The SBR and its biofilm application potentials

P.A. Wilderer* and B.S. McSwain*,**

* Institute of Water Quality and Waste Management, Technical University of Munich, 85748 Garching, Germany (E-mail: *P.Wilderer@bv.tum.de*)

** Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA (E-mail: *bmcswain@nd.edu*)

Abstract Twenty plus years of experience, innovation, and research in the field of biological wastewater treatment and biofilm applications lead to the conclusion that biofilms are in many cases more desirable in reactors than suspended activated sludge. Biofilm reactors can provide very long biomass residence times even when the hydraulic influent loading is low. This makes them particularly suitable when treatment requires slow growing organisms with poor biomass yield or when the wastewater concentration is too low to support growth of activated sludge flocs. Regardless of the settling characteristics of biological aggregates or the hydraulic influent loading the metabolic activity in the reactor can be maintained at a high level. This paper reviews the application of biofilms in sequencing batch reactor (SBR) systems to treat non-readily biodegradable substrates, volatile organic waste constituents, complex waste streams requiring co-metabolism, and particulate wastewaters. Recent research using the SBR to form aerobic granular sludge as a special application of biofilms is also discussed.
Keywords Adsorption; aerobic granules; biofilm reactors; GAC-SBBR; granular activated carbon; SBBR; sequencing batch reactor; sink source

Water Science and Technology **Vol 50 No 10 pp 1–10**

Introduction

Much research in the field of biological wastewater treatment is aimed at overcoming a few classic pitfalls of the completely mixed continuous flow system. This system is often associated with overgrowth of filamentous bacteria that cause bulking or foaming, failure due to fluctuating loading rates or shock loads, and a large area requirement for reactors and clarifiers. These problems are ultimately caused by the design and operation of the reactor and consequently the microbial community composition and physiological states that are selected. In the mid-1970s, researchers began to understand that wastewater treatment systems are generically unsteady-state due to natural variations in load on an hourly and daily basis (Irvine and Davis, 1971). Moreover, it became clear that control of unsteady-state conditions is utterly necessary to gain control over microbial systems, their composition, metabolic capacity and physical properties. Chudoba *et al*. (1973) introduced the selector concept as a means to avoid sludge bulking. In the attempt to achieve nutrient removal Sutton *et al*. (1978) proposed regulation of availability and concentration of electron donors and acceptors (oxygen and nitrate) by adjusting the hydraulic retention time in the aerobic, anaerobic and anoxic zones of a reactor cascade. By switching on and off parts of the activated sludge reactor system engineers tried to maintain the optimal balance between feast and famine conditions irrespectively of the influent loading variations (Wilderer *et al*., 1983). In this way, wastewater engineers began to institute control methods. But these methods were based on experience rather than fundamental scientific knowledge, and reactor design was neither optimal nor fail-safe.

An entirely different approach was chosen by Irvine *et al*. (1971, 1979). Based upon previous experience (Ardern, 1927) he and his coworkers proposed integration of the clarifier in the bio-reactor and replacement of sludge recycling by time controlled sequences of process phases such as fill, react, settle, decant and idle. Meanwhile, the sequencing batch reactor (SBR) concept has become a worldwide accepted alternative to the continuous flow activated sludge process (Wilderer *et al*., 2001).

By controlling and regulating unsteady-state conditions, the reactor controls the shifting of activated sludge between zones of high and low substrate concentration and between anaerobic, anoxic, and aerobic zones. Over time, these constantly repeated variations select for robust microbial communities with good settling properties, high substrate removal efficiencies, and the ability to withstand unplanned fluctuations.

Since its conception in the late 1970s, the SBR has had a wide range of benefits and applications. In comparison to continuous flow reactors the SBR typically performs well, and it can accomplish industrial wastewater treatment, nitrogen and phosphorus nutrient removal, and fully anaerobic treatment. SBR technology has also proven to be highly adaptable for more complex treatment schemes. The basic SBR uses suspended growth activated sludge flocs to accomplish the biological metabolism of wastewater, but the SBR has alternatively used biofilm growth for a variety of treatment purposes. In the following, biofilms and their application to SBR systems will be reviewed.

Biofilms and the SBR

Biofilms have been defined as aggregates of microorganisms growing at an interface, mostly at solid–liquid interfaces (Wilderer *et al*., 2001). Biofilms can be more desirable in reactors than suspended activated sludge because high metabolic potentials can be maintained regardless of the settling characteristics of biological aggregates or the hydraulic loading. The biofilms can also have very long biomass residence times, which make them particularly suitable when treatment requires slow growing organisms with poor biomass yield or when the wastewater concentration is too low to support growth of activated sludge flocs (Wilderer, 1992; Wilderer *et al*., 2001). Microorganisms growing in a diffusion controlled biofilm community also receive protection from the extracellular polymeric substances (EPS) they are embedded in. EPS can minimize the impact of changes in pH, temperature, and concentration of toxic substances (Wingender *et al*., 1999). Another advantage of biofilm reactor systems is that non-readily biodegradable matter can be sorbed onto and transferred into the biofilm and periodically removed by desorption and subsequent biodegradation.

Although biofilm reactors are sometimes more desirable than suspended growth systems, biofilms have a few basic limitations. In biofilm systems, the mass flux of substrate between the bulk liquid and the microbial aggregate is one dimensional, and substrate must be transported across this liquid–solid interface before biological conversion can proceed. Once the substrate has crossed this interface, there will be a concentration gradient within the biofilm itself due to diffusion limitations. As a result, only a fraction of the biofilm may contribute to the overall metabolic processes. Qualitatively, the active fraction of the biofilm is affected by the concentration of substrates in the bulk liquid, the actual metabolic rates within the biofilm, and the thickness of the biofilm. In general, the efficiency of biofilm reactors increases with decreasing biofilm thickness and with increasing surface area of the biofilm support material relative to the volume of the reactor (Wilderer *et al*., 2001).

Because biofilms can grow on a multitude of support materials, which can be suspended or fixed in a reactor, biofilm reactors come in many different forms. These include packed bed reactors, submerged packed bed reactors, trickling filters, fluidized bed bioreactors, biological activated carbon, and biological membrane reactors. The reactor configuration is usually chosen for a given wastewater and treatment goal, and several different types of biofilm reactors have been operated in a periodic mode – giving the general term SBBR (sequencing batch biofilm reactor).

Sink-source applications

Wastewater treatment plants are subject to sometimes extreme variations of flow, composition and substrate concentration, especially in tourist areas or in industry. Reactors of low hydraulic buffer capacity exposed to a high inflow rate are particularly vulnerable, and internal equalization methods have been used to minimize the fluctuations of hydraulic and biomass loading. In suspended growth systems treating readily biodegradable substrates, the SBR cycle applies a high load during the fill phase (fill) followed by a period of low substrate concentration during the later stage of the react phase (react). This has been termed a feast–famine regime, and it describes the substrate uptake and storage of readily biodegradable substrates followed by the metabolism of those stored substrates during the react phase (Chiesa and Irvine, 1985). This concept of feast–famine or storage– regeneration is not easily applicable when the substrates are not readily biodegradable or require complex metabolic pathways, such as co-metabolism. However, several SBBR studies have investigated the use of biofilm and biofilm support material, via sorption, as a temporary sink during high loading periods and a subsequent source of substrate during low loading periods (Wilderer *et al*., 2000).

The SBBR can function as a sink–source system when influent waste constituents are stored onto biofilm support media by means of adsorption, ion exchange, or absorption processes. In this way, high loads of degradable substrates and non-readily and/or toxic compounds are removed quickly from the bulk liquid in the reactor. As the react phase continues, desorption processes provide a source of substrate to the bulk liquid, which can be metabolized by the biofilm organisms. Cycles of sink–source processes applied in an SBBR provide protection to bacteria against harmful shock loads, and it prevents effluent concentrations from exceeding discharge levels (Kolb and Wilderer, 1997; Wilderer *et al*., 2000). A schematic of sink–source in an SBBR is shown in Figure 1.

SBBRs using sink–source mechanisms have been applied to several systems at the laboratory- and pilot-scale, treating both industrial and municipal wastewater. Overall, the studies show that biofilms growing on sorptive biofilm support media are beneficial for minimizing peak loading conditions, for treating persistent waste constituents, and for keeping the effluent concentration low. The studies also address the treatment of volatile chemicals and the problems associated with competitive waste constituents for sorption and limitations of desorption.

A textbook case – thio-glycolic acid

Degradation of thio-glycolic acid ($C_2H_4O_2S$) was achieved in a fixed bed biofilm reactor packed with granular activated carbon, operated as an SBBR. Thio-glycolic acid is

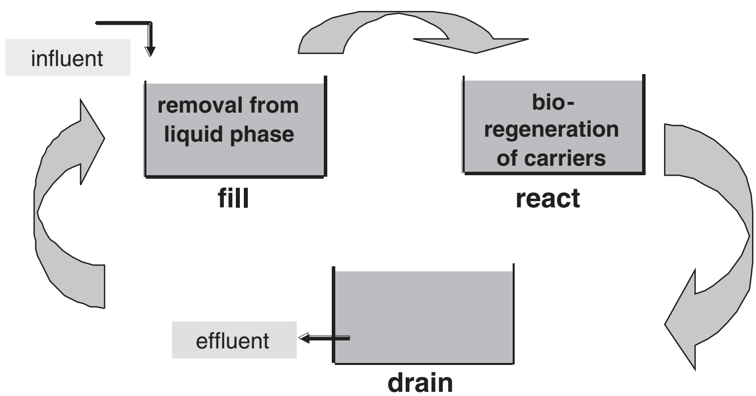

Figure 1 The sink–source cycle in an SBBR (provided by J. Keller, University of Queensland, Australia)

biologically degraded aerobically to SO_4 as an end product. A schematic of the SBBR is provided in Figure 2.

At high loading situations during the fill phase, sorption of thio-glycolic acid (TGA) to the granular activated carbon (GAC) is the dominant process. During the following react phase, desorption and metabolism become the dominant processes. Figure 3 shows a typical concentration profile of TGA, SO_4, and dissolved oxygen (DO) during a 26 hour SBBR cycle. TGA is almost completely removed from the bulk liquid within the first two hours of the fill phase, but the slow rise of DO and SO_4 shows that degradation continues over the next 18 to 23 hours (Jaar, 1991).

Nutrient removal – ion exchange

An SBBR with ion exchange capabilities has been used to treat an ammonium-rich wastewater. Ammonium may become inhibitory to bacteria when present in high concentrations,

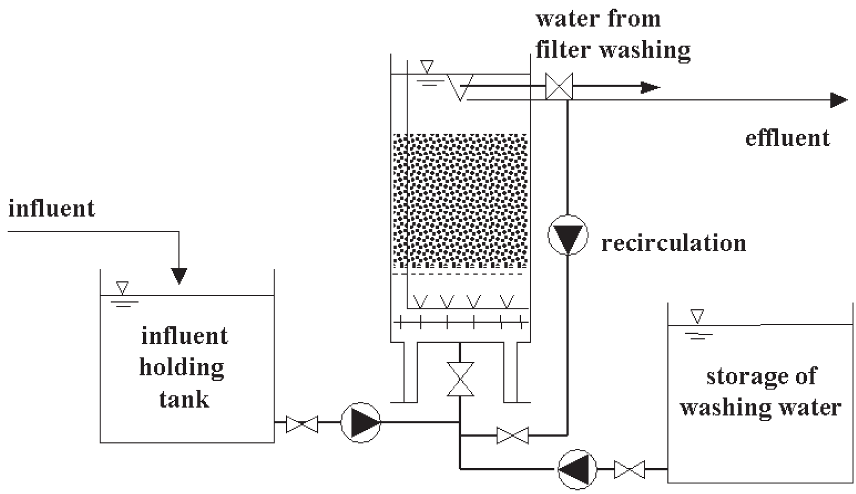

Figure 2 Schematic of fixed bed biofilm reactor packed with granular activated carbon

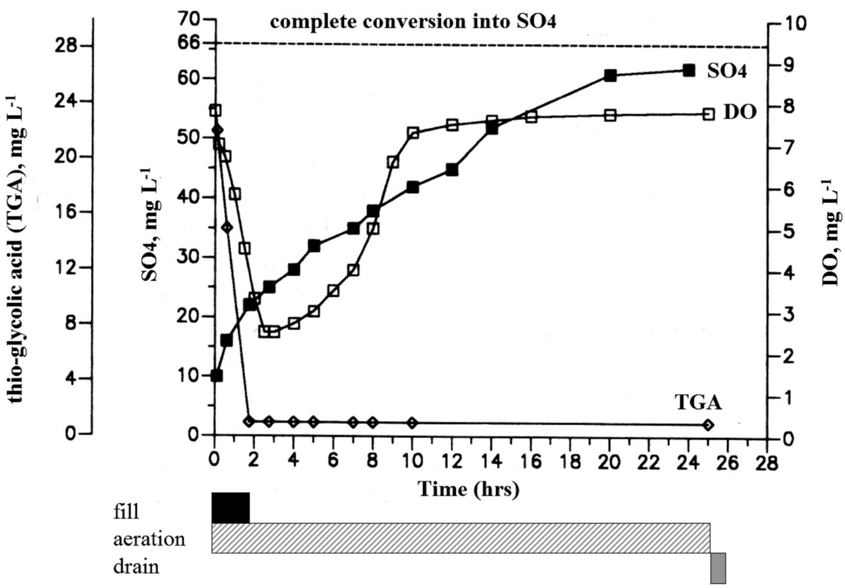

Figure 3 Removal (sink) of TGA and subsequent metabolism (source) in a GAC-SBBR (Jaar, 1991)

but the fast storage of ammonium ions onto biofilm carrier material and slow desorption circumvents this problem.

In a bench scale study, an SBBR was filled with zeolite granules as a cation exchanger. During the first part of the cycle, the SBBR was fed a rich ammonium wastewater followed by 3.5 hours of non-aerated mixing. This time allowed the ammonium ions to become bound to the zeolite, and it provided an anaerobic phase for dentrification of nitrate generated in the previous cycle. Next, the zeolite granules were settled, and 60% of the reactor volume was removed. The second phase of the SBBR cycle involved 8 hours of aeration, during which the ammonium was desorbed from the zeolite and nitrified.

Concentration profiles of COD, ammonium (NH_4), and nitrate (NO_3) during one SBBR cycle are presented in Figure 4. This figure also shows results of a control reactor, which contained quartz sand as the biofilm carrier rather than zeolite granules. The results show that ammonium is removed faster from the bulk liquid when zeolite granules are present, and more total nitrate is produced in the aerated react phase.

There is one major drawback of using ion exchange as a mechanism for sink–source application: zeolite and other ion exchangers may take up ammonium ions as well as other cations from the wastewater. However, desorption and regeneration driven by nitrification in the adjacent biofilm will occur for sorbed ammonium ions only. If the wastewater contains a range of cations, the zeolite will quickly lose its exchange capacity, and the process will fail. Therefore, ion exchange in biofilm reactor systems is only applicable for wastewaters with a low concentration of competing ions, such as condensate from sludge dryers, rainwater run-off, or specific industrial process wastewaters (Kruzic, 1986; Wilderer *et al.*, 2000).

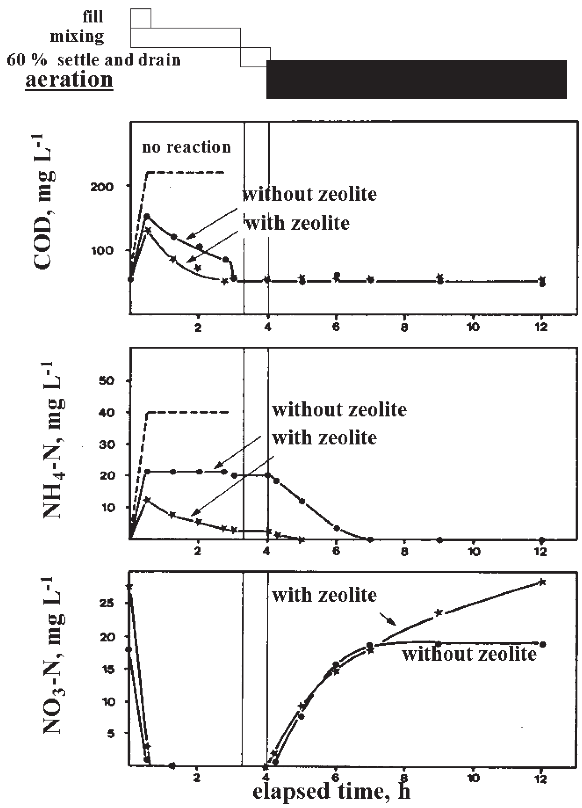

Figure 4 Concentration profiles in an SBBR with zeolite granules, and quartz sand respectively, as biofilm support media (Kruzic, 1986)

Thus far, a few cases have been presented of SBBRs treating single constituent wastewaters. The application of sink–source in SBBRs can be complicated by multiple constituent wastewaters, co-metabolism requirements, or volatile organic components which are easily stripped from aerobic systems. To investigate these factors, an SBBR was operated with GAC, and with a bubble-free oxygenation system.

To avoid the problem of stripping, a GAC-SBBR was designed with external recirculation of the bulk fluid through the lumen of silicon rubber tubing exposed to an oxygen-enriched gas space. The surface of the silicon rubber allows microorganisms to adhere, leading to biofilm growth at the inner side of the tubings. Interestingly, the microorganisms are supported with substrates from the liquid side of the biofilm, and with oxygen from the back side of the biofilm, the silicon rubber surface. The advantages of this aeration system are that stripping of volatile chemicals into the atmosphere is prevented, and the specific membrane surface area can be adjusted easily to meet aeration demands since it is a modular unit (Kolb and Wilderer, 1997).

The membrane GAC-SBBR was tested at laboratory scale with two combinations of organic pollutants: benzene (Ben)/2-chlorophenol (2-CP) and phenol (Ph)/trichloroethene (TCE). Ben and Ph were intended to act as readily biodegradable co-substrates for 2-CP and TCE, respectively. In particular, the aerobic degradation of TCE requires a proper co-substrate. The GAC-SBBR had a total volume of 16.5 L with an adsorption column containing 500–1,400 g of GAC. The SBR cycle varied between 12 and 24 hours with 10–14 L of synthetic wastewater being added in less than 0.2 hours.

For the benzene/2-chlorophenol system, the biological conversion of the co-substrates under high loading (1,500 < COD < 3,000 mg/L) and low GAC content occurs during two phases. Phase I involves COD biodegradation and uptake from the bulk liquid via sorption onto GAC, and Phase II includes desorption and biodegradation of the sorbed organics. This process is schematically shown in Figure 5 with measurements taken during one treatment cycle. During Phase I, the oxygen concentration decreases while the chloride concentration only increases slightly. This data reveals that the primary substrates (benzene and phenol, respectively) are metabolized during this phase while the co-substrates are mostly sorbed. In Phase II, the chloride concentration increases when the chlorinated organics are dehalogenated and degraded. For this combination of substrates, up to 95% of the organics are degraded within a 24 hour cycle.

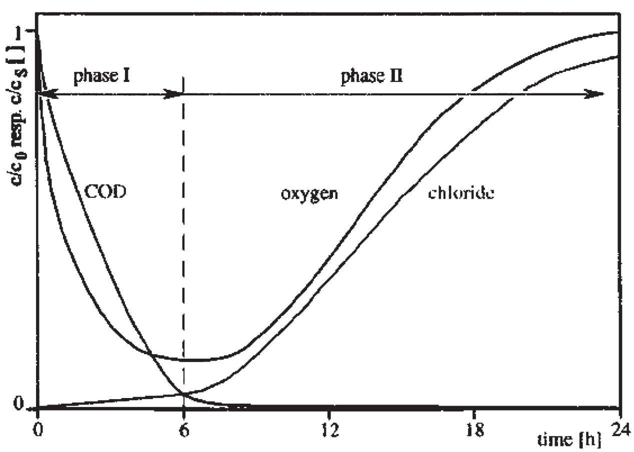

Figure 5 Concentration profiles over one cycle, GAC-SBBR fed with benzene/2-chlorophenol (Kolb and Wilderer, 1997)

P.A. Wilderer and B.S. McSwain

For the phenol/trichloroethene system, batch experiments to obtain adsorption isotherms showed that TCE is sorbed to GAC very effectively with little subsequent desorption, yielding a poor bioavailability. This fact causes the GAC-SBBR to be only slightly effective for TCE degradation. With a synthetic wastewater containing 80% phenol and a TCE concentration of 100 mg/L, TCE was degraded at a rate of 0.197 mg/h for the first 24 hours. A longer observation period showed that 14 mg/L TCE could be biologically degraded within 4 days.

The results with benzene and 2-chlorophenol co-substrates show that the membrane GAC-SBBR can be highly efficient and cost effective for the regeneration of activated carbon systems. Removal rates up to 95% were achieved within 24 hours, and more than 30% of the GAC load was converted biologically within 30 days. In this way, *in situ* bioregeneration can extend the endurance of GAC, reduce overall operating costs, and reduce the amount of spent GAC that must be disposed of (Kolb and Wilderer, 1997; Kolb, 1997). The treatment system may be less appropriate for strongly sorbing co-substrates, such as TCE, but batch adsorption tests can be used to quickly estimate the treatability of different waste streams.

Aerobic granular sludge – self-immobilized biofilms

Biofilms have hereto been defined as aggregates of microorganisms, held together by EPS, which grow at any type of interface. Granular sludge has been considered to be a special case of biofilm growth without the addition of a carrier material (Grotenhuis *et al*., 1991; El-Mamouni *et al*., 1995; Beun *et al*., 2002). Granules are a collection of self-immobilized cells into a somewhat spherical form. The upflow anaerobic sludge blanket (UASB) bioreactor using anaerobic granules is one of the best-known self-immobilization processes and has been extensively applied to anaerobic wastewater treatment. Alternatively, aerobic granulation in wastewater has only been reported for a few years and is currently a subject of intense research. The formation of aerobic granules requires very different operating conditions than the formation of anaerobic granules due to the differences in aeration. Some aerobic granulation has been reported in continuously-fed biofilm airlift suspension (BAS) reactors which have carrier material added (van Loosdrecht *et al*., 1995). However, spontaneous aerobic granulation of suspended growth aggregates is a phenomenon that has been most frequently observed in systems applying the SBR concept.

The cultivation of aerobic granules in SBR systems offers a new tool to optimize wastewater treatment since granules settle very quickly and compactly, eliminating the need for long settling times. Granular sludge also allows high biomass retention times and subsequently the establishment of slow growing organisms or complex metabolic communities. This has been witnessed in granules performing nitrification and denitrification simultaneously, without the need for alternating anaerobic and aerobic cycles. Such granules may contain multiple active layers of biomass that enable aerobic and anoxic bacteria to function simultaneously within an oxygen gradient. Despite promising research in SBR systems for the application of aerobic granular sludge, a clear understanding of the formation, structure, and composition of aerobic granules is far from the current scope of knowledge.

The influence of feast-famine on granule formation

Thus far, a few reactor operating parameters have been shown to be important to granule formation:

- The application of a short settling time to select for fast settling flocs and granules (Beun *et al*., 1999, 2002).
- A sufficient supply of shear force, usually provided by a high aeration rate or superficial upflow gas velocity (Tay *et al*., 2001).

- The application of the SBR cycle with a short fill period, creating a feast–famine regime in the reactor (McSwain *et al.*, in press; de Kreuk *et al.*, in press).

A recent experiment investigated the role of the SBR and feast–famine in the formation of aerobic granules. The studies conducted by Chiesa and Irvine (1985) showed that intermittent feeding in the SBR produces feast–famine conditions that select for better settling sludge by selecting against filamentous organisms. Generally, floc-forming bacteria, with relatively high substrate uptake kinetics, have an advantage over filamentous bacteria if food is supplied intermittently, forcing bacteria to acquire and store the food for cell maintenance and growth during periods of starvation (Chudoba *et al.*, 1973). The experiment applied these principles to biofilm growth and organism selection within granular reactors. Three parallel SBRs were operated with the same settling time, aeration rate, and volumetric loading rate. The fill phase was varied by changing the amount of static (or non-aerated) versus aerated fill, systematically decreasing the amount of "feast" accumulated during static fill and increasing the time for substrate uptake during aerated fill phase. The ratios tested were 100%, 66% and 33% static fill for a 90 minute fill phase. Microscopic images of the sludge formed in each reactor are presented in Figure 6.

In general, the higher the ratio of static to aerated fill, the more smooth and less filamentous the granule. These results indicate that SBR application of feast–famine regimes is necessary for the formation of smooth, compact aerobic granules (McSwain *et al.*, in press).

Removal of particulate matter by aerobic granules

Most laboratory-scale reactor studies use synthetic wastewaters as substrates. This ensures wastewater consistency over time, allowing researchers to systematically study different parameters, but it ignores particulate and colloidal matter, which is a major fraction of real wastewaters. Municipal and industrial wastewaters can contain 50–90% of total COD in the form of colloids and particles. To study the efficiency of aerobic granular sludge fed with particulate wastewater, barley dust was collected from a malt factory and used to create a synthetic wastewater characteristic of real, malt house wastewater. Two lab-scale SBRs were operated at a working volume of 12 L. An 8 hour SBR cycle included 6 min fill, 120 min idle, 345 min aerated react, 2–5 min settle, and 4 min of effluent draw. The volumetric exchange ratio was set to 66%, resulting in an HRT of 0.5 days. The average COD_{total} loading rate was 3.2 kg/(m^3·d) with an average TSS-content in the influent of 0.95 g/L.

Over the period of operation, an average removal efficiency of 50% COD_{total} and 80% $COD_{dissolved}$ was achieved. Hydrolysis of the particulate matter in the feed was concluded to be the limiting factor for substrate removal efficiency, although two distinct mechanisms of particle removal were observed for granular sludge. During initial granule formation, particles were incorporated into the biofilm-matrix, but for mature granules a high level of

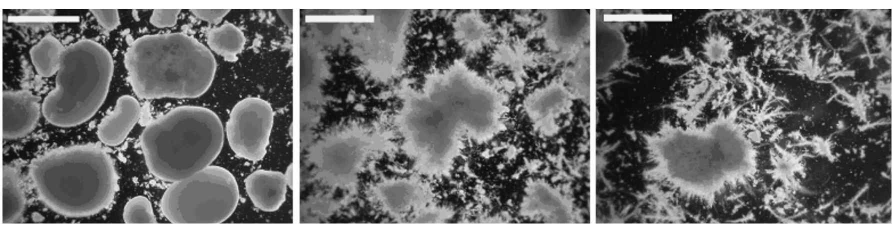

Figure 6 Selection of different sludge types in SBRs with 100, 66, and 33% static fill, respectively (bar = 5 mm). Smooth aerobic granules only formed in the SBR with 100% static fill (McSwain *et al.*, in press)

protozoal growth on the granule surface accounted for the ability to ingest particulate COD (Schwarzenbeck *et al.*, in press). The study shows that granular sludge can be applied to highly particulate wastewater with high removal efficiencies.

Conclusions

The work which is presented herein represents 20 plus years of experience, innovation, and research in the field of SBR technology, and it should serve as a foundation for new innovations and applications. One of the major advantages of the SBR is that it is easy to adapt to specialized applications by simply altering cycle times, volumetric exchange rates, sequence of react phases and sludge age. When the application requires a biofilm system, the SBR can be designed and operated in a multitude of ways, each providing specific advantages. It is the "art of engineering" and the obligation of engineers to select and apply the reactor design and operation so that the treatment requirements are met in the most efficient and cost-effective way. It should be clearly understood that there is no universally applicable wastewater treatment technology. In-depth knowledge, ingenuity and openness to novel technological developments are important factors in the process of meeting the needs of both the consumers and the environment in the receiving waters. In the past, biofilm SBRs have been used to treat ammonium rich wastewaters, volatile organics, industrial constituents requiring co-metabolism, and particulate wastewater. Recently, investigations into self-immobilized biofilms, or aerobic granular sludge, have explored the application of biofilms without carrier material. In the future, it is likely that researchers will continue to meet the demands of new industries and new wastewaters with ever-evolving biofilm reactor designs.

References

Ardern, E. (1927). The activated sludge process of sewage purification. *J. Soc. Chem. Ind.*, **36**, 822–830.

Beun, J.J., Hendriks, A., van Loosdrecht, M.C.M., Morgenroth, E., Wilderer, P.A. and Heijnen, J.J. (1999). Aerobic granulation in a sequencing batch reactor. *Wat. Res.*, **33**(10), 2283–2290.

Beun, J.J., van Loosdrecht, M.C.M. and Heijnen, J.J. (2002). Aerobic granulation in a sequencing batch airlift reactor. *Wat. Res.*, **36**, 702–712.

Chiesa, S.C. and Irvine, R.L. (1985). Growth and control of filamentous microbes in activated sludge: an integrated hypothesis. *Wat. Res.*, **19**(4), 471–479.

Chudoba, J., Grau, P. and Ottova, V. (1973). Control of activated sludge bulking ll. Selection of microorganisms by means of a selector. *Wat. Res.*, **7**, 1389–406.

de Kreuk, M.K. and van Loosdrecht, M.C.M. (2004). Selection of slow growing organisms as a means for improving aerobic granular sludge stability. *Wat. Sci. Tech.*, **49**(11–12), 9–17.

El-Mamouni, R., Leduc, R., Costerton, J.W. and Guiot, S.R. (1995). Influence of the microbial content of different precursory nuclei on anaerobic granulation dynamics. *J. Biotechnol.*, **39**(3), 239–249.

Grotenhuis, J.T.C., Smit, M., Van Lammeren, A.A.M., Stams, A.J.M. and Zehnder, A.J.B. (1991). Localization and quantification of extracellular polymers in methanogenic granular sludge. *Appl. Microbiol. Biotechnol.*, **36**, 115–119.

Irvine, R.L. and Davis, W.B. (1971). 'Use of sequencing batch reactors for waste treatment – CPC International', Corpus Christi, Texas, *26th Annual Purdue Industrial Waste Conference, Purdue University, West Lafayette, IN*, p. 450.

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

Jaar, M. (1991). *Biologische schadstoffbeladener Aktivkohle am Beispiel der Modellsubstanzen 3-Chlorobenzoesäure und Thioglykolsäure (Biological regeneration of spent activated carbon using 3-chlorobenzoic acid and thioglycolic acid as model substances*. Hamburger Berichte zur Siedlungswasserwirtschaft 9, TU Hamburg-Harburg, Germany.

Kolb, F.R. and Wilderer, P.A. (1997). Activated carbon sequencing batch biofilm reactor to treat industrial wastewater. *Wat. Sci. Tech.*, **35**(1), 169–176.

Kolb, F.R. (1997). *Biologische Reinigung xenobiotica-haltiger Abwässer in einem Aktivkohle-Festbett-*

Schlaufenreaktor mit Membrane-Stoffübertrager (Biological purification of wastewater containing xenobiotics with the aid of a loop flow reactor packed with activated carbon and equipped with a membrane oxygen transfer unit). Berichte aus Wassergüte- und Abfallwirtschaft 128, TU Munich, Germany.

Kruzic, A.Ph. (1986). Zwischenspeicherung von Ammonium zur spateren Nitrifikation (Temporary storage of ammonia for further nitrification). *Anwendung des Sequencing Batch Reactor Verfahrens zur biologischen Abwasserreinigung (Application of SBR technology for biological wastewater treatment)*. (eds) Wilderer, P.A. and Schroeder, E.D. Hamburger Berichte zur Siedlungswasserwirtschaft 4, TU Hamburg-Harburg, Germany.

McSwain, B.S., Irvine, R.L. and Wilderer, P.A. (2004). The effect of intermittent feeding on aerobic granule structure. *Wat. Sci. Tech.*, **49**(11–12), 19–25.

Moy, B.Y.-P., Tay, J.-H., Toh, S.-K., Liu, Y. and Tay, S.T.-L. (2002). High organic loading influences the physical characteristics of aerobic sludge granules. *Lett. Appl. Microbiol.*, **34**, 407–412.

Schwarzenbeck, N., Erley, R., Mc Swain, B.S.,. Wilderer, P.A. and Irvine R.L. (in press). Treatment of malthouse wastewater in a granular sludge SBR. *Acta hydrochimica hydrobiologica*.

Sutton, P.M., Osborn, D.W., Nicholas, H.A. and Barnard, J.L. (1978). Optimization of activated-sludge process for biological removal of phosphorus. *Progr. Wat. Tech.*, **10**(1–2), 304–305.

Tay, J.-H., Liu, Q.-S. and Liu, Y. (2001). The effects of shear force on the formation, structure and metabolism of aerobic granules. *Appl. Microbiol. Biotech.*, **57**, 227–233.

Van Loosdrecht, M.C.M., Eikelboom, D.H., Gjaltema, A., Mulder, A., Tijhuis, L. and Heijnen, J.J. (1995). Biofilm structures. *Wat. Sci. Tech.*, **32**(8), 35–43.

Wilderer, P.A., Staud, R. and Hartmann, L. (1983). Optimization and control of the activated sludge treatment process by quasi-continuous operation – concept, strategy and results. *37th Industr. Waste Conf., Purdue University, Ann Arbor Sc.*, 709–718.

Wilderer, P.A. (1992). Sequencing batch biofilm reactor technology. *Harnessing biotechnology for the 21st century*. Ladisch, M.R, Bose, A., (eds), *Am. Chem. Soc.*, 475–479.

Wilderer, P.A., Arnz, P. and Arnold, E. (2000). Application of biofilms and biofilm support materials as a temporary sink and source. *Wat., Air, Soil Pollut.*, **123**, 147–158.

Wilderer, P.A., Irvine, R.L. and Goronszy, M.C. (2001). *Sequencing Batch Reactor Technology*. IWA Publishing, London.

Wingender, J., Neu T.R. and Flemming, H.-C. (eds) (1999). *Microbial Extracellular Polymeric Substances*: *Characterization, Structure and Function*. Springer, Berlin.