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(INNOWATECH)

Antonio Lopez, Claudio Di Iaconi,
Giuseppe Mascolo and Alfieri Pollice

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Foreword

Industrial wastewater streams have often very different characteristics from domestic sewage, such as high salinity, significant toxicity due to different compounds, large variabilities in composition, pH, temperature etc. These differences make it very difficult to successfully treat many industrial effluents in conventional (domestic) wastewater treatment plants. However, the alternative approach typically requires significantly more complex treatment trains with associated higher capital and operating costs, increased operator skill levels and often significant environmental impacts.

Optimal solutions to tackle these challenging waste streams need to look at both the specific local situation in each industrial facility and at industry-wide approaches to better manage the wastewater pollutants. At both scales, the characterisation and minimisation of the key pollutant sources needs to be prioritised to enable the identification of effective up-front solutions such as separation of high-strength streams or reduction/elimination of problematic compounds in the production process. Nevertheless, this rarely eliminates the need for selective and targeted treatment solutions in most industries.

In many cases, the provision of specific source control actions and pre-treatment processes can significantly improve the biodegradability of the remaining pollutants. These may include the use of more environmentally benign or biodegradable substances, stream segregation, often in combination with selective removal of key contaminants or partial chemical treatment to increase bio-availability of the remaining compounds.

In this context, the European Commission, through its Sixth Framework Programme (FP6), co-financed the project "Innovative and integrated technologies for the treatment of industrial wastewater", with the acronym innowatech (www.innowatech.org).

The aim of this project was to assess, investigate and enhance promising innovative technologies and processes aimed at tackling some of the regular and relevant problems encountered when treating industrial wastewater, e.g.:

- Inefficient biological treatment with limited operational flexibility and stability;
- High sludge production and treatment/disposal costs;
- Occurrence of recalcitrant and/or toxic compounds impacting on overallplant performance;
- Lack of technologies for selective removal or recovery of raw materials and/or priority organic pollutants;
- Non-optimalintegration and adaptation of treatment options for specific processes.

The technologies chosen for further investigations in this project were selected on the basis of their broad applicability across various sectors, their ability to specifically target key pollutants or characteristics of common industrial wastewaters or based on their innovative concepts or features.

The INNOVATECH project was structured into six work packages (WPs), with three focused on selected key technology areas such as aerobic granular sludge systems (WP1), integrated advanced oxidation and biological processes (WP2); and membrane-enhanced industrial wastewater treatment processes (WP3). A number of different wastewater types were tested in these processes, including from food and meat processing, pharmaceutical and chemical industries, and fresh and mature landfill leachates. The remaining three WPs were mainly targeting end-users application and implementation aspects, as well as technology transfer and project management tasks. This included ecological and economic evaluations using life cycle assessment (LCA) and costing (LCC) methodologies (WP4), technology dissemination and exploitation within the project and across the industry sectors (WP5), and overall project coordination and management (WP6).

The main achievements from the project activities can be summarised as follows:

- The aerobic granular sludge systems have been shown to be effective in treating biodegradable industrial wastewater streams (e.g. from food/beverage or meat processing industries). This novel technology was shown to require a smaller footprint and to produce less excess sludge compared to conventional alternatives.
- When treating complex wastewaters (e.g. mature municipal landfill leachates or from pharmaceutical industries), the integration of biological and chemical treatment processes results in synergistic effects that increase treatment efficiency and generate costs savings.
- The exploitation of solar light in photochemical reactors achieves savings in chemical and energy use without reducing the treatment effectiveness for the removal of toxic pollutants such as those present in pharmaceutical or pesticide containing wastewater.
- Innovative methods for immobilizing photo-catalysts on the surface of commercial polymers have created a technology that can be used at near neutral pH to enhance the performance of photo-Fenton or similar processes for a range of wastewater pollutants. Further benefits were achieved through reduced chemical sludge production and the ability to regenerate the catalyst under solar irradiation.
- Innovative silicone coated, selective membranes were developed for use in a Membrane Contactor, which was optimised for the cost-effective recovery of organic acids and bases even in small- and medium-scale applications typically used in chemical industries.
- Membrane coupled photo-catalysis reactors (i.e. Membrane Chemical Reactors) were further developed and optimised to demonstrate their performance with a number of industrial wastewaters.
- Development and implementation of conceptual models of existing treatment systems and of innovative treatment solutions developed in this project have allowed comparisons of the sustainability performance of the different technologies investigated in this project.

Overall, these novel and innovative achievements will directly benefit industrial wastewater treatment systems in improving their removal performance, effluent quality, operational stability, energy efficiency and particularly their capital and operating cost bases. At the same time, these improvements will have significant environmental benefits as well. Hence the results from this project, once implemented and optimised in full-scale installations, will have the potential to directly enhance the performance and competitiveness of a range of European industry sectors.

This book reports in detail the activities and results from the various elements of this project together with the technical and operational benefits and outcomes. This should directly assist in the transfer of the findings and technologies into the broader industrial and economic communities across Europe and the world.

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Chapter 1

Aerobic granular biomass processes

Shane Watts, Merle de Kreuk, Maite Pijuan, Claudio Di Iaconi, Achim Ried, Simona Rossetti, Guido Del Moro, Annalisa Mancini, Marco De Sanctis, Andreas Giesen, Mario Pronk, Mark M.C. van Loosdrecht and Jurg Keller

1.1 BACKGROUND

At the end of the 1990s, research on biofilm structure and formation (van Loosdrecht *et al.*, 1995, 1997a) and on the role of storage polymers (van Loosdrecht *et al.*, 1997b; Krishna and van Loosdrecht, 1999) resulted in the idea of growing aerobic granules without carrier material on readily biodegradable substrates in a Sequencing Batch Reactor (SBR) (Morgenroth *et al.*, 1997; Beun *et al.*, 1999; Dangcong *et al.*, 1999). In these studies, the conversion of readily biodegradable COD into a substrate yielding a lower maximal growth rate facilitated granule formation and it was shown to be possible to grow stable granular sludge (Figure 1.1) with integrated COD and nitrogen removal. In 1998, an international patent was submitted and granted (Heijnen and van Loosdrecht, 1998) and later extended to include a description of anaerobic feeding process (van Loosdrecht and De Kreuk, 2004).

Aerobic granule formation has been excessively studied worldwide (Figure 1.2). Many theories about aerobic granule formation have made their way into different studies. Analysis of a cross section of literature published in the last decade shows that substrate type, COD and N-load, superficial gas velocity or shear stress and oxygen concentration are important parameters. An important secondary parameter for the formation and maintenance of dense granules is the growth rate of the organisms that is influenced by cycle configuration or loading rates (De Kreuk *et al.*, 2005a). An extensive overview of various parameters that are important for anaerobic and aerobic granule formation has been given by Liu and Tay (2004a).

The first workshop on aerobic granular sludge was organised in Munich, Germany in 2004 (Bathe *et al.*, 2005). Despite the long-term application of anaerobic granular sludge in wastewater treatment, aerobic granular sludge is a relatively new observation and so during this workshop a definition of aerobic granular sludge was developed: granules making up aerobic granular activated sludge are to be understood as aggregates of microbial origin, which do not coagulate under reduced hydrodynamic shear, and which settle significantly faster than activated sludge flocs (De Kreuk *et al.*, 2005b).The main conclusion from the workshop was: "all participants agreed that up till then a lot of basic knowledge was gained on aerobic granule formation and that the pioneering stage was finished. Researchers should continue with specific research topics (e.g. factors influencing granule strength and formation, microbial diversity, conversion processes, pathogen removal, pilot- and demonstration-scale studies) and that the technology should be put into practice. Within a couple of years, this workshop should be repeated to see how research went from there; hopefully with new insights and with new applications."

In September 2006, a second aerobic granular sludge workshop was held in Delft, The Netherlands, of which a summary of the discussion outcomes is given below.

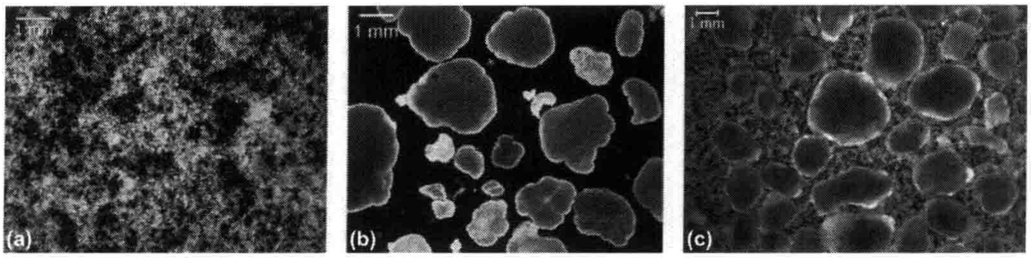

Figure 1.1 Activated sludge from a wastewater treatment plant (a) and aerobic granular sludge cultivated in a laboratory scale reactor (b) and in a pilot plant (c)

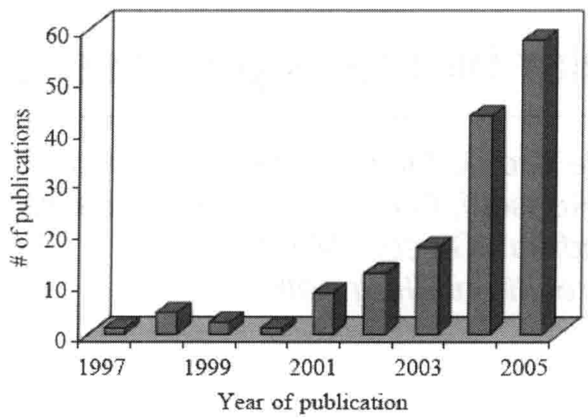

Figure 1.2 Number of publications about aerobic granular sludge per year (Source: Web of Science)

The definition of aerobic granular sludge developed in the first workshop was further expanded with explanations of the statement components:

1. Aggregates of microbial origin: speaking of granular activated sludge in the statement implies that aerobic granules need to contain active microorganisms and cannot only consist of components of microbial origin (such as proteins, EPS, etc.). The microbial population in aerobic granular sludge are to be expected more or less similar to those in activated sludge and/or biofilms, thus there is no need to describe specific groups of microorganisms in the definition. Furthermore, this part implies that no carrier material is intentionally involved or added; the aggregate is formed without the addition of such carrier material.
2. No coagulation under reduced hydrodynamic shear: this describes the difference in behaviour between activated sludge and aerobic granular sludge. Activated sludge flocs tend to coagulate when they settle (when liquid-sludge mixture is not aerated or stirred), whilst granules do not coagulate and settle as separate units.
3. Which settle significantly faster than activated sludge flocs: this means that SVI_{10} (SVI after 10 min of settling) in combination with SVI_{30} should be used as suggested by Schwarzenbeck *et al.* (2004a). The difference between the values gives an excellent indication about the granule formation and indicates the extent of thickening after settling.
4. The minimum size of the granules should be such that the biomass still fulfils point three. This minimum size was set to 0.2 mm, which was decided based on past measurements. This limit could be adjusted per case/granule type, as long as the other demands of the definition hold.
5. Sieving is considered a proper method to harvest granules from activated sludge tanks or from aerobic granule reactors, which also determines certain strength of the required biomass matrix.

When an aggregate fulfils all characteristics as described above, it can be called aerobic granular sludge. This simplifies the interpretation of experimental results and clarifies when to refer to aerobic granular sludge, activated sludge or biofilms.

1.1.1 Formation and morphology of aerobic granular sludge

Many factors have been cited as responsible for the formation and stability of aerobic granular sludge, but it is undecided amongst scientists which is the dominant factor. Workshop discussions focussed on this topic and several parameters were highlighted: a) use or appearance of specific self-aggregating cultures; b) selection by settling velocity; c) applied shear stress; d) growth rate of the organisms; e) substrate gradients inside the granules; f) formation of extra-cellular polymeric substances (EPS).

Formation of aerobic granular sludge in laboratory experiments mostly occurs with a strict selection regime for well settling sludge by applying increasingly shorter settling times. The aggregate forming organisms are maintained in the reactor, while other organisms are washed out with the effluent. To enhance the start-up of an aerobic granular sludge reactor, the use of specific self-aggregating cultures was suggested by the researchers of Nanyang University (Singapore). Non-pathogenic cultures with self-aggregating abilities were selected and added to a reactor during stat-up. This shortened the start-up time considerably (3 days instead of 9 days without specific inoculum). The selection for specific organisms to enhance granule formation and stability has also been applied by other researchers, e.g. the use of phosphate or glycogen accumulating organisms (Dulekgurgen *et al.*, 2003; De Kreuk and van Loosdrecht, 2004) or nitrifying organisms (Liu *et al.*, 2004a). However, the workshop attendees agreed that, based on published research, substrate gradients inside the granules are very important as well and that sharp decreasing substrate gradients inside the granules should be avoided. This can be achieved by using the ability of some microorganisms to convert readily degradable substrates into storage polymers and/or using organisms with low actual growth rates. EPS production by slow growing organisms enhance the granule formation (Liu *et al.*, 2004b; McSwain *et al.*, 2005, presented research results of National Taiwan University) and is seen as an important aspect by the attending researchers as well. Applied shear stress and settling time has been an important topic for studies in the past and still leads to discussions. At the aerobic granular sludge workshop 2006, several researchers showed their results about this topic (Northwestern University, USA; University of Beijing, China; Istanbul Technical University, Turkey). Shear stress is difficult to quantify and is often related to superficial gas velocity. However, factors such as stirring should not be underestimated and reported as well.

At the workshop there was a general agreement on the positive effects of hydraulic selection pressure on granule formation and stability. When aerobic granular sludge is used in combination with a membrane for effluent filtration, the selection pressure for aggregates by settling totally disappears. Even with this effluent filtration, very dense and large flocs were obtained, having a positive effect on the membrane fouling. The high density flocs only met the definition of aerobic granular sludge (above) during short periods of the total experiment, particularly during the periods when autotrophic organisms were present (results presented by INSA, France).

1.1.2 Modelling of aerobic granular sludge

Mathematical modelling has proven very useful to study complex processes, such as the aerobic granular sludge systems (Beun *et al.*, 2001; Lübken *et al.*, 2005). Biological processes in the granules are determined by concentration gradients of oxygen and diverse substrates. The concentration profiles are the result of many factors, including diffusion coefficients, conversion rates, granule size, biomass spatial distribution and density. All these factors influence each other and so the effect of individual factors cannot be studied experimentally. Moreover, experiments in granular sludge reactors take many weeks to reach steady state. A good computational model for the granular sludge process provides significant insight into the most important factors that affect the nutrient removal rates and in the distribution of different microbial populations inside the granules. Further, models could also be used for process optimisation and for scale-up and design (e.g. hydraulics) to full-scale.

Aerobic granular sludge systems can be modelled in different ways, using different modelling tools depending on the fields of interest. When the overall reactor behaviour is described (substrate removal or sludge production), traditional biofilm modelling can be used, as in AQUASIM (Reichert, 1998). Such models have already been developed by the groups in Munich and Delft. The effect of process parameters on the nutrient removal rates could be reliably evaluated with such models. Influence of oxygen concentration, temperature, granule diameter, sludge loading rate and cycle configuration have been analysed. Oxygen penetration depth in combination with the position of the autotrophic biomass played a crucial role in the conversion rates of the different components and thus on overall nutrient removal efficiencies (de Kreuk *et al.*, 2006).

When a more detailed insight into microbial or EPS distribution inside the granule is desired or to study factors influencing granule shape (presence of filamentous outgrowth, biofilm structure modelling), individually based modelling can be used (Kreft *et al.*, 2001). Such a model for aerobic granular sludge was presented by TU Delft and Universidade Nova de Lisboa, Portugal, to describe an aerobic granular sludge SBR (Xavier *et al.*, Submitted). This multi-scale model described the granular sludge reactor in detail, from the metabolism of microbial groups, through the spatial structure of granules to the dynamics of the whole reactor. However, simulations were computationally demanding and use will be restricted to a description of observed trends. With the model a preferential distribution of species along radial distances was shown, which were more heterogeneous than in strict layers. This heterogeneous structure and growth in micro colonies underlined the difficulty of representative micro-electrode measurements. Also, the accumulation of inert material in the cores of the granules was shown (Figure 1.3). Mainly the outer layers of the granule will be eroded, which contain less inert material. Therefore, aerobic granular sludge is expected to contain more inert material resulting from biomass decay than activated sludge.

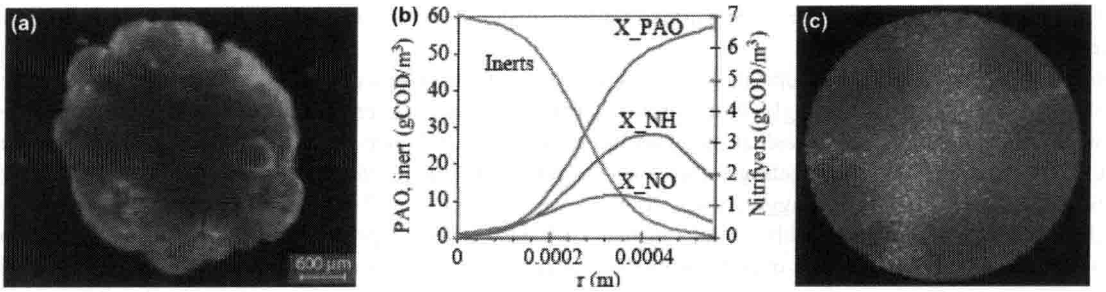

Figure 1.3 (a) Stained granule section (green ¼ live cells; red ¼ death cells); (b) biomass distribution inside a matured granule according a simulation with an ASM-like aerobic granular sludge model (de Kreuk *et al.*, 2006); (c) biomass distribution inside a mature granule according a simulation with a 2-D individually based aerobic granular sludge model (red ¼ PAO; green ¼ $NH4^+$-oxidisers; yellow ¼ NO_2^{2-} oxidisers; grey ¼ inert, Xavier *et al.*, Submitted). Subscribers to the online version of Water Science and Technology can access the colour version of this figure from http://www.iwaponline.com/wst

Waseda University (Japan) and TU Delft developed a similar multi-scale model with nitrifying granules. This model showed that within the nitrifying granules, EPS producing heterotrophic organisms grew on the products from cell lysis. These heterotrophic organisms denitrified a portion of the produced nitrate and located mainly inside the granules. At this position, they excreted EPS, which strengthened the structure of the granule and enhanced the growth of the total granule. The nitrifying organisms, growing mainly in the outer layers, detached more readily, which led to a smaller sludge residence time for these species.

Different effects of shear stress were not taken into account in the models presented at the workshop. Dr. Ivanov, Nanyang University, Singapore pointed out that mechanical compaction of granules by shear stress caused by particle-particle collisions, air-bubbles or mechanical stirring, may affect the distribution of microorganisms, detachment and porosity of the granular sludge. Changing porosity could affect the diffusion in the pores and detached portions from the granules could start new granules, both leading to a different microbial composition of the granule then described with current models.

1.1.3 Aerobic granular sludge in practice

In wastewater treatment, the activated sludge process is the dominant system. Biology of these systems has been optimised and the limits of the system have been reached. However, sludge settleability and washout from clarifiers will remain a point of attention. Major concerns of water authorities are: minimising costs of wastewater treatment; meeting effluent requirements; being prepared for future developments in effluent demands; land availability; environmental aspects such as smell and noise; and energy consumption. Aerobic granular sludge could (partly) meet these concerns. Following successful aerobic granular pilot-plant studies at two sewage treatment plants in The Netherlands by DHV, the first full-scale municipal wastewater treatment plant is planned (presented by water board "Hollandse Delta"). As end-users, water boards in The Netherlands see it as their (public) responsibility to cooperate with consultancies and universities to develop this innovation and invest in full-scale applications.

Several wastewaters from industrial and municipal origin have been used to cultivate aerobic granules and to study the treatment process and the results were presented during the workshop. The first was a pilot plant study (two reactors of 1.5 m^3 each) with the Nereda system treating sewage at a Dutch wastewater treatment plant (presented by DHV Water, The Netherlands) and the second, a demonstration scale sequencing batch biofilter granular reactor (SBBGR, 3.1 m^3) treating sewage at an Italian wastewater treatment plant (presented by IRSA).

1.2 LABORATORY SCALE EXPERIMENTS

1.2.1 Introduction

Most conventional municipal wastewater treatment plants have the disadvantage of large area requirement and high surplus biomass production. In order to overcome these disadvantages, compact systems are developed to decrease the footprint and reduce the sludge production, like the biofilm airlift reactor. The main factor for a compact system is the improvement of the settleability of the sludge (e.g. by growing the biomass as biofilms on carrier material or as granules or dense flocs without support material). Granular sludge is well known in anaerobic systems (such as UASB, IC and EGSB reactors), while in aerobic systems (continuous fed aerated fluidised beds and airlift reactors) sludge is grown on carrier particles to obtain high settling velocities (Nicolella *et al.*, 2000).

Research has shown that it is also possible to grow stable granulated sludge under aerobic conditions and the advantages of a discontinuously over a continuously fed system were shown (Morgenroth *et al.*, 1997; Beun *et al.*, 1999; Dangcong *et al.*, 1999). Besides the flexible operation of these sequenced batch airlift reactor (SBAR) systems, the stability and density of the granules were higher, while different aerobic and anaerobic processes (integrated COD, N and P removal) can occur in the same unit simultaneously and at high efficiency (De Kreuk *et al.*, 2005a). The high settling velocity of the granules makes the use of a traditional settler or 3-phase separator unnecessary, so the installation can be built very compact. All processes take place in one reactor: from influent feeding and conversion of the pollution until settling of the aerobic granular sludge and effluent discharge. The area requirement of a wastewater treatment plant with the granular SBAR will be approximately 25% of the area requirement of a conventional activated sludge system (De Bruin *et al.*, 2004). This one-reactor system leads to lower pump-capacity (no recycle flows) and more efficient aeration and thereby results in at least 30% less energy use during operation. Also the needed material to construct an installation is reduced. This will all lead to less investment and operational costs. All these advantages will lead to a large market for the application of aerobic granular sludge and this new technology (marketed by DHV, The Netherlands under the brand name Nereda™) can compete with activated sludge systems or other compact techniques (as MBR).

1.2.2 Objectives

Aerobic granular sludge is a young technology, up till now grown in well-controlled laboratory scale reactors and pilot plants (De Bruin *et al.*, 2005). Only limited information has been published on laboratory scale reactors treating industrial effluent (malting (Schwarzenbeck *et al.*, 2004b), dairy (Arrojo *et al.*, 2004; Schwarzenbeck *et al.*, 2005) and pharmaceutical effluent (Inizan *et al.*, 2004)) and domestic sewage (De Kreuk and van Loosdrecht 2006). However, the specific influences of process parameters important for industrial applications have not yet been published. Presently, two full-scale plants are realized in (food) industry and with more plants expected in the coming years. However, scaling-up the aerobic granular sludge reactor (GSBR or Nereda™) from a 3-litre laboratory scale to a full-scale application exhibits some bottlenecks and unknown aspects. In order to be able to compare an aerobic granular sludge system to other new techniques for effluent treatment, some aspects still have to be studied at laboratory scale and compared to results obtained in practice. The experimental work is organized in the next three phases.

Particulate and Polymeric COD

This phase examines conversion of particulate and polymeric COD and its influence on granule morphology. Industrial effluents, in particular food industry, can contain a high amount of slowly biodegradable or polymeric substrates. From experiments with municipal wastewater it is known that particulate COD can be converted, but the mechanism is unclear. These substances might also influence the morphology of the granules, as has been shown in biofilm research. Therefore, the influence of this particular influent on the performance of an aerobic granular sludge reactor has to be researched in a laboratory scale reactor. The results of the laboratory experiment would be compared with full-scale applications in food industry.

High Temperature

Industrial effluent can have elevated temperatures, which may influence the granule composition, morphology and substrate conversion processes. Aerobic granule formation at lower temperatures has been studied previously (De Kreuk *et al.*, 2005b; De Kreuk *et al.*, 2007), but the influence of higher temperatures is unknown. For example the effluent of the first full-scale aerobic granular sludge reactor (NEREDATM) in industry fluctuates between 35°C and 41°C degrees. Results from this plant indicate that temperatures above 40°C are critical for changes in the system (unpublished data). Therefore, the influence of high temperatures was studied in the laboratory (30°C to 50°C) and results verified with observation from the full-scale industrial applications.

Toxic Compounds

Xenobiotics can inhibit the processes in the biological plants treating industrial wastewater. Previous research showed that microbial granules could be more resistant to wastewaters containing toxic compounds than suspended microbial sludge (Fang, 2000). It has been reported that granules are more resistant to the toxic effect of phenol than flocculated sludge, because of the compact structure of the granules (Jiang *et al.*, 2003). Liu *et al.* (2005a) found out that for initial phenol concentrations up to 10 mg/L, the nitrifying activity of aerobic granules was recovered after phenol degradation. Liu *et al.* (2009) proposed that the granular structure could provide microbial cells with beneficial protection from phenol toxicity, mainly at a longer exposure time. Generally, all the studies reported that nitrifying bacteria embedded in microbial granules might have a better ability to resist to the shock of toxic compounds in wastewaters than suspended nitrifying bacteria.

Fluctuations of the influent pH and the resulting changes in reactor pH restrict the operation of a biological treatment plant. Previous work showed that the optimal pH for the nitrification process is between 7.0 and 8.2 (Antoniou *et al.*, 1990; Hall 1974; Loveless and Painter, 1968; Painter and Loveless, 1983; Shammas, 1986). Those studies were conducted with activated sludge and/or pure cultures. Smolders *et al.* (1994) highlighted that the rate of P-release under anaerobic conditions was increased as the pH was increased. Similarly, Bond *et al.* (1998) stated that a SBR operated without pH control in the anaerobic phase exhibited an improved P-removal comparing with a SBR which had pH control. So far, the effects of pulse pH shocks on nitrifier and PAO populations in granular sludge have not been investigated.

Thus, it is of practical interest to investigate the effects of pH and 2-fluorophenol (2 - Fluor phenol) on nitrification and phosphate uptake by aerobic granules.

1.2.3 Method description & lab scale reactor setup

Experiments were performed with 2 to 4 granule sequencing batch reactors (GSBR), operated in parallel. Influent or temperature was varied in the different reactors. The experimental set-up of the reactors is shown in Figure 1.4. The reactors were operated as bubble columns with a working volume of 3 litres (diameter 6.25 cm). The effluent was extracted at a height of 50 cm resulting in an exchange ratio of approximately 0.5.

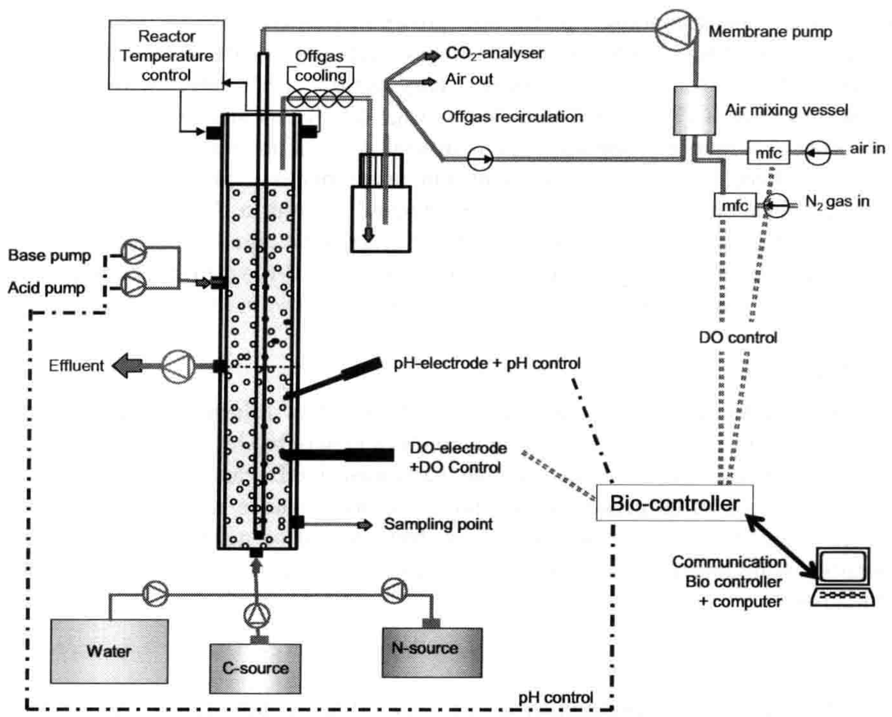

Figure 1.4 Set up of the laboratory scale GSBR's

A sparger with an airflow of 4 l/min (87.5 m^3/hr) was used for aeration. The oxygen was measured on-line continuously with an optional continuous CO_2 measurement. DO control was achieved via the off-gas recycle. The membrane pump recycled 4 l/min of off-gas and via a control based on the DO measurement, nitrogen gas or fresh air was dosed into the main air stream by mass flow controllers. In this way, the oxygen level could be kept constant during the total cycle. The total recycle flow that is dosed to the reactor always remains 4 l/min.

The pH was measured on-line continuously and was controlled with 1 M NaOH or 1 M HCl dosing. Depending on the influent, it was controlled between 6.8 and 7.2 (acetate based influent) or between 7.5 and 7.8 (glucose or starch based influent).

The reactors were operated at room temperature. During the elevated temperature experiments, the temperature was controlled via a water-jacket around the reactor and a temperature measurement in the reactor.

The synthetic influent wastewater consisted of 2 media. Medium A: C-source with a final concentration of 3.96 g COD/L; 3.6 mM $MgSO_4 \cdot 7H_2O$; 4.7 mM KCl. Medium B: 35.4 mM NH_4Cl; 4.2 mM K_2HPO_4; 2.1 mM KH_2PO_4; 10 ml/l trace element solution. From both media approximately 150 ml was dosed to the reactor together with 1.3 litre of tap water resulting in a COD-load of 1.6 kg COD/$m^3 \cdot$ day, a COD/N ratio of 7.9 and a phosphate concentration of