Hydraulic Behaviour in an Activated Sludge Tank
From Tracer Test through Hydraulic Modelling to Full-Scale Implementation

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Cover: Photo of the Rya WWTP in Göteborg, Sweden

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Abstract

Hydraulic behaviour in a large denitrifying activated sludge tank, located at the Rya Wastewater treatment plant (WWTP) in Göteborg Sweden, was investigated and optimized by using full-scale tracer test and hydraulic modelling. The Rya WWTP is a high loaded plant with a small footprint. Expansion of the site is limited due to several restrictions. An efficient use of already existing facilities is therefore of great importance in order to meet the demands of decreased effluent limits, set by authorities.

The presence of a short circuiting stream was identified with full-scale tracer tests and the hydraulic situation was successfully quantified using the Martin model, a compartment model based on curve fitting to the residence time distribution curve (RTD-curve) from the full-scale tracer test. Computational fluid dynamics (CFD) 3D modelling was used for virtual prototyping of different corrective measures near the inlet to break the previously identified short circuiting stream. From an operational point of view, inlet baffles were chosen as the preferable alternative. After implementation, improved tank hydraulics, were verified with another full-scale tracer test. At a normal flow (3.6 m$^3$/s), the space time in the tank was found to be 16 minutes. In the original tank 30 % of the water had a residence time of less than 8 minutes, 49 % of the water had a residence time between 8 and 24 minutes and 21 % of the water had a residence time of more than 24 minutes. After implementation of corrective measures, the tank with baffles had 6 % of the water with a residence time of less than 8 minutes. 77 % of the water had a residence time between 8 and 24 minutes and 17 % of the water had a residence time of more than 24 minutes. Also, the mixing characteristics in the tank achieved a more plug-flow like character.

Full-scale tracer tests are very informative when investigating hydraulic situations in activated sludge tanks. Mathematical modelling using black box approach can help to quantifying the hydraulics in a tank. For example can use of the Martin model help to quantify short circuiting streams and dead volumes.

CFD modelling is a useful and informative tool for analyzing problematic hydraulics at wastewater treatment plants and for the design of theoretical corrective measures. Being a useful tool for virtual prototyping, this type of modelling also deserves to have a more central role when designing large reactors and other hydraulic systems.

Keywords: CFD modelling, hydraulics, mixing, short circuiting stream, wastewater, activated sludge process, dead volume
List of Papers

The thesis is based on the following papers:

I: Short Circuiting in a Denitrifying Activated Sludge Tank.

II: Improved Hydraulic Behaviour in a Denitrifying Activated Sludge Tank.
   R. Kjellstrand, A. Mattsson.
   *Submitted*
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1 Introduction

Why do research about something as filthy and stinky as a wastewater treatment process? Well, firstly, it is commonly known that water is absolutely essential for the existence of life. Every living organism on earth must have water in some form in order to survive and every living cell is composed primarily of water. Thus, clean water is a limited resource of which we must take good care. In our society, water is used mainly for three purposes; agriculture, industry and domestic use. This means that huge amounts of wastewater are produced every day. Nature itself has a fantastic ability to cope with small amounts of wastewater and pollution, but if there were no wastewater treatment plants (WWTP’s), this natural system would be completely overloaded. WWTP’s are in short used to reduce pollutants in wastewater to a level which nature can handle. An efficient use and reuse of water is important in order to sustain our way of life. Also, an ever increasing water use due to an increasing population, calls for more research in the wastewater treatment area. A better knowledge and understanding of wastewater treatment processes enables us to make wise decisions for water management and use.

1.1 Wastewater Treatment and the Activated Sludge Process

Municipal wastewater is treated in similar ways all over the world, but the levels differ. Commonly there are three main steps in the wastewater treatment process; a preliminary step, a primary step and a secondary step. The preliminary step includes screening (removal of larger objects) and grit removal. Suspended solids are then removed by settling in the primary step. Finally, biological degradation of non-settled organic materials is achieved in the secondary treatment. In some WWTP’s there is also a tertiary treatment step where phosphorus and nitrogen are reduced. After these treatment steps, the remaining water, called effluent, is discharged back into the environment.

An example of a secondary treatment step is the activated sludge process. The activated sludge process is an aerobic, continuous-flow biological method for treatment of domestic and biodegradable industrial wastewater. This treatment system was introduced a century ago and has been developed ever since and is today used worldwide. In the activated sludge process, the degradation of organic materials is performed by microorganisms which use the organic materials as a source for their life-sustaining processes. The conventional activated sludge process consists of an aeration basin, with air as the oxygen source. Soluble (dissolved) organic materials are absorbed through the cell walls of the microorganisms and into the cells, where they are broken down and in a later stage converted to more microorganisms, carbon dioxide, water, and energy. Insoluble (solid) particles are adsorbed on the cell walls, thereafter transformed to a soluble form by enzymes (biological catalysts) secreted by the microorganisms. In this aerated basin, flocs of microorganisms are formed. These flocs are settled in a secondary sedimentation tank, thereby allowing separation of the microorganisms from the treated water. From the bottom of the secondary sedimentation tank, a concentrated stream of recycled microorganisms is pumped back into the aeration tank. As a tertiary step, biological nitrification and denitrification under anoxic conditions can also be implemented in an activated sludge process, this to lower the nitrogen content of the treated wastewater. In order for the degradation-, nitrification- and denitrification processes to take place in an activated sludge tank, a suitable environment with long enough water residence time is necessary.
1.2 Hydraulic Behaviour and its Importance for Efficient Wastewater Treatment

The hydraulic behaviour in an activated sludge tank, i.e. the transportation of water through the tank, is of fundamental importance for the function of the tank and thus for the efficiency of the wastewater treatment process. Examples of hydraulic phenomena with negative effect on sludge tank performance include short circuiting streams and dead volumes. Unfavourable hydraulic situations in activated sludge tanks may cause the tanks to be less efficiently used and thus cause higher residual concentrations in the treated water. This may be particularly important in high loaded activated sludge systems. Good hydraulic conditions are characterised by good conditions for high biochemical reaction rates and favourable growth rate for desirable microorganisms.

1.3 The Rya Wastewater Treatment Plant

The Rya WWTP is located in Göteborg on the west coast of Sweden and is one of the largest WWTP:s in Scandinavia. It is owned by Gryaab, the regional sewage works of the Göteborg region including the municipalities of Ale, Göteborg, Härryda, Kungälv, Lerum, Mölndal and Partille. The Rya WWTP treats wastewater from its joint owners, thus handling wastewater from 621 000 inhabitants and industries corresponding to 151 000 equivalents of population. Rya WWTP is a high loaded plant located in a small site (figure 1). Expansion of the site is limited due to several restrictions such as a nearby railway, industrial areas and a nature reserve. However in the west is a woods, adjacent to the nature reserve, originally offset for future plant expansion. Expected objections to intrusion in this wooded area makes it highly desirable to minimize any such exploitation (Balmer et al., 1998). An efficient use of already existing facilities is therefore of great importance to meet the demands of decreased effluent limits, set by authorities.

Figure 1. The Rya WWTP. (Photo: Gryaab)
1.4 Aim and Outline of the Thesis

This work focuses on the characterization and optimization of hydraulics in a large full-scale denitrifying activated sludge tank, using full-scale tracer tests and mathematical modelling including Computational Fluid Dynamics (CFD). The particular tank in focus is located at the Rya WWTP, Göteborg, Sweden where this study was performed.

The first chapter gives an introduction to and purpose of this research project. Chapter 2 reviews hydraulic behaviour in activated sludge tanks and the use of tracer tests for investigation. Hydraulic modelling is discussed in chapter 3, whereas full-scale plant experiments are described in chapter 4. Results and discussion are summarized in chapter 5. Finally conclusions are presented in chapter 6 and future work in chapter 7.
2 Background

2.1 Hydraulic Behaviour

Hydraulic behaviour deals with how water flows throughout a tank, i.e. how the water is transported and moving inside the tank. In continuously operated tanks there are two main types of theoretical hydraulic behaviour: plug-flow and complete-mix.

Ideal plug-flow is characterized by fluid particles passing through the tank and being discharged in the same sequence as in which they entered. The particles remain in the tank for a time equal to the theoretical detention time. This type of flow is approximated in long tanks with a high length-to-width ratio (figure 2a). These types of reactors are also known as tubular flow reactors (Metcalf and Eddy, 1991).

Ideal complete-mix occurs when the fluid particles entering the tank are immediately dispersed throughout the tank. There are no concentration gradients in the tank and the composition is equal all over the tank. Therefore, the effluent of the tank has the same composition as the fluid inside the tank. This type of flow is approximated in round or square tanks if the content of the tank is uniformly and continuously redistributed (figure 2b). Complete-mix reactors are also known as continuously-stirred-tank-reactors, CSTRs (Metcalf and Eddy, 1991).

(a) (b)

Figure 2. Illustrations of plug-flow (a) and complete-mix (b) hydraulic behaviour.

The actual hydraulic behaviour of most activated sludge tanks treating wastewater, fall somewhere in-between plug-flow and complete-mix. It is therefore necessary to characterise the hydraulic behaviour within an individual tank, if its effects on the treatment process is to be understood (Burrows et al., 1999).

In real reactors various hydraulic phenomena may occur. Two common phenomena are short circuiting streams and dead volume. A short circuiting stream is a situation in the tank where the incoming flow or a part of the incoming flow is taking a short cut, thus bypassing the reactor (figure 3). A short circuiting stream will therefore have a low residence time in the tank. Dead volumes (or dead zones) are water volumes in the tank that are stagnant. Typically, the volume near a corner in a tank may act as dead volume if the mixing is insufficient (figure 3). In dead volumes there are none (or little) exchange between the bulk flow in the tank and the dead volume. Dead zones reduce the effective reactor volume, as a consequence, the active reactor volume is smaller than expected (Vogler, 2001).
2.1.1 Factors Affecting the Hydraulics

The performance of an activated sludge process is influenced by its hydraulic behaviour. The hydraulic behaviour is in its turn affected by a number of factors such as; the geometric design of the reactor, the shape and position of the inlet and the outlet, external mixers, baffles, fluid viscosity, aeration and water flow rate.

2.1.2 Hydraulic Influence on the Treatment Process

An unfavourable hydraulic situation in an activated sludge tank may lead to significant reduction of its capacity, thus causing higher concentration of residuals in the effluent (Bode and Seyfried, 1984).

Improper design of a tank can cause short circuiting streams and dead volume. Short circuiting streams means insufficient time for biological reactions to take place and the degree of completion of the necessary biodegrading reactions may therefore be reduced. Any dead volume in the tank also reduces the actual volume available for reactions, thus lowering the capacity of the tank.

The efficiency of the activated sludge process is dependent on the ability to reduce the level of pollutants and also upon the ability of the active sludge to flocculate and settle in the secondary sedimentation tank. Many studies have shown the influence of mixing characteristics on sludge settleability. In fact, mixing characteristics of an activated sludge reactor can affect both the efficiency of pollutant removal and the settling characteristics of the sludge. Thus the mixing characteristics are very important (Bode and Seyfried, 1984; Burrows et al., 1999). Reactors with hydraulic behaviour approximated to plug-flow produce better settling sludges than completely mixed ones do, and are thus to prefer (Burrows et al., 1999).

The mixing will also have a pronounced effect on the concentration of substrate available to the microorganisms and this will, in turn, affect the population of microorganisms present (Metcalf and Eddy, 1991; Horan et al., 1991). Sludge bulking is a term applied to a condition in which an overabundance of filamentous organisms is present. The filamentous organisms cause the
biological flocs in the reactor to become bulky and loosely packed. Bulky flocs do not settle well and are often carried over in great quantities in the effluent of the sedimentation tank.

2.2 Tracer Test Investigation of Activated Sludge Tanks

Tracer tests have been widely used in order to characterise the hydraulic behaviour of bioreactors. In addition to being a non-reactive species that is easily detectable, the tracer should have similar physical properties to those of the reacting mixture and be completely soluble in the mixture (Fogler, 2001). Tracer addition most often takes the form of either pulse addition (Dirac delta function) or as a step input, pulse addition being the most common method.

Figure 4 illustrates a tracer test using pulse addition (injection) to the inlet and detection of tracer at the outlet. Tracer concentrations extracted from the outlet can be plotted against time; this is referred to as a residence time distribution curve (RTD-curve). An RTD-curve describes how much time each tracer molecule has spent in the reactor. If, as mentioned, the tracer has physical properties similar to those of the reacting mixture and is completely soluble in the mixture, RTD-curves generated from the tracer test will give a good black box representation of the fluid flowing through the reactor.

![Figure 4](image)

**Figure 4.** Illustration of a tracer test using pulse addition to the inlet and detection at the outlet. Tracer concentration curves are representing both the pulse of tracer at the inlet and also the tracer concentration detected at the outlet (RTD-curve) plotted against the time (Fogler, 2001).

Different tracers have been used in RTD experiments for wastewater bioreactor studies, including soluble salts such as lithium salts, chlorides, dyes, radioactive compounds or microorganisms. Among them, the utilisation of lithium salts is very common because of its low and constant concentration in municipal wastewater and because it is neither degraded nor adsorbed by microorganisms (Olivet et al., 2005).

There are several examples of tracer tests being used to indicate the presence of for example short circuiting streams and dead volume. Hydraulic characterisation is then performed by RTD curve analysis (Bode and Seyfried, 1984; Newell et al., 1998; Williams and Beresford, 1998; Burrows et al., 1999; Martin, 2000 and Olivet et al., 2005).

Parallel with investigation of hydraulics, the RTD-curves generated from the tracer tests can be used for calculation of the flow rate passing through the tank as well as for other purposes. The
recovery of tracer can for example be estimated if the flow rate is known by a separate flow meter.
3 Hydraulic Modelling

As well as for hydraulic characterisation, the outcome of a tracer test may also be used for creation and calibration of hydraulic models. Several models for description of hydraulic behaviour have been proposed (Burrows et al., 1999). Typical models are the dispersion model, the tanks-in-series model and compartment models based on combinations of continuously-stirred-tank reactors and plug-flow reactors arranged in different configurations (Levenspiel, 1962). In 1962 Levenspiel described the tanks-in-series model where a series of equal CSTRs are used. The tanks-in-series model is today a simple and widely used model. In 1981 Monteith and Stephensen combined a CSTR and a bypass stream when modelling the mixing efficiency in full-scale anaerobic digesters. In 1999 Burrows et al. used the strand concept in the Martin model, where each parallel strand is represented by a series of CSTRs. In common, all of the above mathematical models only describe the hydraulics at a global or black box level, thus not revealing the actual state inside of the tank.

Some mathematical models of activated sludge systems, such as the IAWQ (International Association on Water Quality) models, allow the representation of hydraulic characteristics through modelling tanks as an integer number of tanks in series. This parameter can be shown to have significant effects on the models output and, hence, the models accuracy can be improved through tracer studies to ascertain the mixing characteristics (Burrows et al., 1999).

Today, improvements in computer and computational technology and the development of a new generation of highly efficient computer programs have made it possible to simulate real fluid flow within several types of geometries. This has made it possible to show the inside dynamic flow situation in structures such as clarifiers and activated sludge reactors (Karama et al., 1999). Thus, CFD analysis is a powerful tool for better understanding of the hydraulic situation in water processes and can be used for improving design and operation of water and wastewater treatment plants (Zang et al., 2004; Brouckaert et al., 1999; Salter and Williams, 2000).

3.1 Mathematical Modelling

3.1.1 Tanks-in-series Model

The tanks-in-series model assumes that the flow through the reactor can be characterized by a series of $N$ equal sized CSTRs. The mathematical expression describing the concentration of tracer in the effluent of the last tank is (Burrows et al., 1999):

$$
C_N(t) = C_0 \frac{N}{(N-1)!} (N\theta)^{(N-1)} e^{-(N\theta)}
$$

where $\theta = \frac{t}{Q/V}$

(3.1)

where $C_N(t)$ is the tracer concentration (g/m$^3$) in the $N^{th}$ tank and $C_0$ is the tracer concentration (g/m$^3$) in the first tank at $t = 0$, $\theta$ is normalised time, $t$ is time (s), $Q$ is total flow rate (m$^3$/s), $V$ is the total volume (m$^3$). The number of tanks $N$, can be found by differentiating equation (3.1)
with respect to $\theta$ to give $\theta = (N-1)/N$ when $dC/d\theta = 0$. Equation (3.1) can be written for all positive integer values by introducing the Gamma distribution $\Gamma(N)$.

$$C_N(t) = C_0 \frac{N}{\Gamma(N)} (N\theta)^{(N-1)} e^{-N\theta}$$  \hspace{1cm} (3.2)

### 3.1.2 Model by Monteith and Stephenson

Monteith and Stephenson used the following model to describe the washout curve of an anaerobic digester:

$$\frac{C}{C_0} = \frac{[(v_1 V / v^2)/\bar{t}_a]}{\exp^{-t/\bar{t}_a} + (v_2 / v)\delta_{t=0}}$$ \hspace{1cm} (3.3)

where $C$ is the tracer concentration (g/m$^3$) at the time $t$, $C_0$ the tracer concentration (g/m$^3$) at $t = 0$, $v_1$ is the flow rate (m$^3$/s) through the actively back mixed zone, $v_2$ is the bypass flow (m$^3$/s) rate due to short-circuiting, $v$ is the total flow rate (m$^3$/s), $V$ is the total volume (m$^3$), $\bar{t}_a$ is the mean hydraulic retention time (s) of the actively mixed zone and $\delta$ is the delta input function. From regression of the ln($C/C_0$) against $t$, the gradient of the decay portion of the curve provided an estimate of $\bar{t}_a$. The intercept provided an estimation of $v_1$. The short-circuiting flow rate is calculated from $(1- v_1 / v)$. The actively mixed volume $V_a$, is found from $(v_1 \cdot \bar{t}_a / V)$ and the “dead” zone from $(1- V_a / V)$.

### 3.1.3 Martin Model

Burrows et al. (1999) used the Martin method for modelling of hydraulic behaviour. The Martin method is based on a number of separate “strands” through the tank (figure 5). Each strand is modelled by a tank-in-series model. In this way, short-circuiting can be evaluated in a manner consistent with mathematical models of the activated sludge process. Burrows et al. (1999) applied the Martin method with two strands where one of the strands represents the main flow and the other strand represents the bypass flow. The Martin model can also include dead volume.

![Figure 5. Chart showing the strand concept of the Martin model including two strands and dead volume.](image)

The Martin model (Burrows et al., 1999) returns the tracer concentration exiting the reactor at each time-step and the mathematical expression for this is:
\[ C_{we} = \sum_{s} f_s \int_{t_s}^{\bar{t}} I_t \frac{n_s^s}{\Gamma(n_s)} \theta_s^{-n_s} e^{-\theta_s \bar{t}} \, dt \]  \hspace{1cm} (3.4)

where \( C_{we} \) is the tracer concentration (g/m\(^3\)) in the reactor effluent, \( f_s \) is the flow fraction to each strand, \( t \) the time (s), \( t_e \) the elapsed time (s), \( \bar{t} \) the mean residence time (s) for the system, \( \bar{t}_s \) the mean residence time (s) for the strand, \( I_t \) the tracer concentration (g/m\(^3\)) in the feed to the system at the time \( t \), \( \Gamma \) the Gamma distribution, \( n_s \) the number of CSTRs in the strand and \( \theta_s \) the normalized time for the strand. For each strand there are individual flow fractions, tank volumes and numbers of tanks in series. Subscript 1 and 2 for the first and second strands, are defined respectively. The total reactor volume \( V \) (m\(^3\)) is divided into \( V_1 \) (m\(^3\)) and \( V_2 \) (m\(^3\)) and the dead volume, \( V_{\text{dead}} \) (g/m\(^3\)). An optimization routine is used to select the values for the parameters of the model \((N_1, N_2, f_1, f_2, V_1, V_2)\) to achieve the best correlation with the experimental data points. Microsoft EXCEL\textsuperscript{®} built in solver can be used as optimization routine. The normalized variances \( (\sigma^2_0) \) of the RTD-curve can be shown to be equal to 1/\( N \). The number of tanks can be extracted from the equation \( \theta = (N-1)/N \). Approximate values of the times of the local maximum tracer concentrations and approximate values of the variances can be extracted from the RTD-curve. These values serve as start values for the optimization routine. Martin further describes a reactor network structure for modelling (Martin, 2000). This reactor structure is based on “threads” and “knots”, i.e. a reactor network structure of series and/or parallel combined tanks-in-series models.

### 3.1.4 Correlation Coefficient

In order to compare mathematical hydraulic models to results from full-scale tracer tests the correlation coefficient was used. Equation for correlation coefficient \( r_{xy} \) is shown in equation 3.5 and is taken from fundamental statistics literature.

\[ r_{xy} = \frac{n \sum x y - \sum x \sum y}{\sqrt{\left[n \sum x^2 - (\sum x)^2\right]\left[n \sum y^2 - (\sum y)^2\right]}} \]  \hspace{1cm} (3.5)

### 3.2 CFD Modelling

Several computer software programs have been developed for CFD modelling. In this study Comsol Multiphysics 3.2 and the 3D k-\( \varepsilon \) turbulence model in the Chemical Engineering Module was used. During this study hydraulic CFD modelling began with the definition of tank geometry. Secondly fluid characteristics and boundary conditions were defined. The momentum balance including the turbulence model and continuity equations were then solved numerically for the tank using the finite element method. Finally, the obtained solution was post-processed to be properly visualised.

Common mathematical hydraulic model equations used for CFD modelling include the momentum balances for a non-compressible viscous media (equation 3.6) and the continuity equation (equation 3.7) (Comsol, 2006).
\[
\rho \frac{\delta U}{\delta t} - \nabla \cdot \left( \left( \eta + \rho C_\mu \frac{k^2}{\varepsilon} \right) \nabla U + (\nabla U)^T \right) + \rho U \cdot \nabla U + \nabla P = F
\] (3.6)

\[\nabla \cdot U = 0\] (3.7)

\(U\) denotes the average flow velocity vector, \(P\) the average pressure (Pa), \(\eta\) dynamic viscosity (Pa·s), \(\rho\) density (kg/m³), \(t\) time (s), \(C_\mu\) a model constant, \(k\) the turbulent kinetic energy (m²/s²), and \(\varepsilon\) the dissipation of turbulent energy (m²/s³). \(F\) is a volume force term (N/m³) which is zero in both the \(x\) and \(y\) directions. Physical data (density and viscosity) for water were used in this study.

The \(k-\varepsilon\) turbulence model is used for turbulent flows and includes equations for kinetic energy (equation 3.8) and for dissipation of kinetic energy (equation 3.9):

\[
\rho \frac{\delta k}{\delta t} - \nabla \cdot \left( \left( \eta + \rho C_\mu \frac{k^2}{\varepsilon} \right) \nabla k \right) + \rho U \cdot \nabla k = \rho C_{\mu} \frac{k^2}{2\varepsilon} \left( \nabla U + (\nabla U)^T \right)^2 - \rho \varepsilon
\] (3.8)

\[
\rho \frac{\delta \varepsilon}{\delta t} - \nabla \cdot \left( \left( \eta + \rho \frac{C_{\varepsilon} k^2}{\sigma_k \varepsilon} \right) \nabla \varepsilon \right) + \rho U \cdot \nabla \varepsilon = \rho C_{\varepsilon 1} \frac{k}{2} \left( \nabla U + (\nabla U)^T \right)^2 - \rho C_{\varepsilon 2} \frac{\varepsilon^2}{k}
\] (3.9)

The model constants \((C_\mu, C_{\varepsilon 1}, C_{\varepsilon 2}, \sigma_k, \sigma_\varepsilon)\) in the above equations have been determined from experimental data and are set to standard parameters (Wilcox, 2000):

\[C_\mu = 0.09, C_{\varepsilon 1} = 0.1256, C_{\varepsilon 2} = 1.92, \sigma_k = 0.9, \sigma_\varepsilon = 1.3\]

### 3.2.1 Mass Transfer

Modelling of tracer tests was done by introducing a mass balance on top of the hydraulic model. Mass transport of tracer is described through convection and diffusion (equation 3.10).

\[
\frac{\partial c}{\partial t} + \nabla \cdot (D \nabla c + cu) = 0
\] (3.10)

Here, \(c\) denotes the tracer concentration (g/m³), \(D\) denotes its diffusion coefficient (m²/s) and \(u\) denotes the velocity vector. The velocity vector is given by the stationary solution of the \(k-\varepsilon\) turbulence equations and the diffusivity is given by the turbulent viscosity \(\nu_t\) (m²/s), given from the \(k-\varepsilon\) simulation (equation 3.11).

\[\nu_t = C_\mu \left( \frac{k^2}{\varepsilon} \right)
\] (3.11)
The mass transfer model is solved using a time-depending solver which makes it possible to model the tracer test. The hydraulic steady-state solution is locked during the mass transfer modelling and the mass transfer model is not affecting the hydraulic solution.
4 Full-Scale Experiments

4.1 The Rya Wastewater Treatment Plant

4.1.1 Site Description

Wastewater is transported by gravity in tunnels and reaches the treatment plant 19 m below the ground surface. After pre-screening, the wastewater is pumped to ground level. At the Rya WWTP wastewater is treated by preliminary treatment including fine screening and grit removal followed by primary treatment including settling. In secondary treatment, phosphorus is removed through simultaneous precipitation with iron sulphate in a non-nitrifying activated sludge system with two-tray settlers. Nitrogen removal is achieved by recirculation of a part of the clarified effluent to nitrifying trickling filters. The nitrified effluent of the trickling filters is recirculated to the non-nitrifying activated sludge system for denitrification (Mattsson, 1997). A process scheme of the Rya WWTP is shown in figure 6a.

![Diagram of Rya WWTP process scheme](image)

**Figure 6.** (a) Process schemes of the Rya WWTP. (b) The activated sludge line where tracer tests were carried out and data of the tanks. The figure shows a scheme of the activated sludge line seen from above. Arrows indicate the flow direction.

4.1.2 The Activated Sludge System

The activated sludge system consists of three lines, each with a train of three tanks in series (figure 6b). The first tank is always anoxic, the second tank is divided into two compartments, where the first compartment is always anoxic, whereas the second compartment can be either aerated or anoxic. The third tank is always aerated. Thus, the trains can be operated with the first 40 or 60 % of the volume anoxic and the reminder aerated. Ethanol is added intermittently (on demand) to the first tank of the series, this to compensate for periods with lack of carbon source. This addition of external carbon source is controlled by the nitrate concentration in the second tank (Wik et al., 2003).
4.1.3 The Investigated Sludge Tank

Investigation of the hydraulic situation was performed in one of the trains. Photos of the first tank are shown in figure 7. The inlet has an area of 3 m x 2 m and is located in the upper part of the short side of the tank. The outlet (3 m x 5.5 m) is located on one of the long sides at the opposite end of the tank. The tank is fitted with six vertical propeller mixers (2 m impeller, 27 rpm). The mixers have a designed pump flow capacity of 108 m³/min. Due to the large depth of the tank, 14 concrete beams are installed in order to distribute the structural loading on the walls. The second tank is fitted with 12 impellers. Aerators are installed in the second compartment of the tank. The third tank is without impellers. Aerators are installed throughout the tank.

![Figure 7. Photos of the first tank showing the tank without water. The supporting beams and mixers can be seen. (Photo: Gryaab)](image)

4.2 Full-Scale Tracer Test

Tracer tests were performed using pulse addition of lithium chloride (LiCl). A mass of 10.0 kg LiCl was dissolved in water and diluted to form a 25 liter brine. The brine was poured into a 50 m long hose. By using pressurized wash-water, the tracer was injected into the inlet of the first tank, all within a few seconds. Approximately 150 samples (100 ml each) were taken during the tracer tests. Samples were taken at four different locations in the activated sludge line: the outlet of the first tank, the outlet of the second tank, the outlet of the third tank and in the channel before entering the basins, this for tracer background level detection. Wastewater flow rate and the air supply to the tanks were stabilized during the tests, as was the recirculated nitrified effluent and recycled activated sludge flow rate.

4.2.1 Sample Analysis and Creation of RTD Curves

The samples were allowed to settle and the supernatant was filtered (1.2 µm membrane filter, Titan 2 HPLC Filter Orange 30 mm) in order to reduce interference of solids. The lithium concentrations of the samples were measured using a flame photometer (Eppendorf ELEX 3631). This was calibrated on site, using final effluent as diluant when creating a lithium standard curve.
Measured lithium values were used for creating RTD-curves. From the first tank, arithmetic mean values based on tracer concentrations from three sample positions in the outlet (centre, upper right downstream corner, lower left upstream corner) were used when plotting the curve.
5 Results and Discussion

5.1 Full-Scale Tracer Test

Tracer concentrations in the effluent of the three tanks in the train were measured and the results at a total flow rate of 3.6 m$^3$/s per train are presented as RTD-curves in figure 8. As mentioned, each data point from the first tank is an average of 3 data points of samples extracted from different levels in the effluent stream. RTD results generated from the effluent of the first tank show an extreme initial lithium concentration peak at $\theta \sim 0.15$ (figure 8a). The lithium concentration in the effluent of the second (anoxic) and third (aerated) tanks reached maximum concentration at $\theta \sim 0.85$ (figure 8b), and $\theta \sim 0.8$ (figure 8c), respectively.

The initial peak of the first tank clearly indicates a short circuiting stream. Considering a 10 m deep tank and no baffles, the design likely allows the inlet jet to cause a powerful horizontal short circuiting stream in the upper part of the tank. The tank is fitted with 6 vertical propeller mixers but they are dimensioned to prevent settling and do not affect the short circuiting stream.

At a flow of 3.6 m$^3$/s passing through an inlet passage of 6 m$^2$, the mean velocity of the inflow can be estimated to 0.6 m/s. This is a very high velocity. The peak concentration of tracer appears after 2.5 minutes in the 60 m basin, mean velocity of the short circuiting stream can hereby be estimated to 0.4 m/s.

![Figure 8](image)

**Figure 8** RTD-curves showing lithium concentration detected in the effluent of (a) the first, (b) the second and (c) the third tanks in the tracer test. Normalised time is defined as in equation 3.1 where $V$ is the volume between the addition point of tracer and the sample point. In (a) the volume 3400 m$^3$ was used, in (b) 10200 m$^3$, and in (c) 13600 m$^3$. 
The RTD-curves from the second and the third tank have no obvious peaks indicating short circuiting streams (figure 8). Thus, the short circuit stream in the first tank of the activated sludge reactor is probably suppressed in the following tanks. The passage between the first and second tanks and the second and third tanks is perpendicular to the flow direction, which is favourable for the hydraulics. Furthermore, the aeration of the third tank with bubbles rising from the bottom of the tank, counteract the short-circuiting stream by its travelling perpendicular to the bulk water flow. Focus in this project was concentrated to the first tank due to the presence of short circuiting streams.

The purpose of extracting samples at different positions in the effluent of the first tank was to investigate radial gradients. Tracer concentrations from two positions are plotted in figure 9a. Samples extracted 0.2 m below the surface of the effluent stream indicate an extreme initial peak. However, the lithium concentrations are strictly higher at $\theta > 1$ in samples extracted at 0.2 m above the bottom of the outlet (1.4 m below the surface) in the effluent stream. This supports the theory that the short circuiting stream is located in the upper part of the tank. It also shows the importance of the choice of sampling points in systems with short circuiting streams.

![Figure 9a](image)

![Figure 9b](image)

**Figure 9.** Results from the tracer test in the first tank. (a) RTD-curves showing radial gradients in the effluent of the first tank. Samples were extracted 0.2 m below the surface of the effluent stream and 0.2 m over the bottom of the outlet. (b) Plot showing recovery of tracer substance during the test. The mean value of the detected concentrations in the effluent was used.

Recovery of tracer in the effluent of the first tank is plotted in figure 9b. The total amount of tracer detected in the effluent was 108 % of the amount added to the inlet. The radial gradient of tracer concentrations in the effluent makes it difficult to obtain representative tracer samples. Mean hydraulic residence times were calculated from the RTD-curves. Space time $\tau$ (tank volume divided by volumetric flow rate entering) (min) and mean hydraulic residence time $t$ (min) are presented in Table 1.
### Table 1. Mean residence time calculated from the RTD-curve and space time.

<table>
<thead>
<tr>
<th></th>
<th>Flow (m$^3$/s)</th>
<th>Mean hydraulic residence time $t$ (min)</th>
<th>Space time $V/Q$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outlet of first tank</td>
<td>3.6</td>
<td>15.9</td>
<td>15.7</td>
</tr>
<tr>
<td>Outlet of second tank</td>
<td>3.6</td>
<td>50.2</td>
<td>47.2</td>
</tr>
<tr>
<td>Outlet of third tank</td>
<td>3.6</td>
<td>82.7</td>
<td>78.7</td>
</tr>
</tbody>
</table>

### 5.2 Mathematical Modelling Results

The extracted data from the tracer test was used to calibrate models for the hydraulic behaviour in the first tank. Modelling of the first tank was carried out with a tanks-in-series model, and with the model developed by Monteith and Stephenson (1981) and also by the Martin model. Tracer data at a total flow of 3.6 m$^3$/s and output of the models are plotted in figure 10.

**Figure 10.** Experimental data points of lithium concentrations from tracer test plotted with the corresponding models of (a) Tanks-in-series model. (b) Model by Monteith and Stephenson (1981). (c) Martin model (Burrows et al., 1999).

The best correlation between tracer data and output from model, was seen with the Martin model (Table 2), with a correlation coefficient of 0.979. The tanks-in-series-model did not re-create the short circuiting stream and therefore gave a poor fit (correlation coefficient 0.669). The Monteith and Stephenson model does compensate for short circuiting stream, but this model presumes that the main flow through the main volume can be modelled by a single CSTR. The short circuiting stream is further presumed as a peak flow without retention time at $t=0$. Monteith and Stephensen used this approach when modelling an anaerobic digester. This model however gives a poor correlation (correlation coefficient 0.410) when applied to model the hydraulics in the first tank.
Table 2. Hydraulic characterization of the first tank; flow fractions, residence time, number of tanks and volumes. Calculated correlation between model output and fullscale tracer test concentrations.

<table>
<thead>
<tr>
<th>Model</th>
<th>Flow, residence time and number of tanks</th>
<th>Volume</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow, t mean, N</td>
<td>Flow, t mean, N</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(%) (min) (-)</td>
<td>(%) (min) (-)</td>
<td>(-)</td>
</tr>
<tr>
<td>Tanks-in-series</td>
<td>- - 100 18.9 1.2</td>
<td>- 100 -</td>
<td>0.669</td>
</tr>
<tr>
<td>Monteith &amp; S.</td>
<td>-14.8 114.8 13.7 1</td>
<td>- 100.2 -0.2</td>
<td>0.410</td>
</tr>
<tr>
<td>Martin model</td>
<td>8.1 3.0 68 91.9 15.2 2.4</td>
<td>1.3 85.8 12.8</td>
<td>0.979</td>
</tr>
<tr>
<td></td>
<td>Q = 3.6 m³/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tanks-in-series</td>
<td>- - 100 9.8 1.2</td>
<td>- 100 -</td>
<td>0.408</td>
</tr>
<tr>
<td>Monteith &amp; S.</td>
<td>12.0 78.0 12.0 1</td>
<td>- 87.3 12.7</td>
<td>0.416</td>
</tr>
<tr>
<td>Martin model</td>
<td>24.3 2.4 36 75.7 14.1 1.7</td>
<td>4.5 88.5 7.0</td>
<td>0.990</td>
</tr>
</tbody>
</table>

5.3 Hydraulic Characterization using Martin Method

The Martin model generated the best fitting RTD-curve reproduction of the tested models. Thus, the Martin model was used to quantify the short circuiting stream and dead volume. At a total flow of 3.6 m³/s the reactor was characterized with 12.8% dead volume, 85.8% main volume and 1.3% short circuiting volume. The inflow was divided into 91.9% entering the main volume and 8.1% entering the short circuiting volume. In a similar experiment with a higher flow rate of 4.7 m³/s, the reactor was characterized with 7.0% dead volume, 88.5% main volume and 4.5% short circuiting volume (Table 2). The inflow was divided into 75.7% entering the main volume and 24.3% entering the short circuiting volume. It indicates that the short circuiting problem is increased at a higher flow rate (of 4.7 m³/s compared to 3.6 m³/s).

The short circuiting stream has a reduced retention time in the tank and a reduced denitrifying capacity can therefore be expected. Also, as a consequence, the retention time in the main volume is increased. This effect may to some extent compensate for the decreased retention time in the short circuiting flow, especially if there are high nitrate concentrations in the reactor. Although, in a situation with complete denitrification in the main stream, high nitrate concentration in the effluent can still appear even though there is further denitrifying capacity in
the main volume. This is due to the short circuiting stream. Dead volumes in the tank are another factor that also reduces the denitrifying capacity.

5.4 Hydraulic Characterization using CFD

The results from the full-scale tracer test in the first tank, plotted as a RTD-curve, are shown in figure 11. The inlet flow to the tank was 3.6 m$^3$/s during the tracer test. This corresponds to a space time of approximately 16 minutes. As shown in figure 11, a large initial peak (after approx. 3 min.) was seen, thus indicating short circuiting streams in the tank. The “tail” of tracer extending after the initial peak, indicates areas with poor mixing in the tank. Both the initial peak indicating a short circuiting stream and the “tail” of tracer indicating an inactive volume, were seen in the CFD model as well as in the tracer tests (figure 11).

![RTD-curves from the full-scale tracer test in the first tank and corresponding CFD model.](image)

Figure 11. RTD-curves from the full-scale tracer test in the first tank and corresponding CFD model.

CFD modelling of the tank allows the creation of a theoretical velocity profile in the tank. The hydraulics in the tank shown as a velocity field represented by arrows, are shown in figure 12a. The velocity profile obtained show the main flow passing straight through the upper part of the tank (above the supporting beams). This is most likely caused by the short circuiting stream creating the initial peak in the RTD-curve. Below the beams the water seems to be slowly transported back towards the entrance of the tank. This phenomenon is causing the “tail” of tracer shown in the RTD-curve. The volume below the beams is clearly not as “active” as the volume above the beams. Therefore, the tank performance could be improved by better use of the idle capacity of this volume. Also, the six mixers which are installed to promote mixing in the tank, are obviously not able to impact the short circuiting stream.

CFD modelling and the possibility hereby to directly obtain information about the tank velocity profile, enables a much better understanding of the hydraulic situation. Most importantly, the similarity between the RTD-curve resulting from the full-scale tracer test and the modeled RTD-curve, verifies the results of the CFD model.
Figure 12. Results from CFD modelling of the original first tank and also from three models featuring different corrective measures to improve hydraulics in the tank.

a) Velocity field in original tank.

b) Velocity field with a powerful mixer near the inlet.

c) Velocity field with a wall near the inlet.

d) Velocity field with baffles near the inlet.
5.5 Virtual Design using CFD for Improvement of Tank Hydraulics

To obtain a practical suggestion for improvement of the activated sludge tank profile, CFD modelling of the hydraulics was used to evaluate different corrective measures. Three main corrective measures were studied; a powerful mixer, a wall and also baffles at the inlet. All three measures are intended to deal with the high velocity of the inlet flow. RTD-curves generated from the CFD-models of the different corrective measures are plotted in figure 13.

![RTD-curves from CFD-models](image)

**Figure 13.** RTD-curves from CFD-models.

In figure 13, the RTD-curve from a model with ideal inlet flow profile is also plotted. The ideal inlet flow profile is modeled with the flow of 3.6 m³/s distributed evenly over the short side (6 m x 10 m) generating an even inlet velocity of 0.06 m/s. This ideal inlet flow profile model can be seen as the theoretical maximum hydraulic improvement that can be obtained by corrective measures at the inlet. The RTD curve from this ideal inlet has a peak at about 14 minutes and is still not showing a narrow peak at 16 minutes (space time). This is because only the inlet flow profile is ideal, whereas the fluid is not. Also, the tank is not an ideal plug-flow reactor.

With a good design all three corrective measures have the capacity to break the short circuiting stream and also reduce the dead zones in the tank. This is shown in figures 12b, 12c and 12d. As shown in figures 12b, 12c and 12d the high velocity in the upper part of the tank caused by the inlet jet is neutralized by all of the corrective measures. In the lower part of the tank, the bulk flow rate is increased, which in its turn leads to a decreased dead volume.

In order to try to quantify the improvement of the hydraulics, a comparison of residence times is presented in Table 3. A reasonable residence time was assumed being space time $\tau \pm 50\%$. 

---

22
Table 3. Portion of water in residence time interval (calculated from CFD modelling). $\tau$ is the space time.

<table>
<thead>
<tr>
<th>Portion of water (%) in residence time interval</th>
<th>Water with low residence time</th>
<th>Water with reasonable residence time</th>
<th>Water with high residence time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau - 50%$</td>
<td>$\tau \pm 50%$</td>
<td>$\tau + 50%$</td>
</tr>
<tr>
<td></td>
<td>$&lt; 8$ minutes</td>
<td>$8 - 24$ minutes</td>
<td>$&gt; 24$ minutes</td>
</tr>
<tr>
<td>Original tank (CFD)</td>
<td>42</td>
<td>41</td>
<td>17</td>
</tr>
<tr>
<td>Tank with baffles (CFD)</td>
<td>2</td>
<td>84</td>
<td>14</td>
</tr>
<tr>
<td>Tank with wall (CFD)</td>
<td>7</td>
<td>84</td>
<td>9</td>
</tr>
<tr>
<td>Tank with mixer (CFD)</td>
<td>10</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>Tank with ideal inlet flow profile (CFD)</td>
<td>11</td>
<td>82</td>
<td>7</td>
</tr>
</tbody>
</table>

According to the CFD modelling, the portion of water with a reasonable residence time will be increased from 41 % to 84 % with baffles. This can be compared to the theoretical ideal inlet flow were the portion of water with a reasonable residence time is 82 %. Similar results are obtained from the CFD modelling with additional mixer or a damper wall (Table 3).

However, from an operational point of view a passive solution is preferable. Also, a wall at the inlet was feared to act as a trap for litter and grease on the surface. The baffle alternative was thus chosen. It consists of 4 baffles, each with a length of 5 m (1.2 m wide) installed 2.5 meters from the inlet. The baffles cover 80 % of the width of the basin and about half of the depth.

5.6 Hydraulics in Tank with Baffles Installed

The results from the full-scale tracer tests in the tank with baffles installed, plotted as a RTD-curve, are shown in figure 14a. The inlet flow to the tank was 3.5 m$^3$/s during the tracer test. This corresponds to a space time of approximately 16 minutes. The RTD curve from the full-scale tracer test in the tank with baffles can be seen in figure 14b together with the RTD curve from the full-scale tracer test of the original tank. The large initial peak seen in the original tank is eliminated, thus indicating that the short circuiting streams now are eliminated. The peak in tracer concentration occurs at about 12 minutes (quite close to the space time of 16 minutes). The “tail” of tracer (after about 30 minutes and forward) is also decreased compared with the original tank. This is indicating that the inactive part of the tank has decreased. The RTD-curve generated from CFD-model is also plotted in figure 14a.
Figure 14. (a) RTD-curves from full-scale tracer test in the first tank with baffles installed and corresponding CFD model. (b) RTD-curves from full-scale tracer tests in original first tank and in the first tank after baffles were installed.

Table 4 shows the result from the tracer test after installation of baffles compared with the tracer test in the original tank. The portions of water in residence time interval have been calculated from the RTD-curve in the same way as in table 3. The result in table 4 corresponds with predicted results by the CFD modelling in table 3. Water with a residence time less then 8 minutes has been reduced from 30% to 6%. This is consistent with the elimination of the short circuiting stream. Water with a residence time between 8 and 24 minutes has increased from 49% to 77%. A larger part of the water has a residence time close to the space time (16 minutes) compared to the original tank. Water with a residence time of more than 24 minutes has decreased from 21% to 17%. The mixing in the tank now has more of a plug-flow character.

Table 4. Portion of water in residence time interval. Calculated from full-scale tracer tests. $\tau$ is the space time.

<table>
<thead>
<tr>
<th>Portion of water (%) in residence time interval</th>
<th>Water with low residence time</th>
<th>Water with reasonable residence time</th>
<th>Water with high residence time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$&lt; \tau - 50%$</td>
<td>$\tau \pm 50%$</td>
<td>$\tau + 50%$</td>
</tr>
<tr>
<td>$&lt; 8$ minutes</td>
<td>30</td>
<td>49</td>
<td>21</td>
</tr>
<tr>
<td>Tank with baffles (Tracer test)</td>
<td>6</td>
<td>77</td>
<td>17</td>
</tr>
</tbody>
</table>

During the tracer test in the tank with baffles, samples were also extracted from the middle (25 m from inlet) part of the tank. Samples were extracted near the surface (0.5 m below surface) and also near the bottom of the tank (8 m below the surface, which is 2 m above the bottom). The tracer concentrations from these positions are plotted in figure 15. The peak of tracer
concentration for the upper position is at about 5 minutes and the peak of tracer for the lower position is at about 8 minutes. This is indicating that the tracer reaches the upper position before the lower position. After the peak the tracer concentration also decreases more rapidly in the upper position than the lower position.

Figure 15. Tracer concentration detected during the full-scale tracer test in the middle part (25 m from the inlet) of the first tank with baffles installed. Tracer concentrations are detected in the upper part (0.5 m from surface) and in the lower part (8 m from surface) in the tank.
6 Conclusions

Full-scale tracer tests are very informative when investigating hydraulic situations in activated sludge tanks but is tedious work and claims a lot of personal. Mathematical modelling using black box approach can help to quantifying the hydraulics in a tank. For example can use of the Martin model help to quantify short circuiting streams and dead volumes.

CFD modelling is a useful and informative tool for analyzing problematic hydraulics at wastewater treatment plants and for the design of theoretical corrective measures. The process analysis is further detailed due to CFD. This type of modelling also deserves to have a more central role when designing large reactors and other hydraulic systems, being a useful tool for virtual prototyping.

Conclusions from the investigations of the activated sludge tank:

~ The tracer tests clearly indicated that there was a short circuiting stream in the first tank of the tank train. The short circuiting stream passed through the upper part of the tank and decreased the efficiency of the tank. This problem became worse at higher inflows to the tank. Of the black box models, the Martin model was found to give the best description of the hydraulic situation and also the best quantification of the short circuiting stream and the dead volume.

~ CFD modelling was consistent with the tracer test results and demonstrated poor use of reactor volume, with a large short circuit flow followed by an extended tail of tracer. The velocity profile obtained with CFD modelling showed the main flow passing straight through the upper part of the tank. This is most likely the short circuiting stream creating the initial peak. The CFD modelling also showed that the lower part of the tank is not very active and the water appears to be slowly transported back towards the entrance of the tank. The installed mixers were not able to impact the short circuiting stream.

~ Virtual design using CFD was useful in order to evaluate the effect of three different corrective measures. The three alternatives: an inlet damper wall, a mixer and a set of baffles were all found to be able to eliminate the short circuiting stream. Implementation of baffles was chosen from an operational point of view and improved hydraulics was successfully verified with a full-scale tracer test.
7 Future work

Hydraulic behaviour
Characterisation and optimisation of hydraulics in wastewater treatment facilities is an interesting field and can be applied in many ways. Further development of the concept of using tracer tests, modelling and virtual design before implementation is interesting in other WWTPs. As well as modelling activated sludge tanks other tanks, channels and volumes are interesting to optimize.

Kinetics of microbial growth and biochemical reactions
The hydraulic CFD model gives interesting information about the physical conditions in the tank. However, kinetics of microbial growth and biochemical reactions would be interesting to connect with this model. Consequences on the concentrations of nitrite, ammonium, nitrate or other parameters due to changes in hydraulic conditions could then be modelled and compared with a full-scale plant.

Suspended solids model
In the CFD models, physical data for water were used for the fluid. However, fluid in an activated sludge tank is composed of wastewater and activated sludge which contains microorganisms and suspended solids. For example, viscosity could be modelled as dependent on the particle concentration.

A fluid model which contains the particle concentration is also interesting because it is possible to include particle sedimentation in such a model. Sedimentation characteristics can be obtained from settling experiments in a laboratory scale. This would also make it possible to model sedimentation tanks. For example, corrective measures for channels and other facilities where sedimentation is unwanted could be computer-simulated before installation.

A suspended solids model may also be linked to kinetics of microbial growth and biochemical reactions, making it possible to model changes in suspended solids concentration due to microbial growth.
### 8 Glossary

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>CSTR</td>
<td>Continuously Stirred Tank Reactor</td>
</tr>
<tr>
<td>Gryaab</td>
<td>Göteborgsregionens Ryaverks Aktiebolag – owners and operators of the Rya WWTP</td>
</tr>
<tr>
<td>IAWQ</td>
<td>International Association on Water Quality</td>
</tr>
<tr>
<td>LiCl</td>
<td>Lithium Chloride</td>
</tr>
<tr>
<td>RTD</td>
<td>Residence Time Distribution</td>
</tr>
<tr>
<td>WWTP</td>
<td>Wastewater Treatment Plant</td>
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</table>
9 Acknowledgements

I would like to thank my examiner and supervisor Professor Claes Niklasson and my co-supervisor Professor Mohammad Taherzadeh for giving me the opportunity to do this work under the department of Chemical Reaction Engineering at Chalmers University of Technology.

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Finally my special thanks to my wife Anna. Thanks for your support and love during this time.
10 References


