4 * rPHA + E
dPO4r = YPO4 * rPHA

dDOr = IF V<Vm THEN Qi/V*(DOi-DOr)-ra ELSE -ra
ra = IF DOr>Dl then r ELSE 0
"ra : aerobic respirations

dV = IF V<Vm THEN Qi ELSE 0
dX = IF V<Vm THEN Qi/V*(Xi-X) ELSE 0


"AUXILIARY VARIABLES


A = IF V<Vm THEN -Qi/V*SS ELSE 0
B = IF V<Vm THEN -Qi/V*SA ELSE 0
C = IF V<Vm THEN -Qi/V*SNH ELSE 0
D = IF V<Vm THEN Qi/V*(NO3i-NO3) ELSE 0
E = IF V<Vm THEN Qi/V*(SPO4i-SPO4) ELSE 0
F = IF DOr>Dl THEN 1 ELSE IF NO3>Nl THEN Fden ELSE 0
G = IF DOr>Dl or NO3>Nl THEN 1 ELSE 0
H = (Xpp/(Xpao*1000))/(Kpp+Xpp/(Xpao*1000))

Xpao = IF X>0 THEN fpao*X ELSE 0.001

Xpp = Xppi-PO4r
Xppi = Xppin*X


"RATES


rS = IF SS>0 THEN X * G *(rmS*SS/(KS+SS))*F ELSE 0
roS = rS * (1-Yh)

rPHA = IF G<1 AND SA>0 THEN (qPHA * SA/(KA+SA))*H*Xpao ELSE 0

rNH = IF SNH>0 AND DOr>Dl THEN rmNH*SNH/(KNH+SNH) * X ELSE 0
roNH = 4.57*rNH

rNO3 = IF DOr>Dl THEN -rNH ELSE raNO3
raNO3 = IF NO3>Nl THEN (rS + rend) / 2.86 ELSE 0

rend = X*K1*exp(-K2*t)*F


r = roNH + roS + rend

END
```

```
CONTINUOUS SYSTEM PPSTO

"MODEL FOR THE RESPONSE OF RESPIRATION RATE AND PHOSPHORUS IN AN
"ANOXIC/AEROBIC SBR (REACTOR 2) THAT RECEIVES MIXED LIQUOR FROM
"AN ANAEROBIC SBR (REACTOR 1), WITH NITRIFICATION, CARBON
"OXIDATION, DENITRIFICATION AND PHOSPHORUS REMOVAL BIOMASS
"POPULATION.


TIME t
STATE SS SNH NO3 SPO4 DOr V X Xpao Xpha Xpp
DER dSS dSNH dNO3 dSPO4 dDOr dV dX dXpao dXpha dXpp


"CONSTANTS

Qi : 1500        "return sludge flow (l/h)
SSi : 80         "SS in Reactor 1 (mg COD/l)
SNHi : 45        "SNH in Reactor 1 (mgN/l)
NO3i : 0         "nitrate concentration in Reactor 1 (mgN/l)
SPO4i : 40       "PO4 concentration in Reactor 1 (mgP/l)
Xi : 2.5         "biomass concentration in Reactor 1 (g MLVSS/l)
Xphai : 90       "PHA concentration in Reactor 1 (mg COD/l)
Xppi : 10        "PP concentration in Reactor 1 (mgP/l)

K1 : 10.5        "empirical constant (mgO2/l*h*g MLVSS)
K2 : 0.26        "empirical constant (1/h)
Kipp : 0.02      "inhibition coef. for Xpp storage (mgPP/mgXpao)
Kmax : 0.34      "maximum ratio Xpp/Xpao (mgPP/mgXpao)
KNH : 1.0        "half-velocity constant for SNH (mgN/l)
KP : 0.2         "half-saturation coefficient for SPO4 (mgP/l)
Kpha : 0.01      "half-saturation coef. for Xpha (mgPHA/mgXpao)
KS : 20          "half-saturation coef. for SS (mgO2/l)

qPP : 52         "rate constant for storage of PP (mgPP/gXpao*h)
rmS : 120        "maximum rate of SS consumption (mgCOD/l*h*gX)
rmNH : 3.3       "maximum rate of SNH oxidation (mgN/l*h*gX)

Yh : 0.5         "yield for heterotrophic biomass
Ypha : 0.20      "PHA requirement for PP storage (mgCOD/mgP)

Fden : 0.55      "denitrifier fraction of heterotrophic biomass
fOP : 0.35       "ratio O2 used per SPO4 uptaked (mgO2/mgP)
fpao : 0.2       "fraction of PAO in the biomass

t1 : 0.7         "start aeration (h)
t2 : 2.7         "end of aeration (h)

Dl : 0           "limiting oxygen concentration (mgO2/l)
Nl : 0           "limiting NO3 concentration (mgN/l)

DOs : 8          "oxygen saturation concentration (mgO2/l)
Kla : 30         "overall mass-transfer coefficient (1/h)
Vm : 1000        "maximum volume of mixed liquor in Reactor 2 (l)
```

```
"INITIAL VALUES

SS : 0          "SS in Reactor 2 (mgO2/l)
SNH : 0         "SNH in Reactor 2 (mgN/l)
NO3 : 12        "NO3 concentration in Reactor 2 (mgN/l)
SPO4 : 1        "PO4 concentration in Reactor 2 (gmP/l)
DOr : 0         "DO in Reactor 2 (mgO2/l)
V : 700         "volume of mixed liquor in Reactor 2 (l)
X : 4.7         "biomass concentration in Reactor 2 (g MLVSS/l)
Xpao : 0.01     "PAO concentration in Reactor 2 (g MLVSS/l)
Xpha : 0        "PHA concentation in Reactor 2 (mgCOD/l)
Xpp : 40        "PP concentration in Reactor 2 (mgP/l)


"MODEL EQUATIONS

dSS = - rS + A
dSNH = - rNH + B
dNO3 = - rNO3 + C
dSPO4 = - rPP + D

dDOr = OT-ra
OT = IF t>t1 AND t<t2 THEN Kla*(DOs-DOr) ELSE 0
"OT : net input in the aerated period
ra = IF DOr>Dl then r ELSE 0
"ra : aerobic respiration

dV = IF V<Vm THEN Qi ELSE 0
dX = IF V<Vm THEN Qi/V*(Xi-X) ELSE 0
dXpao = IF V<Vm THEN Qi/V*Xi*fpao ELSE 0
dXpha = IF V<Vm THEN Qi/V*Xphai ELSE -Ypha*rPP
dXpp = IF V<Vm THEN Qi/V*(Xppi-Xpp) ELSE rPP


"AUXILIARY VARIABLES

A = IF V<Vm THEN Qi/V*(SSi-SS) ELSE 0
B = IF V<Vm THEN Qi/V*(SNHi-SNH) ELSE 0
C = IF V<Vm THEN Qi/V*(NO3i-NO3) ELSE 0
D = IF V<Vm THEN Qi/V*(SPO4i-SPO4) ELSE 0
E = IF DOr>Dl THEN 1 ELSE IF NO3>Nl THEN Fden ELSE 0
F = SPO4/(KP+SPO4)
G = (Xpha/(Xpao*1000))/(Kpha+Xpha/(Xpao*1000))
H = (Kmax-Xpp/(Xpao*1000))/(Kipp+Kmax-(Xpp/(Xpao*1000)))


"RATES

rS = IF SS>0 THEN (rmS*SS/(KS+SS))*E*X ELSE 0
roS = (1-Yh)*rS

rNH = IF SNH>0 AND DOr>Dl THEN rmNH*SNH/(KNH+SNH)*X ELSE 0
roNH = 4.57*rNH

rNO3 = IF DOr>Dl THEN -rNH ELSE raNO3
raNO3 = IF NO3>Nl THEN (roS + rend) / 2.86 ELSE 0
```

```
rPP = IF DOr>Dl THEN qPP*F*G*H*Xpao ELSE 0
roPup = fOP*rPP

rend = K1*exp(-K2*t)*E*X

r = roS + roNH + roPup + rend


END
```

CURRICULUM VITAE

The author of this thesis was born on February 9th, 1955 in São Paulo, Brazil. In December 1977 he completed his Civil Engineering studies at UNICAMP, State University of Campinas, in São Paulo state. After that, he worked as an advisor in different municipalities in the field of sanitary engineering. In 1986 he received his MSc. degree in Hydraulics and Sanitary Engineering from USP, São Paulo University. From 1984 until 1986 he served as an advisor for the government of São Paulo state in the Municipalities Bureau. In 1987 he received his Diploma in Sanitary Engineering from IHE-Delft, The Netherlands. In 1988 he joined the Department of Civil Engineering at UnB, University of Brasília, Brazil, as a lecturer, where he is still working. In June 1990 he started his PhD. programme at the Department of Environmental Technology at the Wageningen Agricultural University, which has culminated in the present thesis.