Nigerian Research Journal of Engineering and Environmental Sciences 5(1) 2020 pp. 223-238

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

RJEES

**Review Article**

# A Review on Sequencing Batch Reactors: Process Design, Operation and Modelling

***Rasheed, A.A. and Ciroma, S.I.**

Department of Chemical and Petroleum Engineering, Faculty of Engineering, Bayero University Kano, PMB 3011, Kano, Nigeria
*aarasheed.cpe@buk.edu.ng

**ARTICLE INFORMATION**

*Article history*:
Received 14 Mar, 2020
Revised 03 Apr, 2020
Accepted 07 Apr, 2020
Available online 30 June, 2020

*Keywords*:
Sequencing batch reactor
Activated sludge process
Design
Modeling
Optimisation

**ABSTRACT**

*The sequencing batch reactor (SBR) is perhaps one of the most promising of the activated sludge process modifications today for the removal of both organic matter and nutrients. The SBR differ from conventional continuous-flow activated sludge plants because they combine all the treatment steps and processes into a single tank, thereby eliminating the need of multiple units. Holistic design of the process and optimisation of the operating parameters is still a major issue of concern due to its transient nature of operation. Most of the studies on modelling the SBR are selective, aimed at either optimising the operation of existing treatment units to determine optimal operational policies, or finding the optimum filling strategy or time sequences and scheduling. This research presents a literature review specific to wastewater treatment using SBRs. This review discusses fundamental aspects of aerobic SBR process and operation; design and operating parameters of SBR processes; process modelling and optimisation of the SBR processes.*



## 1. INTRODUCTION

The sequencing batch reactor (SBR) is a variant of the activated sludge system characterised by intermittent flow operation and is an interesting alternative to the conventional activated sludge process due to its relatively low cost and small footprints (Akunna and Shepherd, 2001; Dionisi et al., 2001; von Sperling, 2007). It is a fill-and-draw process that incorporates all the traditional activated sludge treatment processes, namely, biological reactions and solids-liquid separations in a single vessel. In this vessel, treatment processes take place in time sequence rather than separated units as in the case for conventional continuous-flow activated sludge systems (Wilderer et al., 2001; Artan and Orhon, 2005; Wang et al., 2010). The SBR process is inherently a cyclic operation subjected to the following sequence of phases: fill, react, settle, sludge withdrawal and decant, with each phase lasting for predetermined time periods. A major advantage of this process is that the treatment phases can be rearranged or omitted and the duration of each phase as well as the number of cycles can be altered depending on the influent dynamics, treatment requirements and the overall design goals (von Sperling, 2007; Ni et al., 2009). Therefore, it offers flexibility, efficiency, reliability and the capacity of producing high quality effluent (Irvine and Busch, 1979; Irvine et al., 1997; Ketchum, 1997; Dionisi et al., 2001).

## 2. THE SBR PROCESS OPERATION AND PRACTICE

The influent wastewater is fed into the SBR during the fill phase (feeding). The influent containing organic matter and nutrients creates an environment for relevant biochemical reactions through mixing and aeration as necessary, with the exception of static filling. The fill is said to be static if there is no mixing and aeration during the very time influent wastewater is entering the tank. Static fill is normally adopted either during low flow periods to save power or for plants that do not carry out nitrification or denitrification. In todays practice, the duration of fill phase may be varied from an instantaneous dump fill, mostly to create high substrate gradient for filamentous bulking control or to a continuous fill through the entire process if the substrate is inhibiting (to decrease the inhibition effect), depending on the nature of the wastewater and design goals (Wilderer et al., 2001; Artan and Orhon, 2005).

During the react phase (often called aeration), influent filling stops and mechanical mixing and aeration units are turned on. The SBR is henceforth operated as a true batch reactor with this phase until the desired level of completion is reached for targeted biochemical conversions. The reaction phase is normally the longest phase in the SBR cycle because it is where most of the carbonaceous pollutants and nutrients removals occur. In some cases, sludge withdrawal takes place at the end of the reaction phase where appropriate amount of sludge from the well-mixed reactor is withdrawn.

During settling phase, mechanical mixing and aeration is discontinued and the sludge is allowed to settle by gravity under quiescent conditions to the reactor bottom. This phase has no flow entering or leaving the tank. As a result, the sludge settles as a flocculent mass forming a distinctive interface with the clear supernatant.

Effluent withdrawal (often called decant) is the phase where clear supernatant formed over the sludge blanket is withdrawn as effluent. The volume of supernatant withdrawn as effluent is normally the same volume that enters the system during fill phase less the volume of wasted sludge.

In some researches, there is an idle phase which serves as a reserve period between decants and fill phase of the next cycle. According to Artan and Orhon (2005), the idle phase is used to increase the overall operational flexibility of the SBR system and can be used to extend the duration of one of more of the other phases when needed. As SBR is a cyclic operation, the treatment steps described by Figure 1 are repeated for every cycle when a fresh batch of wastewater is received.

According to Schwarzenbeck et al. (2005), the production of an acceptable effluent in activated sludge processes such as SBR intrinsically relies on two factors: (1) the oxidation of the organic matter by the active microorganisms into a final end product of carbon dioxide, water and inert material; and (2) flocculation of the biomass and other suspended materials into large units, is dense enough to coagulate and settle at the reactor bottom so that a high-quality effluent can be obtained. Therefore, working at optimum design and operating parameters such as the number of cycles per day and length of treatment phases is key towards achieving the treatment objectives for a given wastewater.

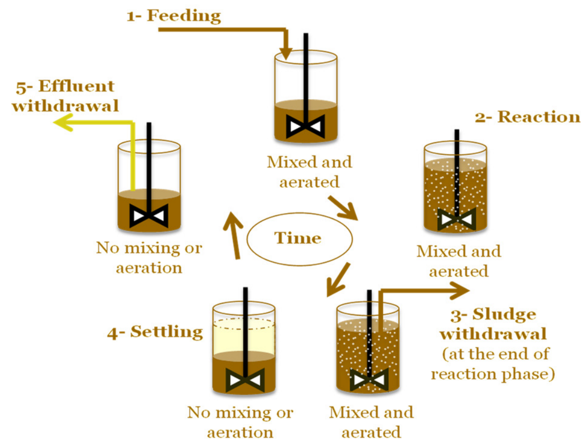


Figure 1: Schematic operation of SBR for one cycle (Wilderer et al., 2001)

### 2.1. Concentration Profiles during SBR Cycle

Since the reactor volume changes during a cycle, the biomass and substrate concentration profiles will also change. However, a periodic steady state is reached when the profiles of biomass and substrate concentration do not change for successive cycles. Figure 2 shows typical profiles of biomass and substrate concentrations during an SBR cycle.

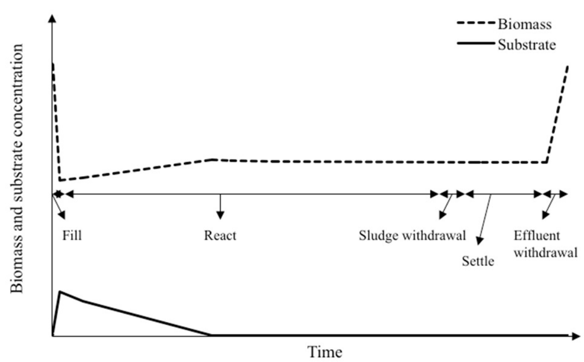


Figure 2: Typical profiles of biomass concentration and substrate during a cycle of the SBR (Dionisi, 2017)

During the fill phase, the substrate concentration increases due to the addition of the feed while the biomass concentration decreases due to dilution with the influent. The substrate is completely removed during the react phase as the biomass concentration increases due to growth at the expense of substrate removal. As the substrate is completely removed, the biomass concentration decreases slightly due to endogenous metabolism and then increases during the effluent withdrawal phase. This is because the supernatant is removed during effluent withdrawal and the same amount of biomass occupies a lower volume.

### 2.2. SBR vs. Conventional Continuous Flow Activated Sludge Systems

There are several operational and economic advantages for using SBR technology instead of the conventional continuous flow mode of operation for the treatment of wastewater as mentioned in Akunna and Shephard (2001), Arora et al. (1985), Dionisi et al. (2001), Irvine and Busch (1979), Irvine et al. (1997) and Ketchum (1997). They include:

- Reliability
- Suited for wide flow variations
- Capacity of producing high quality effluent
- Elimination of separate clarifiers and sludge recycle pumps
- Increased settling area
- Small footprint
- Potential economic savings due to controlled aeration
- Balancing and reducing the effects of variations of flow and strength of loading conditions
- High operational flexibility, which can be used for nitrification, denitrification and phosphorous removal.

However, SBRs have some disadvantages such as complex control system and high level of sophistication and maintenance. Other disadvantages include: need for a flow equalisation tank during high flow rates; and chances of solids escaping during effluent withdrawal.

SBR systems are typically used for flow rates of 20000 $m^3$/day or less. The SBR provides benefits beyond the simple flexibility of varying the cycle phases to improve substrate removal. The SBR has the ability to apply environmental pressures on the microbial conglomeration by controlling the cycle times, flow rates, nutrient and oxygen availability, as summarised in Table 1.

Table 1: Effect of cyclic exposure of microorganisms to different process conditions on SBR performance (Cervantes et al., 2006)

| Factors varied during treatment cycle | Effects achieved |
|---|---|
| High and low concentrations of readily biodegradable substrates | Growth rate differential that suppresses excess growth of filamentous bacteria (Chiesa and Irvine, 1985)<br><br>Minimises sensitivity to shock loads and generation variations in influent constituents (Buitron et al., 2005) |
| High substrate concentration followed by an extended period of starvation | Suppression of excess growth of filamentous bacteria (Chiesa and Irvine, 1985)<br><br>Enrichment of floc-forming bacteria with the physiological characteristics to meet treatment objectives |
| Anaerobic and anoxic conditions | Enrichment of both nitrifiers and denitrifiers for nitrogen removal<br>(Keller et al., 2001) |
| Anaerobic and aerobic conditions | Enrichment phosphorus removal bacteria (Gonzalez-Martinez and Wilderer, 1991) |

The SBR differs from the common activated sludge process mainly in physical structure and in design and operating parameters. The conventional continuous mixed activated sludge process is designed in such a way that influent wastewater and recycled activated sludge are introduced typically at several points in the biological reactor. The biomass concentration, oxygen demand and organic load are all uniform through the reactor.

With regards to the SBR, a fill-and-draw type of reactor system is employed in a single, completely mixed biological reactor where all the treatment steps of the conventional process occur in the single reactor as shown in Figure 1. Normally, two basins are used so that when one is getting filled, the other is already going through reaction, settling and decanting (to be discussed later). Biomass remains in the reactor during all cycles, thereby eliminating the need for separate secondary settling tank. The SBR goes through a number of cycles per day in which a typical cycle could be of 3-hour fill, 2-hour reaction, 0.5-hour settling and 0.5-hour decanting, depending on the influent characteristics and the treatment objectives (Metcalf and Eddy, 2003).

SBR systems are typically designed and operated at longer SRTs and lower F/M ratios than the conventional process. Other differences in design parameters between the conventional continuous flow activated sludge systems and SBR are reported in Table 2.

Table 2: Main characteristic difference between conventional continuous flow activated sludge processes and the SBR (Metcalf and Eddy, 2003)

| General items | Process name | |
|---|---|---|
| | Conventional continuous flow | SBR |
| SRT (days) | 3 - 15 | 10 - 30 |
| F/M ratio (kg COD/kg biomass.day) | *0.5 - 1.0 | *0.2 - 0.5 |
| F/M ratio (kg BOD/kg biomass.day) | 0.2 - 0.6 | 0.04 - 0.1 |
| OLR (kg BOD/$m^3$.day) | 0.3 - 1.6 | 0.1 - 0.3 |
| HRT (hours) | 3 - 5 | 15 - 40 |
| TSS (mg/l) | 1500 - 4000 | 2000 - 5000 |
| BOD removal efficiency (%) | **85 - 95 | £98 |
| TSS removal efficiency (%) | **85 - 95 | £98 |
| Ammonia removal (%) | **85 -95 | £97 |

* Spellman (2013); ** von Sperling (2009); £Wang et al. (2010)

## 3. DESIGN AND OPERATING PARAMETERS OF THE SBR PROCESS

The SBR process is an activated sludge process with a variable volume reactor operating in a cyclic manner and each cycle having a fixed pattern of several phases in succession. The process includes a set of basic parameters inherently associated with its system operation as briefly described below:

### 3.1. Reactor Volume

The process incorporates a variable-volume reactor. The total reactor volume, ($V_{full}$), is made up of two independently controllable fractions, namely initial volume ($V_o$) that is the volume occupied by the settled sludge at the end of the cycle, and a final ($V_f$), which basically is the volume of the wastewater that is fed and decanted every cycle (Artan and Orhon, 2005). Thus, the reactor volume during operation reaches its maximum level at the end of the feeding phase as shown in Figure 3.

### 3.2. Number of Basins

The SBR process can be carried out in a single basin or multiple basins in parallel depending on the flow of influent. Wastewater treatment plants using the SBR technology usually have two reactors that operate in parallel as shown Figure 3. Each SBR operates with the same phases for each cycle and the number of cycles each day may be adjusted as well as the length of the phases to satisfy hydraulic, organic and nitrogenous loading conditions. Influent may enter an equalization tank to hold the wastewater before discharging to one SBR under the fill phase.

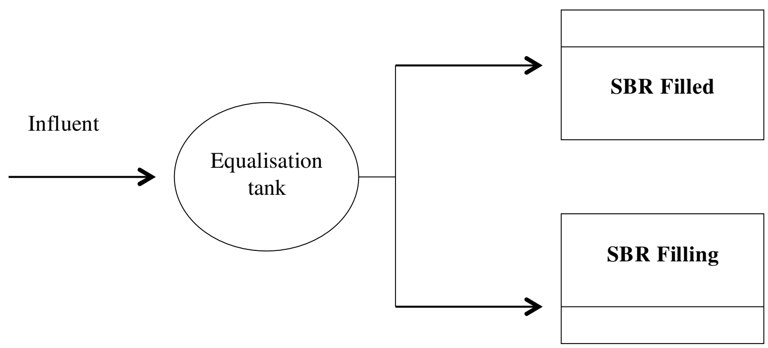


Figure 3: Wastewater treatment plant using two SBRs (Gerardi, 2011)

The timings of cycles of the two SBR must be established in such a way that as one SBR is in its react phase, settle phase and decant phase, the second SBR is in its fill phase (Gerardi, 2011). In reality, increasing the number of reactors will likely increase the total capital cost. However, it is only practical to have more than one tank in larger plants since it allows a higher degree of flexibility to handle variable flow conditions.

### 3.3. Number of Cycles

Cycle frequency per day is an important parameter to be selected in SBR design and operation. It directly defines the total cycle time and the volume of the feed per cycle $V_f$.

$$No\ of\ cycle\ =\ 1/total\ cycle\ time$$

$V_f\ =\ Q/No\ of\ cycle;$ where $Q$ is the daily influent flow rate

The number of cycles per day that are operated in an SBR is dependent on the influent wastewater volume and wastewater strength. Therefore, increasing the wastewater flow will require fewer cycles while decreasing wastewater strength decreases the number of cycles as shown in Figure 4 (Artan and Orhon, 2005; Gerardi, 2011). The numbers of cycles per day in most SBR operations is typically four to six cycles per day.

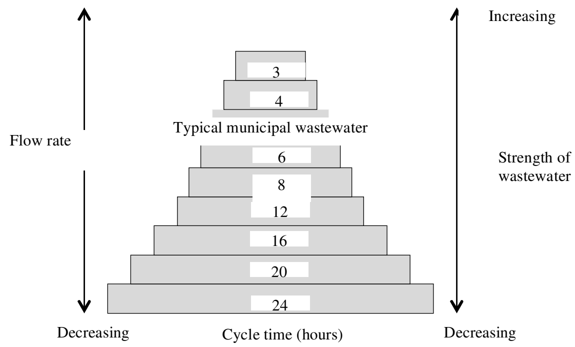


Figure 4: SBR cycles in relation with flow rates and wastewater strength (Gerardi, 2011)

### 3.4. Hydraulic Retention Time (HRT)

The HRT is usually defined for SBRs similar to continuous flow activated sludge systems as the ratio of the volume (*V*) to the flow rate (*Q*). Solids retention time (SRT) and organic loading rate (OLR) are also defined similar to continuous flow activated sludge systems.

### 3.5. Length of Phases in a Cycle

This can be fully aerobic as in the case of COD removal and can have various environmental conditions adjusted by energy input to include nutrient removal such as aerated periods, mixed periods, which can be anoxic or anaerobic depending on the presence of nitrate.

SBR process can be used for both carbon and nutrient removal via simple manipulation of operating parameters. There is no much difference in terms of process options for the SBR systems employed for carbon removal alone and combined with nitrification since both rely on aerobic metabolisms. Also, organic carbon removal and nitrification can both take place in the same reactor with a single aerobic process phase within the cyclic operation. This flexibility of operation has always been the main asset of the SBR. Achieving a desired system performance depends largely on the appropriate selection of sequence and duration of different phases and periods within the cycle as well as the right choices of design parameters such as SRT. The SRT is the quantity of solids maintained in the reactor divided by the quantity of solids coming out of the reactor each day (Grady et al., 2011). The only difference is in terms of energy demands in such plants. For example, for treatments that requires both carbonaceous and nitrogenous matter removals, Figure 5 have shown that the oxygen demand is about 40 % lower if the plants only performs carbonaceous removal, without nitrification.

If nitrification is not required, experiences shows that an SRT in the range of 3 – 15 days is sufficient to achieve the COD removal. However, longer SRT (20 days or more) is required for nitrification, which results in more oxygen consumption and power demand as shown in Figure 5. Increasing the number of cycles per day allows the process to operate at shorter HRT and therefore allows a smaller reactor volume. Increasing the number of cycles mean decreasing the lengths for all the phases, which can be a problem for the effluent quality in terms of suspended solids. This is because for sensitive phases such as settling phase, the length must be long enough to ensure a suitable solid-liquid separation. However, the settling phase should be set to the minimum value that guarantees good separation of the microorganisms from the liquid in the reactor and minimal losses to the effluent because it is an inactive phase of the cycle. The effect of length of the various phases is discussed in many published literatures.

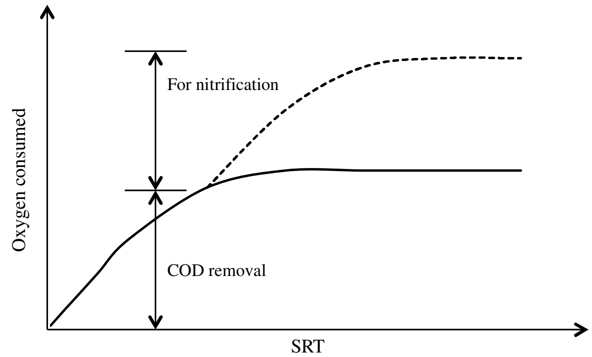


Figure 5: Oxygen demand for carbon removal only and for carbon and nitrification

The fill length has an effect on the substrate profile within a cycle and can range from a small fraction of total cycle length to a large fraction, depending on the nature of treatment. The shorter the fill length the more pronounced becomes the substrate concentration gradient at the start of the cycle which gives a kinetic advantage for substrate removal rate. However, long fill length is required to decrease inhibition effect if the substrate is inhibitory (Artan and Orhon, 2005).

The length of the effluent withdrawal phase should be minimised because it is an inactive part of the cycle (no biological reactions taking place). However, care must be taken to avoid turbulence during decanting especially at high HRT operations. For the react phase, the length should be maximised because it is where most of the biological reactions for substrate removal take place. The length of the sludge withdrawal phase should also be kept to a minimum especially if it immediately succeeds the reaction phase.

## 4. BACKGROUND THEORY FOR EXPERIMENTAL OPTIMISATION OF THE SBR PROCESS

Conventional suspended-growth activated sludge processes such as SBRs are typically designed and operated with a long SRT of 10 - 30 days (Metcalf and Eddy, 2003). Long SRT values require long HRT, which leads to large reactor volume and footprint, and ultimately high capital investments and high energy demands (Ge et al., 2013). Also, the OLR achieved in the treatments is low, typically in the range 0.5 - 1.5 g COD/l.day (Grady et al., 2011; WEF, 2012). Although, a shorter SRT gives higher production of waste sludge with an increase in the sludge treatment costs, a recent study (Ge et al., 2013) however has shown that the sludge of aerobic processes working at low SRT can be successfully used as substrate of anaerobic digestion, with consequent value recovery via methane production. Table 3 reports the values of OLR and SRT maintained in some aerobic treatments carried out in SBR. According to basic principle of activated sludge process, for a given wastewater at a certain flow rate and composition, reducing the HRT minimises the SBR volume and increases the OLR as shown in Figure 6. The SBR volume, HRT and the OLR are linked as shown in Equation 1:

$$HRT = \frac{V}{Q} = \frac{S_0}{OLR} \tag{1}$$

where $V$ is the reactor volume, $Q$ is total daily flow rate, $S_o$ is the initial substrate concentration.

Table 3: SRT and OLR of some aerobic SBR studies reported in the literature

| Reference | Wastewater | Length of cycle (hour) | SRT (days) | OLR (g COD/l/day) |
|---|---|---|---|---|
| Beun et al. (2002) | Acetate | 4 | 4 | 1.15 |
| Serafim et al. (2004) | Waste activated sludge | 8 | 10 | 0.9 |
| Li et al. (2008) | Slaughterhouse | 8 | 14.5 - 25 | 1.2 |
| Hajiabadi et al. (2009) | Milk synthetic wastewater | 24 | 5-20 | 1.4 |
| Ge et al. (2013) | Slaughterhouse | 3 | 2 – 3.8 | 1.4 – 5.8 |
| Rodríguez et al. (2014) | Animal food factory | 8 | 30 | 3.24 |
| Yoong et al. (2000) | Phenol | 4 | 4 | 7.43 |

Decreasing the HRT at fixed SRT consequently increases the biomass concentration in the reactor. This is expected because the total amount of biomass is determined by the SRT, and therefore having a smaller reactor volume (shorter HRT) makes the biomass concentration higher.

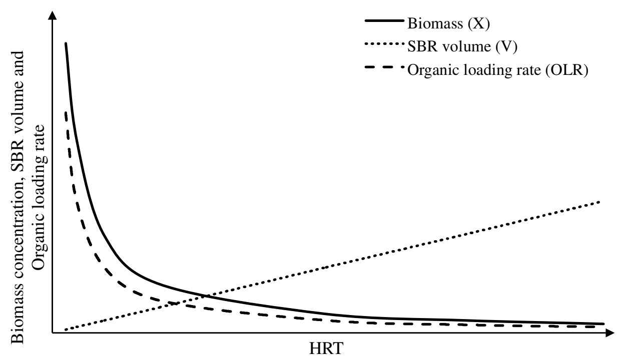


Figure 6: Relationship between HRT, SBR volume and the OLR for a given influent flow rate at a fixed SRT

However, for a fixed SRT, the HRT can only be reduced to an extent because an increase in the biomass concentration results in a decrease in the solids settling rate and increase in the aeration requirements per unit of reactor volume. Therefore, decreasing the HRT while keeping the SRT fixed can potentially cause the process to fail. These potential problems caused by short HRT can be counterbalanced by appropriate manipulation of the SRT because the SRT affects the amount of biomass in the reactor. However, decreasing the SRT is limited by effluent quality. This is because reducing the SRT beyond a certain value compromises the effluent quality in terms of substrate removal. From Figures 7 and 8, decreasing the SRT means less biomass in the reactor and beyond a certain value (of course depending on the growth kinetics) substrate removal decreases.

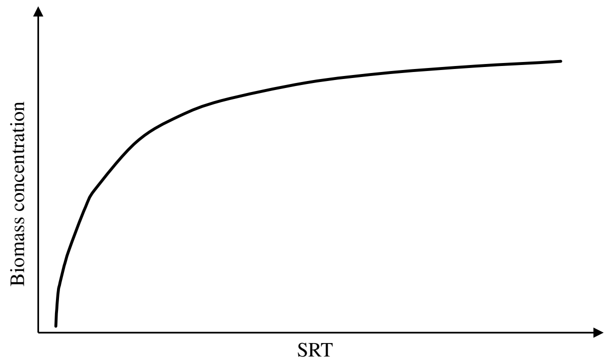

Figure 7: Effect of solids retention time (SRT) on biomass concentration in the reactor (X) at a fixed HRT for a given wastewater flow rate and composition

Figure 8: Effect of solids retention time (SRT) on effluent substrate concentration (S) at a fixed HRT for a given wastewater flow rate and composition

Figure 9 shows that by decreasing the SRT, at a fixed HRT, the oxygen consumption decreases while the biomass production increases. This is because shorter SRT means that the biomass stays in the system for a very short time. A shorter retention time for the biomass means less substrate removal and less endogenous metabolism (i.e. less self-oxidation by the biomass) which both these phenomena increase the oxygen consumption. Endogenous metabolism becomes predominant over substrate removal at longer SRT, and this reduces the amount of biomass produced.

In a nutshell, the SRT is the basically the most important design parameter that determines the performance of the activated sludge process such as SBRs. So, for a given wastewater flow rate and composition, the SRT dictates the effluent substrate concentration, the oxygen consumption and the sludge production. And for a given value of the SRT, the HRT determines the biomass concentration in the reactor and consequently the SBR volume.

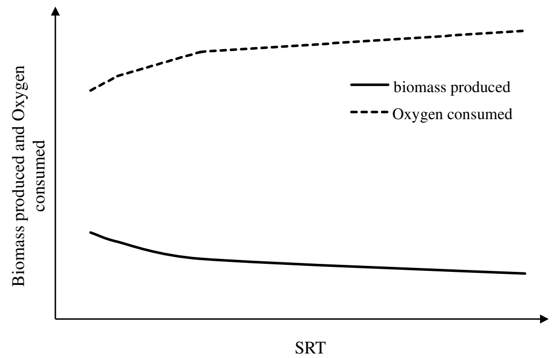


Figure 9: Effect of the solids retention time (SRT) on oxygen consumption and sludge production

From these considerations, it is evident that while reducing the HRT, the SRT needs also to be reduced, in order to achieve a process that requires the minimum reactor volume, while still having acceptable values of the biomass concentration and oxygen requirements and satisfying the effluent quality requirements.

## 5. KINETIC MODELLING OF SBR TREATMENT PROCESS

It has been seen that SBR is a biological treatment system with various design options and many degrees of freedom (Artan and Orhon, 2005, Dionisi et al., 2006). There have been enormous efforts put in to the development of kinetic models for biological wastewater treatment over the last few decades and the literature is full of methods and approaches for designing a continuous-flow activated sludge systems (Arora et al., 1985; Fernandes et al., 1993; Henze et al., 2000). However, no standard and easy procedure has been developed for designing SBR systems using kinetic models.

Most of the efforts channeled to SBR focused on the experimental aspects of design and operation (e.g. Hoepker and Schroeder, 1979; Brenner et al., 1992). Indeed, this lack of unified design standards using kinetic models to predict the performance of SBRs is regarded as the major obstacle hindering its broader practical application (Arora et al., 1985; Artan and Orhon, 2005; Velmurugan et al., 2010). The general trend in design practice of SBRs involve the use of somewhat arbitrary values of operating parameters that have been experimentally tested without so much of an emphasis on process kinetics and stoichiometry. Unfortunately, until recently, such design options are largely based on empirical knowledge where designers usually prefer to use conservative design values for the key design parameters instead of kinetic models, which sometimes prove quite successful in certain cases and detrimental in others (Artan and Orhon, 2005). This non-model design method is more or less a trial and error approach that are based on conceptual, time average models of the activated sludge process (conventional design approach) as reported by many (Arora et al., 1985; Wilderer et al., 2001; Artan and Orhon, 2005; Geselbracht, 2007; von Sperling, 2007). This conventional design approach is no more than a step-wise iterative design procedure based on arbitrary SRT and other practical assumptions as described below:

- Calculate the average BOD loading to the system
- Assume a suitable design F/M ratio
- Determine the biomass concentration required for the selected design F/M ratio and average BOD loading
- Assume a suitable biomass concentration expected at the end of the effluent withdrawal (decant) phase in the SBR

- Calculate the total volume of the SBR occupied by the sludge blanket
- Select the number of SBR reactors (if more than one)
- Determine the volume occupied per tank by the sludge blanket
- Set the number of operating cycles per day
- Calculate the maximum volume of liquid to be handled per decant per SBR tank
- Calculate the total volume per day by adding the volume occupied by the sludge blanket to volume per decant
- Determine the total daily oxygen requirements based on water quality objectives
- Size reactor volume based on the calculated oxygen requirement to be satisfied during aerated fill plus react time provided in the total number of operating cycles per day

The design procedures presented by other authors such as Irvine and Ketchum (1989) and the scientific and technical report by Wilderer et al. (2001) also follows relatively similar approach for wastewater treatment. Design engineers are reluctant to use model-based approach for SBR process design calculations firstly because some mathematical models have compound expressions with model parameters that are either not available or experimentally difficult to estimate and secondly because of the complex nature of the SBR operation, i.e. transient in nature, it is quite difficult to formulate a complete mathematical model for the system (Irvine and Ketchum, 1989; Velmurugan et al., 2010). Therefore, the procedure above is basically the conventional design approach that has been used for steady state systems for many decades. With this approach, it is difficult to optimise the process in terms of design parameters such as HRT, SRT and OLR and also to predict a range of performance for a given range of kinetic parameters. Another major disadvantage of this conventional method according to Velmurugan et al. (2010) is that designs may result in an oversized system and consequently increased costs.

Mathematical models of activated sludge and other biological processes have been a tool for evaluating various system performances for a variety of process configurations, loading patterns and operating conditions. A simple mass balance equation for biomass growth and substrate utilisation in SBR treatment can be expressed as in Equations 2 and 3 (Oles and Wilderer, 1991).

$$\frac{dX}{dt} = r_x - \frac{Q(X_o - X)}{V_o + Qt} \tag{2}$$

$$\frac{dS}{dt} = -r_s - \frac{Q(S_o - S)}{V_o + Qt} \tag{3}$$

where $r_x$ and $r_s$ are the biomass growth rate and substrate utilisation rate respectively, $S_o$ and $X_o$ are the initial substrate and biomass concentrations, $V_o$ and $Q$ are the initial reactor volume at the start of the cycle and influent flow rate respectively, $S$ and $X$ are the substrate and biomass concentrations in the reactor at time, $t$.

Activated Sludge Model No. 1 (ASM1) is a mathematical modelling for design and operation of biological wastewater treatment which was developed to allow the prediction of organic matter, nitrification and denitrification in activated sludge systems (Henze et al., 1987). It is still considered as the “state-of-the-art” model (Velmurugan et al., 2010) in terms of rate equations linking design parameters and kinetic parameters. ASM1 over the years has been updated to a higher version, ASM2 and ASM3 to include other treatment mechanisms and correct other known defects in ASM1 (Gujer et al., 1998; Henze et al., 1995). These advanced models have been used with or without modification for various activated sludge processes by several researchers for process simulation and optimisation.

There are a few studies that used a systematic rational approach for designing the SBR systems based on the principles of process stoichiometry and mass balance as summarised in Table 4. The work by Ni et al. (2009) attempted to modify ASM3 and to simulate the performance of a full-scale SBR plant for municipal wastewater treatment. After incorporating all the relevant processes, the model was validated and used for predicting the activated sludge process in full-scale wastewater treatment plants using appropriate kinetic constants. Other studies such as Artan et al. (2001) developed a systematic approach using process stoichiometry.

Table 4: Steady state procedures for SBR designs in the literature

| Type of SBR | Kinetic Model | Procedure | Reference |
|---|---|---|---|
| Suspended growth | Monod kinetics | Iterative dynamic solving of the equations | Hsu (1986) |
| Suspended growth | Monod kinetics | Fortran 77 computer program that solves the nonlinear ordinary differential equations | Nakhla et al. (1997) |
| Granular system | Monod kinetics (ASM3) | AQUASIM simulation program that solves the nonlinear ordinary equations | Ni et al. (2009) |
| Suspended growth | Monod kinetics | Iterative procedure of solving the Monod equations | Artan et al. (2001) |
| Suspended growth | Mass balance and experimental data | Iterative algorithm that determines the reactor's size and cycle patterns | Abu-Ghunmi and Jamrah (2006) |
| Suspended growth | Monod kinetics (ASM 2) | AQUASIM program | Artan et al. (2002) |
| Suspended growth | Monod kinetics (ASM1) | Iterative dynamic | Coelho et al. (2000) |
| Suspended growth | Mass balance | Model simulator and Fitter (MOSIFIT) simulation program | Demuynck et al. (1994) |

However, the study considered the SBR to be a steady state continuous flow system, ignoring the intrinsic nature of the SBR which is unsteady state in nature. The work by Abu-Ghunmi and Jamrah (2006) shows a design procedure for SBRs treating textile wastewater. The method used simple mass balance concepts and experimental results to determine the reactor volume and cycle length. Hsu (1986) developed a mathematical expression for biomass growth and substrate removal during the react period using Monod kinetics but the simulation procedure was based on solving the differential equations until steady state is reached. A recent study by Dionisi et al. (2016) presented a new mathematical procedure that calculates the periodic steady state of the sequencing batch reactor (SBR). The procedure is based on the mass balances of biomass ($X$) and substrate ($S$) and was applied to show the effect of the operating parameters (SRT, HRT, length of the phases and number of cycles) on the steady state biomass and substrate concentrations.

## 6. CONCLUSION

An overview of the literature has shown that the SBR system is a very good alternative to the conventional Activated Sludge system due to its high efficiency in industrial wastewater treatment, flexibility in mode of operation, relatively low cost and small footprints. The SRT is the basically the most important design parameter that determines the performance of the SBRs. Most SBR studies have not optimised the operating conditions and have been carried out at low organic load and high SRT which corresponds to large reactor volumes, and high oxygen consumption, making aerobic biological treatment to have large footprints and to be energy intensive. The available design procedure is limited to simplistic conventional approach of selecting volumetric and organic loadings and SRT values arbitrarily, based on empirical knowledge with little emphasis on process kinetics and stoichiometry.

## 7. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

## REFERENCES

Abu-Ghunmi, L.N. and Jamrah, A.I. (2006). Biological treatment of textile wastewater using sequencing batch reactor technology. *Environmental Modeling & Assessment*, 11(4), pp. 333-343.

Akunna, J.C. and Shepherd, W. (2001). Comparison of RBC and SBR systems for the treatment of sewage from small communities. *Water and Environment Journal*, 15(2), pp. 147-151.

Arora, M.L., Barth, E.F. and Umphres, M.B. (1985). Technology evaluation of sequencing batch reactors. *Journal of Water Pollution Control Federation,* 57(8), pp. 867-875.

Artan, N. and Orhon D. (2005). *Mechanism and Design of Sequencing Batch Reactors for Nutrient Removal*. Vol. 19. IWA Publishing, London.

Artan, N., Wilderer, P., Orhon, D., Morgenroth, E. and Özgür, N. (2001). The mechanism and design of sequencing batch reactor systems for nutrient removal-the state of the art. *Water Science and Technology*, 43(3), pp. 53-60.

Artan, N., Wilderer, P., Orhon, D., Tasli, R. and Morgenroth, E. (2002). Model evaluation and optimisation of nutrient removal potential for sequencing batch reactors. *Water SA*, 28(4), pp. 423-432.

Beun, J.J., Dircks, K., Van Loosdrecht, M.C.M. and Heijnen, J.J. (2002). Poly-β-hydroxybutyrate metabolism in dynamically fed mixed microbial cultures. *Water Research*, 36(5), pp. 1167-1180.

Brenner, A., Chozick, R. and Irvine, R.L. (1992). Treatment of a high-strength, mixed phenolic waste in an SBR. *Water Environment Research*, 64(2), pp. 128-133.

Buitrón, G., Schoeb, M.E. and Moreno, J. (2003). Automated sequencing batch bioreactor under extreme peaks of 4-chlorophenol. *Water Science and Technology*, 47(10), pp. 175-181.

Cervantes, F. J., Pavlostathis, S. G. and van Haandel, A. (2006). *Advanced Biological Treatment Processes for Industrial Wastewaters*. IWA Publishing. London

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

Coelho, M.A.Z., Russo, C. and Araujo, O.Q.F. (2000). Optimization of a sequencing batch reactor for biological nitrogen removal. *Water Research*, 34(10), pp. 2809-2817.

Demuynck, C., Vanrolleghem, P., Mingneau, C., Liessens, J. and Verstraete, W. (1994). NDBEPR process optimization in SBRs: reduction of external carbon-source and oxygen supply. *Water Science and Technology*, 30(4), pp. 169-179

Dionisi, D. (2017). *Biological Wastewater Treatment Processes: Mass and Heat Balances*. CRC press, Florida.

Dionisi, D., Majone, M., Levantesi, C., Bellani, A. and Fuoco, A. (2006). Effect of feed length on settleability, substrate uptake and storage in a sequencing batch reactor treating an industrial wastewater. *Environmental Technology*, 27(8), pp. 901-908.

Dionisi, D., Majone, M., Tandoi, V. and Beccari, M. (2001). Sequencing batch reactor: influence of periodic operation on physiological state, microbial composition and performance of activated sludge in biological wastewater treatment. *Industrial and Engineering Chemistry Research*, 40, pp. 5110-5119.

Dionisi, D., Rasheed, A.A. and Majumder, A. (2016). A new method to calculate the periodic steady state of sequencing batch reactors for biological wastewater treatment: model development and applications. *Journal of Environmental Chemical Engineering*, 4(3), pp. 3665-3680.

Fernandes, L., Kennedy, K.J. and Ning, Z. (1993). Dynamic modelling of substrate degradation in sequencing batch anaerobic reactors (SBAR). *Water Research*, 27(11), pp. 1619-1628.

Ge, H., Batstone, D.J. and Keller, J. (2013). Operating aerobic wastewater treatment at very short sludge ages enables treatment and energy recovery through anaerobic sludge digestion. *Water Research*, 47(17), pp. 6546-6557.

Gerardi, M.H. (2011). *Troubleshooting the Sequencing Batch Reactor*. Vol. 11. John Wiley and Sons, New Jersey.

Geselbracht, J. (2007). Spreadsheet Implementation of Activated Sludge Model# 1 for Sequencing Batch Reactors. *Proceedings of the Water Environment Federation*, 2007(17), pp. 1597-1606.

González-Martinez, S. and Wilderer, P.A. (1991). Phosphate removal in a biofilm reactor. *Water Science and Technology*, 23(7-9), pp. 1405-1415.

Grady Jr, C.L., Daigger, G.T., Love, N.G. and Filipe, C.D. (2011). *Biological Wastewater Treatment*. CRC press, Florida.

Gujer, W., Henze, M., Mino, T. and Van Loosdrecht, M. (1999). Activated sludge model no. 3. *Water Science and Technology*, 39(1), pp. 183-193.

Hajiabadi, H., Moghaddam, M. A. and Hashemi, S. (2009). Effect of sludge retention time on treating high Load synthetic wastewater using aerobic sequencing. *Journal of Environmental Health Science and Engineering*, 6(4), pp. 217-222.

Henze, M., Grady Jr, C.L., Gujer, W., Marais, G.V.R. and Matsuo, T. (1987). A general model for single-sludge wastewater treatment systems. *Water Research*, 21(5), pp. 505-515.

Henze, M., Gujer, W., Mino, T. and van Loosdrecht, M.C. (2000). *Activated Sludge Models ASM1, ASM2, ASM2d and ASM3*. IWA Publishing, London.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M. C. and Marais, G. (1995). *Activated Sludge Model No. 2*: IAWQ Scientific and Technical Reports. No. 3. IAWQ, London.

Hoepker, E.C. and Schroeder, E.D. (1979). The effect of loading rate on batch-activated sludge effluent quality. *Journal of Water Pollution Control Federation*, 51(2), pp. 264-273.

Hsu, E.H. (1986). Treatment of a petrochemical wastewater in sequencing batch reactors. *Environmental Progress*, 5(2), pp.71-81.

Irvine, R.L. and Busch, A.W. (1979). Sequencing batch biological reactors: an overview. *Journal of Water Pollution Control Federation*, 51(2), pp. 235-243.

Irvine, R.L., Ketchum Jr, L.H. and Asano, T. (1989). Sequencing batch reactors for biological wastewater treatment. *Critical Reviews in Environmental Science and Technology*, 18(4), pp. 255-294.

Irvine, R.L., Wilderer, P.A. and Flemming, H.C. (1997). Controlled unsteady state processes and technologies-an overview. *Water Science and Technology*, 35(1), pp. 1-10.

Keller, J., Watts, S., Battye-Smith, W. and Chong, R. (2001). Full-scale demonstration of biological nutrient removal in a single tank SBR process. *Water Science and Technology*, 43(3), pp. 355-362.

Ketchum Jr, L.H. (1997). Design and physical features of sequencing batch reactors. *Water Science and Technology*, 35(1), pp. 11-18.

Li, J.P., Healy, M.G., Zhan, X.M. and Rodgers, M. (2008). Nutrient removal from slaughterhouse wastewater in an intermittently aerated sequencing batch reactor. *Bioresource Technology*, 99(16), pp. 7644-7650.

Metcalf, E. and Eddy, E. (2003). *Wastewater Engineering: Treatment and Reuse*. McGraw-Hill Inc., New York

Nakhla, G., Liu, V. and Bassi, A. (2006). Kinetic modeling of aerobic biodegradation of high oil and grease rendering wastewater. *Bioresource Technology*, 97(1), pp. 131-139.

Ni, B.J., Xie, W.M., Liu, S.G., Yu, H.Q., Wang, Y.Z., Wang, G. and Dai, X.L. (2009). Granulation of activated sludge in a pilot-scale sequencing batch reactor for the treatment of low-strength municipal wastewater. *Water Research*, 43(3), pp. 751-761.

Oles, J. and Wilderer, P.A. (1991). Computer aided design of sequencing batch reactors based on the IAWPRC activated sludge model. *Water Science and Technology*, 23(4-6), pp. 1087-1095.

Rodríguez, D.C., Lara, P.A. and Peñuela, G. (2014). Pilot study of a sequencing batch reactor for the treatment of wastewater from an animal food factory. *Afinidad*, *71*(565), pp. 43-48

Schwarzenbeck, N., Borges, J.M. and Wilderer, P.A. (2005). Treatment of dairy effluents in an aerobic granular sludge sequencing batch reactor. *Applied Microbiology and Biotechnology*, 66(6), pp. 711-718.

Serafim, L.S., Lemos, P.C., Oliveira, R. and Reis, M.A. (2004). Optimization of polyhydroxybutyrate production by mixed cultures submitted to aerobic dynamic feeding conditions. *Biotechnology and Bioengineering*, *87*(2), pp.145-160.

Spellman, F.R. (2013). *Handbook of Water and Wastewater Treatment Plant Operations*. CRC Press, Florida.

Velmurugan, S., Clarkson, W.W. and Veenstra, J.N., 2010. Model-based design of sequencing batch reactor for removal of biodegradable organics and nitrogen. *Water Environment Research*, *82*(5), pp.462-474.

Von Sperling, M. (2007). *Activated Sludge and Aerobic Biofilm Reactors*. IWA Publishing, London.

Wang, L.K., Shammas, N.K. and Hung, Y.T. (2010). *Advanced biological treatment processes.* Vol. 9. Springer Science & Business Media, Berlin.

Water Environment Federation (WEF) (2012). *Wastewater Treatment Plant Design Handbook.* Alexandria, VA, USA.

Wilderer, P.A., Irvine, R.L. and Goronszy, M.C. (2001). *Sequencing Batch Reactor Technology*.Vol. 10. IWA Publishing, London.

Yoong, E.T., Lant, P.A. and Greenfield, P.F. (2000). In situ respirometry in an SBR treating wastewater with high phenol concentrations. *Water Research*, 34(1), pp. 239-245.