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Mixed integer optimal control of an intermittently aerated sequencing batch reactor for wastewater treatment

Juan Antonio Delgado San Martín[a,*], Mariano Nicolás Cruz Bournazou[b], Peter Neubauer[b], Tilman Barz[a]

[a] Chair of Process Dynamics and Operation, Department of Process Engineering, Technical University Berlin, Sekr. KWT-9, Str. des 17. Juni 135, D-10623 Berlin, Germany
[b] Chair for Bioprocess Engineering, Department of Biotechnology, Technical University Berlin, Sekr. ACK24, Ackerstr. 71-76, D-13355 Berlin, Germany

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ABSTRACT

Optimal aeration control strategies for sequencing batch reactors in WWT with bypass nitrification are hereby studied. The operation is defined alternating aerobic and anoxic phases with high frequency. The controlled variable, the aeration, can only adopt fixed values, on and off, leading to a discrete trajectory of bang–bang type. The problem is to compute the number of switches and individual length of each aerobic and anoxic stage. This leads to a mixed integer nonlinear optimal control problem (MINTOC). The solution is challenging, since both integer and continuous variables ought to be considered in the optimization. In contrast to previous work, where optimization is performed based on the separation and independent solution of the integer and continuous problem, we apply an algorithm originally proposed by Sager (2005). The optimization program minimizes operation time and energy consumption. Effluent concentrations are considered as nonlinear constraints in accordance to environmental regulations.

1. Introduction

Finding optimal aeration profiles, specifically an optimal intermittent aeration profile (OIAP) is a challenging task in waste water treatment (WWT) plants (Spagni and Marsili-Libelli, 2009). A repeated change of aerobic to anoxic conditions and back allows the consumption of biodegradable matter and ammonia while redrate accumulation. This method with a high number of aerobic–anoxic phases, known as bypass nitrification (Turk and Mavinic, 1986), has shown to offer a number of advantages over the standard nitrification–denitrification process. Still, finding the optimal number of both intervals, aerobic/anoxic, as well as their respective lengths represents a complex optimization problem involving integer variables, highly nonlinear dynamics and a tightly constrained operating range. Yet, the effort is justified. On the one hand, OIAP reduces the operation time and the chemical oxygen demand (COD) input by achieving maximal efficiency of bacterial growth and substrate consumption. On the other hand, OIAP economizes energy input but also energy consumption through reduction of the aeration feed volume (Sinha and Annachhatre, 2007).

1.1. Sequencing batch reactor

The semi-continuous sequencing batch reactor (SBR) technology, developed in the seventies (Irvine and Davis, 1971), is widely used given its small footprint, its capacity of treating reduced load charges, variable influent quality and its high flexibility (Mahvi, 2008). The basic SBR system consists of a batch basin where five phases take place: idle, fill, react, settle, draw (Mahvi, 2008). Aerobic phases are defined by simply turning aeration on and off during the fill and the reaction phases. Additionally, operation conditions may be changed from cycle to cycle, which then also requires an adaptation of the OIAP (Cruz Bournazou et al., 2013).

Moreover, as the volume of SBRs is significantly smaller compared to continuous plants, the sensitivity of the process to changes in the quality of the water is significantly higher.

Abbreviations: ASP, activated sludge process; BN, bypass nitrification; IAP, intermittent aeration profiles; IPH, integrated penalty homotopy; (O)IAP, (optimal) intermittent aeration profiles; PH, penalty homotopy; RL, relaxed solution; SBR, sequencing batch reactors; WWT, wastewater treatment; COD, chemical Oxygen demand.

* Corresponding author at: AstraZeneca, 35F107, iMed Oncology DMPK, Alderley Park, Macclesfield, Cheshire SK10 4TG, United Kingdom Tel.: +44 01625 516672.
E-mail addresses: juan.ADS.delgado@astrazeneca.com (J.A. Delgado San Martín), mariano.n.cruzbournazou@tu-berlin.de (M.N. Cruz Bournazou), tilman.barz@tu-berlin.de (T. Barz).

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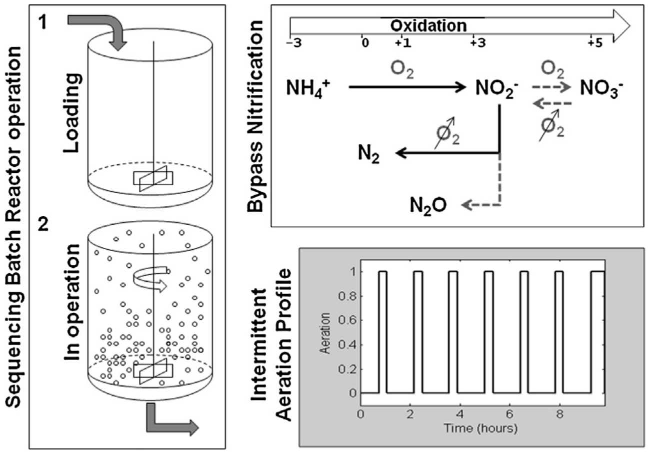

Fig. 1. SBR technology with BN. SBRs operate sequentially to achieve a semi-continuous process (top arrow represents wastewater (inlet), bottom arrow is cleared water (effluent)). During operation, a series of desired (solid lines) and undesired reactions (dashed lines) may occur. In BN, oxidation of NH_4^+ and reduction of NO_2^- is realized to obtain molecular nitrogen (N_2). To establish this partial oxidation, an appropriate advanced control system is necessary to obtain the OIAP.

1.2. Bypass nitrification

Bypass nitrification (BN) enables denitrification directly from nitrite skipping nitrate accumulation (Sinha and Annachhatre, 2007; Yoo et al., 1999; Chung et al., 2006; Peng and Zhu, 2006). BN also offers a number of advantages including a reduction of the oxygen demand for nitrification by up to 25% and an increase of the denitrification rate by 63% and CO_2 emissions by 20% (Turk and Mavinic, 1986; Peng and Zhu, 2006; Turk and Mavinic, 1987; Abeling and Seyfried, 1992).

The use of an intermittent aeration profile (IAP) has been shown to be an effective method to accomplish bypass nitrification (Spagni and Marsili-Libelli, 2009; Yoo et al., 1999; Peng and Zhu, 2006; Katsogiannis et al., 2003; Akın and Ugurlu, 2005; Yang et al., 2007; Yongzhen et al., 2007).

Fig. 1 illustrates the basic concept of the SBR technology with BN. The intermittent aeration leads to an alternation of aerobic and anoxic phases with high frequency. The OIAP defines the combination of parameters (number of aeration intervals, length of each interval) that minimizes time, energy input and COD while maximizing removal nitrogen compounds.

1.3. Optimal intermittent aeration profile in SBR

The SBR is a dynamic process involving binary switches in the aeration control, which define aerobic and anoxic phases. The length of each phase is defined by a variable time grid. There is a number of publications dealing with the optimization of the IAP (Cruz Bournazou et al., 2013; Coelho et al., 2000; Chachuat et al., 2005; Fikar et al., 2005; Holenda et al., 2007; Kim et al., 2008; Souza et al., 2008; Balku et al., 2009; Chai & Lie, 2008) and also some based on experimental evidence (Sin et al., 2004). However, none of them considered integer and continuous variables simultaneously. Instead, the adopted solution approach is based on a simplification computing the specific aeration interval length (continuous problem) for a given number of intervals (integer problem). Unfortunately, this independent computation of the interval number and interval length leads to suboptimal solutions (Cruz Bournazou et al., 2013).

1.4. Mixed integer optimal control problems

In mixed integer nonlinear programming (MINLP) both integer and continuous variables are combined in a nonlinear system such as mechanistic physico-chemical or biological multi-variable models. For the here studied optimal control problems, the models are described by a set of differential equations. The incorporation of a control system which can only adopt fixed values, such as this case, turns the problem into a mixed integer optimal control (MINTOC) problem (Logist et al., 2010).

An algorithm for the solution of MINTOC problems was presented by S. Sager and applied a number of times (Sager, 2005, 2009). Hereby MINTOC found some popularity among Volterra type problems (Sager, 2005), various vehicle gear control systems (Sager, 2005; Logist et al., 2010), as well as in circadian cycle in-silico simulation (Shaik and Goerecki, 2008) and in engineering or simple medical substance tracking applications (Sager, 2005; Slaby et al., 2007).

1.5. Model for SBR bypass nitrification

Many models for the description of the activated sludge process (ASP) have been published in the last three decades (Hauduc et al., 2013). Although the ASM1 is still the most referred model, it lacks the description of the nitrification–denitrification process in two steps and is therefore unsuitable for simulations of the BN. Instead, models which describe the two step reaction of the nitrification–denitrification process are needed. Therefore, the extended version of the ASM3 has been selected in this work (Kaelin et al., 2009). The extended ASM3, includes seven new differential equations, with a stoichiometric matrix of dimension 15×20 (15 differential equations and 20 reaction rates). This version has shown some complication when applied for control purposes. Firstly, the identification of the model parameters is not possible with the information obtained from online measurements. Secondly, it has proved to be very stiff in BN conditions (Cruz Bournazou et al., 2014).

However, the model describes many states that we can in fact neglect for the specific case of SBR processes (Balku et al., 2009; Velmurugan et al., 2010). Thus, a reduced nonlinear version of the extended ASM3, namely the 5-State model, has been developed (Cruz Bournazou et al., 2012). Its capacity to mimic the behavior of the extended ASM3 in complex optimizations, when the process is restricted to the SBR conditions, has been demonstrated (Cruz Bournazou et al., 2013).

2. Methods

We consider the optimal operation of one batch sequence (one cycle) for a given loading, e.g. wastewater quality. To achieve this, an OIAP must be computed such that: (1) the total batch time is minimized, (2) the effluent (characterized at the end of the batch) complies with environmental regulations, (3) the required aeration (energy input) is minimized, while (4) the switch between anoxic-aerobic phases achieves BN. This requires the solution of a MINTOC problem. There are two factors which need special attention:

- The optimal solution is defined by various effluent constraints which restrict the maximum allowed concentrations at the end of the cycle.
- The cycle time is minimized which leads to a so called minimum time optimal control problem. The minimization drives the studied process to the limits of the feasible operating region defined by constraints.