Intelligent sequencing batch reactor control from theory, through modelling, to full-scale application
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ABSTRACT
Sequencing batch reactors (SBR) can provide a high level of treatment and have potentially great flexibility in their modes of operation enabling the operator – in principle – to adjust the way the SBR operates to provide the desired treatment goal. In practice, however, SBRs are most often operated using simple phases with fixed time intervals. Advanced control techniques can be used to enable an SBR to realize its full treatment potential and maximize its capacity and this paper describes several online measurements and control approaches that can be used to do so.
A case study is presented that demonstrates how first a process model was used to test three control options for the Daniel Island wastewater treatment facility in South Carolina, USA, followed by field testing of two approaches and the subsequent implementation of one of these to enable the plant to maximize its treatment capacity.

Key words | control, dissolved oxygen, respirometry, sequencing batch reactor

BACKGROUND
The genesis of activated sludge treatment is rooted in batch operation. The initial findings of Arden & Lockett (1914) – credited with discovering the activated sludge process – were based on a fill-and-draw approach. Similarly, one of the earliest patents for sewage treatment using activated sludge was filed in the UK by Jones & Attwood Ltd (1914) who proposed the use of a looped channel - not dissimilar to modern ditch systems - that could be operated either as a continuous flow or intermittent fill-and-draw treatment system. In the Introduction to the IWA Scientific and Technical Report “Sequencing Batch Reactor Technology,” Wilderer et al. (2001) provide a good history of SBR technologies throughout the 20th century. They particularly describe the resurgence of interest in SBRs in the latter decades of the century that was facilitated by the availability of improved automation and control.

The basic operating phases of SBRs are well documented (e.g. ASCE/WEF 1998; Wilderer et al. 2001; Bungay 2007) and are generally designated: Fill, React, Settle, Draw, and Idle. During the “Fill” phase, wastewater flows into the reactor. The “React” phase constitutes a period of time when the activated sludge is treating the wastewater under aerobic (i.e. aerated), anoxic or anaerobic conditions. By inference of the separate designation of a “Settle” phase, during which mixers and aerators are turned off to allow activated sludge to settle and a clear liquid layer to form, the React phase includes the requirement to keep the activated sludge in suspension through aeration or mechanical mixing. However it should be noted that reactions do continue in the activated sludge during all phases including Settle and Draw. Having settled the activated sludge, treated effluent is decanted from above the settled sludge during the “Draw” phase (also termed “Decant”). Finally, an “Idle” time is allowed to provide dead time between the operation of phases (usually as an extension to the Draw phase) that is necessary to ensure the correct sequencing of SBR phases for systems with multiple reactors. The basic operating phases described here can be combined and sequenced in different orders to give different process conditions. Most notably the “Fill” and “React” phases...
can occur concurrently (“Fill & React”) or separately to affect different biomass loading conditions under aerobic, anoxic or anaerobic conditions. It is also possible to continue the Fill operation while the reactor is in the Settle and Decant phases provided that the reactor basin is configured properly to enable this.

An often underappreciated but critically important aspect of SBR operation is the timing and control of sludge wasting to maintain a stable sludge age. In a continuous process, the excess activated sludge (EAS) is most often taken from the return activated sludge (RAS) line which has a relatively consistent, predictable and measurable concentration. However, in an SBR if EAS is wasted at the end of the Settle or Decant phase, the concentration of the waste sludge is very much dependent on the settling characteristics of the activated sludge which can vary widely and are notoriously difficult to predict, making it difficult to set the correct wastage time. This issue can be circumvented by wasting mixed liquor during a React phase but this does require the plant to have adequate facilities to process the higher volumes of lower concentration EAS that this produces (e.g. by using dissolved air flotation thickeners).

Finally, a single SBR train can include multiple reactors in a similar manner to a continuous system particularly to provide small volume selectors to improve settling and filament control, or to provide dedicated anoxic or anaerobic treatment zones separate from the main reactor.

The type and duration of each of the phases (or combination of phases) could be varied depending on the treatment needs, which – in principle at least – provides almost limitless flexibility in the way the SBR treats the incoming waste. This should enable the SBR to provide the optimum level of treatment for any given waste. As two of the authors noted in a previous paper, “the SBR is the most controllable process option for wastewater treatment.” (Shaw & Watts 2002) In practice, however, the phases and timings are usually fixed which in part may be attributed to the lack of measurements and control algorithms that make use of this inherent “controllability.”

Given that SBRs have the potential for great flexibility in their operation, what measurements can be made to optimise their operation and how can they be used? This paper presents several ideas for advanced control options and provides a real-life case study for the application of one of the ideas.

**ADVANCED CONTROL APPROACHES**

There are fundamentally three limiting criteria in the operation of an SBR which are:

1. **Hydraulic capacity.** The SBR has to handle the flow of wastewater including its variability. The difference between the lowest decant level and the highest fill level effectively governs how much wastewater can be processed in each batch. If the peak flow exceeds what can be handled in a single batch then the sequencing of SBRs has to be moved through more rapidly using shorter phase times or by changing the number of phases to allow more batches to be processed.

2. **Biological capacity.** Depending on the type and level of treatment required, sufficient biomass must be retained in the reactor (i.e. adequate sludge age) with enough reaction time in each of the reaction phases to provide the substrate and nutrient removals required.

3. **Settling rate.** As noted previously, the settling characteristics of activated sludge are difficult to predict and control. The settling rate of the activated sludge has a direct impact on the time that must be allowed for the Settle and Draw phases. The settling curve also limits how low the decanter can go before solids are entrained in the effluent.

Consideration of the hydraulic capacity is generally understood by engineers and in most cases reactors and control systems are well designed to cope with flow variations (e.g. special operating modes that change phases and timings for “storm flows”). However, in very few cases are adjustments made to React phase timings to make the best use of biological capacity or adjustments made to the Settle and Decant operation to account for changes in the settling characteristics of the activated sludge. The authors offer the following 7 control concepts for consideration for the advanced control of SBRs, many of which have proved successful at pilot or full scale:

1. Oxygen Uptake Rates (OUR) to determine when aerobic treatment is complete;
2. Dissolved Oxygen (DO) measurement to indirectly measure OUR;
3. Rate of change of DO to indicate complete treatment;
4. The use of Oxidation Reduction Potential (ORP) and pH to indicate completion of various stages of treatment (anoxic, anaerobic, aerobic);
5. Online ammonia and nitrate analyzers to directly measure nitrification and denitrification rates and to indicate when treatment phases are completed;
6. Online phosphate analyzer to dynamically measure phosphorus release and uptake;
7. In-situ optical solids probe to measure mixed liquor suspended solids (MLSS) concentrations and as a feedback measurement to control the decant speed.

**OUR control (and DO surrogates)**

The “iSBR” concept uses respirometric measurements to determine when aerobic treatment is complete during the React phase. It has been described in several papers, presentations and workshops (Shaw & Watts 2002; Barnard et al. 2003; Shaw 2003). The following is a brief description of its principles.

Figure 1 shows how OUR changes as an SBR goes through various phases for an example SBR system modeled using GPS-X (in blue). Ammonia (green) and nitrate (red) concentrations for the same time period are also plotted. It can be seen that at the point where the ammonia is used up and treatment is complete the OUR suddenly drops which is the characteristic “nitrification shoulder” shape typical of respirometers for nitrifying systems. In this example, treatment is complete at 3 hours, even though the aerate phase continues for another 1\(\frac{1}{2}\) hours to 4\(\frac{1}{2}\) hours. The time from 3 hours to 4\(\frac{1}{2}\) hours is a period where no useful treatment occurs and air is effectively wasted.

The iSBR control works by detecting the nitrification shoulder in the OUR curve and ceasing aeration at this point. The SBR can then go into an extended settle period or the settle and decant phases advanced to allow the total cycle time to be shortened and more cycles to be completed in a day.

Several potential benefits of the iSBR control system have been identified, including: energy savings by ceasing aeration when treatment is complete; increased viability of the nitrifying biomass by reducing the time when the biomass undergoes aerobic endogenous treatment; shorter aerate times, facilitating more cycles per day (increased hydraulic capacity), or longer settle times; reduced potential for filament growth under low food to microorganism (F:M) conditions; reduced nitrate concentrations as biomass is aerated for a shorter proportion of the treatment time, facilitating more denitrification.

The principles for the iSBR concept using respirometric control are simple to understand and apply, however they require the online and continuous measurement of OUR using a respirometer which can be costly to purchase and maintain. An alternative, surrogate, approach to measure...
the OUR is to simply use DO measurements coupled with airflow or blower speed to directly measure or at least provide a rough estimate of the OUR. The iSBR approach does not require an accurate estimate of OUR to work properly; only an indication of the relative OUR as it is the sudden change in OUR that is detected and not the absolute value.

For systems with fixed-speed aeration the iSBR concept can be modified to simply detect the change in DO at the point at which the OUR suddenly drops. This can either be a simple trigger set point to show that treatment is complete or a slightly more sophisticated calculation can be made of the rate of change of DO concentration (i.e. the derivative) to more clearly show when the DO suddenly rises. Figure 2 is an example output from an SBR model with a fixed speed aerator. A sudden increase in the DO plot can be seen at about 0.90 days indicating that the OUR has dropped and treatment is complete. In this example a simple DO set point control could be used to stop aeration when the DO jumped above 3.5 or 4 mg/L. Alternatively, the rate of change of the DO (dO/dt, plotted above the DO curve in Figure 2) can be used to detect the end point. In this example if the dO/dt increases above 200 mg/L/day during the aerate phase then this indicates treatment is complete.

ORP and pH

Researchers have suggested the use of various parameters to control SBRs, most notably using ORP and pH. In a similar manner to detecting the point at which the OUR or DO changes in the iSBR control, so can pH or ORP be used to detect the end point for different treatment phases. Cho et al. 2001 compared DO, pH and ORP control in their test work and concluded that ORP provided the best total nitrogen removal. Andreotta et al. (2001) carried out similar testing with similar outcomes and Demoulin et al. 1997 used an ORP-based system for the full-scale cyclical activated sludge technology (CAST) system at the Großarl Wastewater Treatment Plant.

Nutrient analyzers

More sophisticated nutrient analysers can be used to monitor nutrients within the SBR during various React phases designed for nutrient removal. In the case of nitrification, direct measurement of ammonia within the basin can be used to detect when nitrification is complete. Similarly, nitrate measurement can also be used to measure when nitrification is complete (nitrate stops increasing) and, during anoxic React phases, to detect when denitrifi-
cation is complete. For SBRs designed for biological phosphorus removal, it is feasible to use an online phosphate monitor during the anaerobic phase to measure phosphorus release and during the aerate cycle to monitor phosphorus uptake. If supplemental carbon is added either to enhance phosphorus release or denitrification then the online monitors can be used to dynamically measure the impact this has on the removal rates and adjust the addition accordingly.

The main advantage of using nutrient analysers for control over the other methods is that they not only show the end points of the various reactions, but they also provide a direct measurement of the removal rates that can be then compared to design and modelled values. A significant disadvantage is the cost of purchasing and maintaining more sophisticated analysers to carry out the measurements. In recent years, in-situ probes have been developed that provide robust measurement of ammonia and nitrate at a more reasonable cost such that they could be used for SBR control. (Winkler et al. 2004; Rieger et al. 2004)

**Online solids measurements**

The final measurement suggested by the authors for the arsenal of advanced SBR control is the use of an optical solids probe to serve the dual purpose as an online mixed liquor suspended solids (MLSS) monitor and to provide feedback measurement to control the decant speed. The former application is self evident but the latter needs some explanation. The suggestion is to locate the solids probe on the decant mechanism such that the sensor face is some fixed distance below the decant level (say 1 metre down). The sensor moves up and down with the decanter but is always a fixed distance below the liquid surface. During the Settle phase, the sensor will initially be in mixed liquor, but once the blanket passes it, the sensor will be in clear liquid and will suddenly see a much lower signal. At this point the control system can be informed that the blanket has dropped past the sensor and decanting can commence at some fixed time after this. If, during decanting, the sensor detects the blanket - indicating that the decanter is catching up with the blanket - the decant rate can be slowed or stopped to prevent overflow of solids with the decanted water. As a further enhancement to this system, the time it takes for the sensor to initially detect the passing of the blanket could be recorded and this measurement used to give an indication of the settling rate of the sludge, which could in turn be used to adjust the speed of the decanter.

**CASE STUDY: FROM PRINCIPLES TO PRACTICE AT DANIEL ISLAND**

The Daniel Island WWTP in South Carolina, USA, consists of two SBRs designed to treat average day flows up to 1900 m3/d, followed by filtration and UV disinfection. Daniel Island is an area undergoing rapid development, which is causing the plant influent flows to increase dramatically. As a result, the plant was approaching its design capacity. In order to accommodate these increasing flows in the near-term, investigations were carried out to develop options to optimize and maximize the treatment capacity of the SBRs beyond their existing design capacity using the “iSBR” principles.

**Process modeling**

As part of the study to rerate the Daniel Island SBRs the iSBR control concept was first tested using a dynamic process model of the plant on the Hydromantis GPS-X simulator. The simulations proved successful and control approaches based on three different measurements were developed: OUR, dissolved oxygen (DO) and rate of change of DO (or “dO/dt”). These approaches were described previously in this paper.

**Full scale testing**

Having proved the iSBR control approach in a simulator, it was then successfully field-tested for one week on one of the SBRs at Daniel. Figure 3 shows the results from one cycle in the test period. During the react phase for this cycle, additional measurements were taken, for ammonia and the DO was validated manually using the plant’s handheld probe. At the end of the react phase for this cycle it was evident that ammonia concentrations were dropping close to 1 mg/L and a further 35 minutes of aeration would probably enable the SBR to reach endogenous and so the
The react phase was extended by 35 minutes (labeled “Extended Aerate”) in order to test the iSBR control which successfully shut off the blowers when the DO reached 2.5 mg/L.

In Figure 3 it can be seen that the rapid increase in DO occurs when the ammonia concentration reaches zero as predicted by the model and described in the iSBR principles. This figure also shows that the ORP curve doesn’t respond quite as rapidly as the DO curve. Finally, from this figure it can be seen that the online DO measurement which was based on fluorescent technology gave similar readings to the handheld galvanic probe.

The full-scale test proved very successful using either the DO or the dO/dt approach. iSBR control was continued beyond the initial one week trial and both SBRs have since been configured to use this control system. An influent equalization tank and extra blower capacity were installed and, in conjunction with the iSBR control, enabled the 2 ML/d plant to be rerated to 4 ML/d.

**LIMITATIONS AND CONSTRAINTS OF CONTROL**

The ideas presented in this paper are straight forward and to many may be self evident, so the question must be asked as to why very few full-scale installations use the ideas presented here and most experience is restricted to lab-scale experiments. A major problem in implementing any of the ideas are the restrictions placed on multiple SBRs by engineers keen to provide cost effective solutions by sharing equipment between the reactors but in doing so remove much of the operational flexibility inherent in single SBRs (e.g. in lab-based units). As basins need to share and coordinate the use of central blowers or pumps, the operating phases are constrained to enable the use of equipment to be choreographed between basins. Unfortunately, for systems with shared blowers and pumps (the majority of large scale SBRs for domestic applications) it is unlikely that they will ever be designed in such a way to throw off the shackles of shared equipment and the operation of advanced control will necessarily be complicated and somewhat constrained.

A further complication lies in the difficulties of dealing with a continuous influent flow using batches. At any given time at least one of a group of SBRs has to take the flow coming to the plant which constrains the timings to make sure volume is always available for the incoming flow. Two approaches can be taken to overcome this limitation and allow greater operational flexibility. Either an influent...
equalization tank can be used to hold up the influent feed or the SBRs can be engineered with a constant feed. Influent equalization provides arguably the best means of maximizing SBR capacity and the potential for advanced control. At Daniel Island, for example, it was possible to double the SBR capacity using an influent equalization tank.

CONCLUSION

On paper at least, SBRs are extremely flexible in the number, duration and variants of the operating phases that are possible and these can be adjusted to give optimum treatment. Several measurement and control ideas have been presented that make use of this flexibility and “controllability”, including a practical example of how the iSBR control approach using a simple DO probe was used on the SBRs at Daniel Island. Unfortunately, most SBR installations have their flexibility constrained by the way they are implemented with multiple units sharing common equipment (usually blowers) and the need to always handle continuous incoming flow. The use of an influent equalization basin overcomes the latter constraint and can help the SBRs to increase their treatment capacity considerably.

REFERENCES


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