Cyclic bioreactors – a discussion on technology application and possible future developments

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Abstract  Wastewater treatment systems based on cyclic reactors started to be applied more widely in Asia about two decades ago. A number of variants have been introduced but the focus of this paper is on the intermittent feed–intermittent decant variant, the SBR. Based on the basic SBR concept, specific reactor configurations which have been introduced include the pretreatment anaerobic reactor (anSBR), the aerobic reactor (aeSBR), and the sludge digester (SBD). This paper discusses some of the issues around the argument for selecting the SBR – particularly the aeSBR, equipment which are unique to this cyclic reactor, the concerns around such equipment selection, operating difficulties, and the possible future developments with this reactor concept.

Keywords  Bioreactors; cyclic; SBR; applications; operating difficulties; future developments

Introduction
The countries in Asia have, over the last two decades, experienced rapid economic development and are likely to do so again in the future after they come out of the recent economic difficulties. Such economic development has, unfortunately, led to activities which may have an adverse impact on the environment unless appropriate care is exercised. In this respect, the water environment can often be obviously affected. The range and complexity of water pollution problems caused by domestic, agro-industrial, and industrial discharges have increased throughout the region.

Biotreatment systems are the most commonly used systems for treatment of such wastewaters. These systems would include the aerobic processes and to a somewhat lesser extent the anaerobic processes. The majority of such systems would be of the continuous-flow type where the unit processes are largely arranged on a spatial frame and the resulting plants can thus be sprawling. Asian populations are becoming increasingly urbanized and economic activities clustered. The consequence of this is wastewater treatment facilities are faced with significant space constraints and are often required to be constructed and operated in close proximity with human habitation or activities. This has, among others, led to aesthetic and nuisance issues with neighbors. Notwithstanding the considerable investments made on such treatment facilities, the quality of the manpower available for their operation can also be disappointing. This can, unfortunately, lead to frequent process and/or plant failures and hence further compounding the issues already present as a consequence of space constraints and proximity to human habitation or activities.

It was against the above backdrop that the cyclic bioreactor found increasing applications from the mid-1980s onwards as an alternative to the more commonly encountered continuous-flow systems. A number of variants of this reactor and the consequent plant configuration were introduced and a common version among these is the Sequencing Batch Reactor (SBR). At that point in time, the quantity of literature describing the SBR, its design, and operation was comparatively sparse. While the published literature on such cyclic systems has increased over the years, it still remains relatively sparse and largely
laboratory derived (compared to the conventional systems). This would particularly be so if one was to search for information drawn from site experience and plant operations. This paper draws on impressions gathered over almost two decades of designing, constructing, and operating cyclic reactors and is intended to highlight some of the reasons why a wastewater treatment system designed around SBRs might be considered a viable alternative, potential process and operating issues, and what developments one might expect to take place over the next decade.

Discussion
The literature holds increasing numbers of reports on cyclic reactors, such as the SBR, tested on a variety of wastewaters in the laboratory. Examples would include ABS (acrylonitrile butadiene styrene) wastewater (Chang et al., 2000) and even organics contaminated slurries (Cassidy et al., 2000). Unpublished data which would, largely, be proprietary in nature would include successful full-scale applications of cyclic reactors such as the aerobic SBR on sewage with and without biological nutrient removal (BNR), industrial wastewaters such as those from manufacturers of pharmaceuticals, chemicals, and food, and agro-industrial wastewaters such as those arising from animal husbandry, slaughterhouses, and oilseed processing. Most of such treatment facilities would have been required to meet discharge standards where the bioprocess design would have aimed at satisfying limits on BOD5 and SS at 20 or 50 mg/L and 30 or 50 mg/L respectively. A number of these would have aimed at not only satisfying BOD5 and SS of 20 and 30 mg/L respectively but additional requirements on nitrogen and phosphorous.

The cyclic reactor variants which have been introduced over the last two decades may be broadly classified in terms of their feed and discharge patterns. The three more common categories would be the continuous feed–intermittent discharge, intermittent feed–intermittent discharge, and “reversing” flow. Of the three, the first two would more closely resemble each other in terms of operating protocols. The following discussion deals primarily with the first two types and particularly the intermittent feed–intermittent decant type (or SBR). Reactors in the continuous feed type would have a baffle wall in the reactor to reduce the risk of untreated wastewater exiting the reactor during decant and so the reactor is effectively bi-chambered. Aside from this, the equipments used in the two types are largely similar although arrangement details and equivalent numbers can differ. Of these equipment items in the reactor, two clusters have attracted particular attention. These are the decanter and the aeration systems. The decanter system is probably unique to this type of bioreactors and this may take the form of the moving arm or fixed point types. The former is more commonly found in the bigger systems and particularly those intended for sewage treatment while the latter has largely been used for industrial and agro-industrial wastewater treatment. Both have been used successfully at full-scale although the fixed-point type does require a better understanding of the process and microbial properties as the designer would need to quite accurately estimate settling velocities and where the sludge blanket–clarified effluent interface would eventually be while trying to avoid vortex formation within the reactor during decant. The decision to use the fixed-point type is often dictated by economic considerations and would be found more frequently in the mid to smaller sized plants.

The treatment train in SBR-based sewage treatment plants without the water reclamation option would typically include coarse screens, degritters, oil and grease traps, fine screens, buffer chambers, reactors, and chlorination chambers. Clarifiers, both primary and secondary, would be absent from the system. In plants where BNR is practiced for nitrogen and phosphorous removal, this would also occur in the said reactors. Similarly, chemical augmented phosphorous removal would take place in the reactors over a predetermined
period in the operating cycle. The preceding would mean reactors in SBR plants could, in terms of functions performed, be more than the aeration basins found in conventional activated sludge systems. SBR plants for industrial wastewater treatment would retain the buffer chambers and reactors but the unit processes before and after these would depend on the nature of the wastewater. This would particularly be so for unit processes in the headworks and examples of unit processes not found in systems intended for sewage treatment could include nutrients supplementation and pH control which are frequently found ahead of the reactors in the former. Where strong wastewaters require treatment, pretreatment to reduce organic strength ahead of the aerobic process may include an anaerobic reactor and there are already full-scale working examples of such reactors being operated on a protocol based on the aerobic SBR (ie. the anSBR). In support of the wastewater treatment train would be the sludge management facilities and these could include thickeners, aerobic or anaerobic digesters, and dewatering devices. To simplify control and operations, the digesters could and have been designed to operate like the SBR and again there are already full-scale examples of these in service. The control structure of such a plant, incorporating the anSBR, aerobic SBR (aeSBR), and SBD, can in effect be quite simple as the three would share a similar temporal frame.

SBRs have often been promoted on the basis of its lower area requirements compared to equivalent continuous-flow activated sludge processes. While theoretical batch (or more correctly semi-batch in the SBR) versus continuous-flow considerations would support such a claim in terms of aeration basin sizes (ie. the reactors), much larger space savings have been gained through the elimination of clarifiers and the spatial arrangement of the physical infrastructure. In sewage treatment the primary clarifiers have often been replaced with a series of screens. Certainly in domestic sewage treatment, treatment trains without primary clarifiers have not compromised plant performance in terms of treated effluent quality or operability. Very convincing evidence of the smaller area requirements has been provided when existing plants have been retrofitted into SBRs with significantly larger treatment capacities. Replacement of the clarifiers with the much more compact fine screens has also on the other hand simplified and reduced odour control requirements since the latter can be more easily and economically covered. The trapped odorous air would then be extracted and treated before release.

In the aerobic SBR (aeSBR) aeration efficiency in the reactor is obviously a very important issue as it affects the size of the aeration system, energy requirements, and hence operating costs. Aeration needs in the SBR can often be more intense (and airflow rates variable) than the conventional activated sludge system because aeration is not continuous throughout the day and substrate concentrations can be very much higher at the start of a cycle compared to the concentrations in the discharge at the end of the cycle. Notwithstanding this, early aeSBRs would consider incorporating aeration devices such as coarse air diffusers, surface aerators, and submerged aerators. This was because there was concern the fine air diffusers which could have provided better oxygen transfer efficiencies (particularly against the coarse air diffusers) would clog after repeated cycles of the sludge blanket resting on them during the settle and decant phases. While ceramic fine air diffusers would not be used, membrane fine air diffusers have been successfully used. Systems used over a decade have not indicated unusual levels of maintenance requirements nor losses in oxygen transfer efficiencies. Such diffusers have also been successfully used in the aerobic SBDs where solids concentrations can be in the 1 to 3% range under complete–mixed conditions.

As in the continuous flow activated sludge systems, SBRs can also be seriously affected with foaming caused possibly by Nocardia spp. With the possible exception of the coarse air diffusers, foaming difficulties have been experienced with the other three types of aera-
tion devices. Foaming in SBRs can frequently occur during the start-up phase when substrate loadings may not be within the design range (ie. apparent F/M is lower than design). In new catchments, because it is necessary to have the plant in operation before all the residents have moved in, the sewage received can be significantly weaker than design (ie. possibly lower than expected sludge wasting and hence longer sludge residence times). Foaming, aside for the aesthetic issues, leads to loss of biomass and this can adversely affect the time required to successfully complete the start-up phase. Other than the start-up phase, when substrate loading conditions are not within the design range over lengthy service periods foaming can also occur. Again aside from being an aesthetic issue, foaming can lead to operational difficulties including the “blinding” of level sensors, poorer decant quality when foam enters the decanters, constrained air supply, and foam spillage when the freeboard, perhaps because of hydraulic load reasons, has been reduced or was inadequate in the first instance. The foam index can be used as an indicator of the extent of the problem (Ng et al., 2000a). This measured the portion of the MLSS which would be trapped in the foam. From the view of operations, it is interesting to note the index relates well with the filament count determined using the Neubauer haemacytometer. Figure 1 shows such a relationship between the two parameters. It has been noted that over time, a plant’s operators could be trained to regularly collect samples of MLSS and to view these under the microscope for filaments and to estimate these so as to gain an idea of any impending foaming difficulties before obtaining further indications from the foam index.

The activated sludge process and its variants (including the aeSBR) depend on satisfactory performance of bio-oxidation and liquid-solids disengagement. Overall quality of the discharge is largely dependent on the settleability of the activated sludge. It has been estimated bulking sludge is a problem which could affect as many as half the activated sludge plants world-wide (Tomlinson and Chambers, 1976). Control methods derived from the microbiological approach of bulking is slow to implement and can be quite expensive if requiring modification of the existing plant. The aeSBR, as a result of its control protocol, does provide opportunities for bulking control through manipulation of the substrate and DO residual concentrations profiles with respect to cycle time. Even allowing for this, SBRs do suffer from bulking problems and particularly so when handling easily degradable industrial wastewaters (e.g. ethanol, ethanoic acid). Given the batch nature of SBR operation, a predictive tool which could warn of the possibility of impending process difficulties could allow these to be preempted with adjustments to the system. A system-specific, non-mechanistic bulking model was formulated through statistical analyses of data from a full-scale SBR. The dependent parameter, SVI, was expressed in terms of independent process parameters and wastewaster characteristics determined through an on-site monitoring program (Ng et al., 2000b). SVI could be correlated as follows:

Figure 1 Correlation between foam index and filament count
SVI = \alpha(COD_{inf}) + b(COD_{inf})^2 + c(MLVSS) + d(pH_{ml}) - e(pH_{ml})^2 - f(FM_f) + g(FM_f)^2 + h(FM_f) - i(FM_f)^2 - k(Q_{air})

where
COD_{inf} = influent COD, mg/L;
MLVSS = mixed liquor volatile suspended solids, mg/L;
pH_{ml} = mixed liquor pH;
FM_f = fill F/M ratio, 1/d;
FM_r = react F/M ratio, 1/d;
Q_{air} = airflow rate into reactor, m^3/h;
\alpha-k = parameter coefficients.

Figure 2 shows the model fit from Days 1 to 60 and its predictive accuracy from Days 61 to 75. Before further refinement, the model was found to over-estimate the SVI by an average of +12%.

Control of foaming and bulking can be achieved through an alternating feast–fast mode of operation. The intermittent feed operation of the SBR inherently creates “feast” conditions at the beginning of a cycle and this would then transit towards “fast” conditions at the end of the cycle before the settle and decant stages. This inherent feature of the SBR can be further exploited to correct an existing condition or enhance control so as to reduce incidence of its occurrence. The intensity of the “feast–fast” condition can be manipulated (within limits) by adjusting the ratio of fill to react periods, the ratio of aerated to non-aerated periods, and the intensity of aeration during specific blocs of time within the aerated periods. Control strategies built around these would suggest a process control approach which possibly hinged on the growth kinetics of relevant groups of bacteria. The work reported by Chua et al. (2000) lends support to this. They noted the specific growth rate of N. amarae was much higher than that of non-filamentous bacteria like P. aeruginosa at lower substrate concentrations. Examination of biosludge samples drawn from full-scale reactors which were foaming and/or bulking do indeed show microbial morphologies very similar to that observed by Chua et al. (2000) but these reduced or disappeared once proper control could be exerted on the reactor by means outlined above.

In the introduction, mention was made of the space constraints which could be faced by designers of wastewater treatment facilities. Such constraints are unlikely to diminish but could instead be expected to intensify. The search for new urban types in architecture to accommodate population growth would have to address issues such as scarcity of usable land, possible dependency on imported water for particular localities, and high population densities coupled with the need for acceptable urban spatial quality. These and the possible need to preserve the existing fabric of an urban centre (possibly because of conservation requirements) may argue for decentralized wastewater treatment infrastructure. The argument taken to the “extreme”, may call for integration of the treatment facilities into

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**Figure 2** Model fit and validation
different forms of housing, commercial, and industrial use environments (Lim and Kallianpur, 2001). In this approach compact treatment systems such as the SBR, because it is arranged on a temporal frame as opposed to the spatial frame of conventional continuous flow systems, could have an advantage.

However, even cyclic reactors in their current form may not be sufficiently compact. To further reduce the size of reactors, an approach could be to increase the reactor’s MLSS. A development, the membrane bioreactor, could well be the answer and the SBR could be the bioreactor. Membrane driven liquid–solids separation is a possible approach towards reducing the size of a reactor since the settle stage would not be required and settling and the related high solids flux difficulties no longer an issue. Given the latter, MLSS of 10 g/L or more can be accommodated. The higher MLSS would allow, for a given reactor volume, higher concentration or greater volumes of a wastewater to be treated. Although there are still issues such as membrane fouling, oxygen transfer, and the consequent possible diminution of nitrification to be addressed (Ng et al., 2000c), membrane reactors do offer promise in terms of increased capacity and hence compactness. Furthermore, the treated effluent is of such quality (e.g. in terms of SS) as to make it attractive for reclamation to be considered.

As more compact systems are implemented, especially within urban centers, sludge management can be expected to become an ever larger issue. A conventional method towards reduction of biosludge generation is to extend the sludge residence time (SRT) and hence shift the process towards endogenous respiration (i.e. extended aeration mode). The downside of this approach would be the size of the plant brought about by the large aeration basins. An alternative approach could be the use of ozonation to modify the observed biomass yield ($Y_{\text{obs}}$). In the aeSBR, ozone dosages could range from 0.05 g O$_3$/g SS to 0.2 g O$_3$/g SS depending on the rate at which biomass is withdrawn for contacting with the ozone. The results of laboratory studies using an ethanoic acid based synthetic wastewater with no influent SS would suggest the $Y_{\text{obs}}$ could be nearly zero while the biomass activity was not noticeably affected as determined in terms of effluent quality and oxygen utilization rate (OUR) (Ng et al., 2000d). It should be noted a near zero $Y_{\text{obs}}$ would not be a reasonable expectation with a real wastewater since influent SS can be expected and there would be a significant component of non-volatiles in this.

**Conclusion**

Two decades of exposure to both laboratory studies and full-scale applications would suggest the cyclic bioreactor concept is indeed a viable alternative to the continuous flow arrangement. While there are presently a number of variants, the aeSBR configuration has seen numerous full-scale applications in a number of countries in Asia with perhaps greater numbers treating industrial and agro-industrial wastewaters than domestic sewage at the moment. In most of these applications, their locations are more often within the urban rather than the rural setting. The former has meant the savings in area requirements derived from coupling arrangement of the plant infrastructure with the inherently more compact cyclic reactors has given some competitive advantage to the system. The aeSBR has in many instances been supported with pretreatment and sludge management unit systems designed on the SBR concept. These are the anSBR and SBD. The major biological systems in a continuous flow plant which is often designed around the conventional activated sludge process can therefore be replaced with cyclic systems. This had meant process and equipment control for the major unit systems within the plant can be designed on similar concepts – hence simplifying design and eventually control. Early concerns with equipment such as the decanter and aeration devices have also been largely allayed with the experience gained under actual site conditions. SBRs are, however, not entirely without...
operational difficulties and problems such as foaming and bulking can occur quickly. Such occurrences during start-ups would delay their completion and consequently plant handover (with potential attendant financial penalties) while occurrences during a plant’s service life could result in compromised treated effluent quality (and failing to meet the legal discharge limits). Experience drawn from plant operation would suggest such problems could be controlled with appropriate manipulation of the SBR cycle and could, perhaps, even be pre-empted. Just as it had been with the continuous flow systems like the activated sludge and its variants in the past, the body of accumulated knowledge on the design and operation of cyclic systems would probably have reached a stage now to facilitate more frequent discussions and diffusion into the wastewater management industry and among users. Perhaps with this and in the not too distant future, the SBR would also be classified as one of the conventional systems.

References