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Optimal model-based aeration control policies in a sequencing batch reactor

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ABSTRACT

We present a non-linear programming formulation for the computation of optimal aeration policies in a sequencing batch reactor for wastewater streams treatment. We assume that organic matter and nitrogen are the main pollutants to be removed to meet water quality targets. The novelty of the work lies in the fact that no binary variables are required to compute the switching time between the aerobic and anoxic stages of the water treatment process leading to a simpler, robust and easier to compute optimization formulation. Moreover, because the control valve, through which air is fed to the reactor, can take either its minimum or maximum bounds as well as any fractional values between such bounds, improved optimal aeration profiles are reported. Such improved profiles mean that shorter processing times are required, compared to previous solutions, leading also to a reduction in the operation cost of the wastewater treatment process. Although the optimal operation policies were computed for a typical home wastewater stream, the optimization formulation can also be extended for the treatment of other polluted streams.

1. Introduction

There are two widely used process for biological wastewater treatment (Grady et al., 1999; Wiesmann et al., 2007) (see Fig. 1a): the continuous activated sludge (CAS) (Eckenfelder et al., 1985) and the sequencing batch reactor (SBR) (Irvine and Ketchum, 1989; Mace and Mata-Alvarez, 2002) processes. In both systems the organisms used for wastewater treatment grow in suspension. In this work we will assume that influent wastewater is mainly composed of organic matter and nitrogen to be removed such that to meet water quality targets. Besides the organic matter in the wastewater stream, there are also inorganic compounds which have a relevant role in the eutrophication, mainly phosphates and those that contain nitrogen. For this reason, their removal is important; the phosphates frequently precipitate together with metals and can be separated trough sedimentation. On the other hand, the nitrogenous compounds are more soluble and the first step in the treatment is their conversion to ammonium (ammonification), which can be carried out under aerobic or anoxic conditions. Another potential route consists in transforming them into nitrate (nitrification) and from here into nitrogen (denitrification). Three processes are carried out by different microorganisms depending on the presence of oxygen. The nitrifying aerobic bacteria fulfil the nitrification and the efficiency of the process is related with the pH and biochemical oxygen demand (BOD) levels. In contrast, denitrification is performed under low levels of oxygen or in its absence (Bilton, 2011).

In the biological wastewater treatment approach two main operation phases can be identified related to the reaction basin: operation under aerobic and anoxic conditions. Under aerobic conditions ammonium is oxidized to nitrate using autotrophic organisms (nitrification step), whereas under anoxic conditions nitrate is transformed into nitrogen deploying heterotrophic organisms (denitrification step). Organic compounds are removed at any stage by heterotrophic organisms. One of the main differences between the CAS and SBR processes lies in the way both systems are run. The CAS process is composed of a reaction basin and decanters operated in a way such that the flowrate of pollutants moves from a given tank to the next one following a continuous pattern of operation (i.e. no accumulation of mass or energy inside the parts of the system). Commonly, in CAS systems the volume of the tanks remains fixed during operation. Moreover, the reaction basin consists of a set of reactors where separated aerobic and anoxic operating stages take place. On the other hand, in the SBR process the wastewater treatment system can be composed of either a single or a set of tanks. The relevant feature of SBR systems is that they are operated in a dynamic rather than in a continuous steady-state operating manner, for this reason they are sometimes referred to

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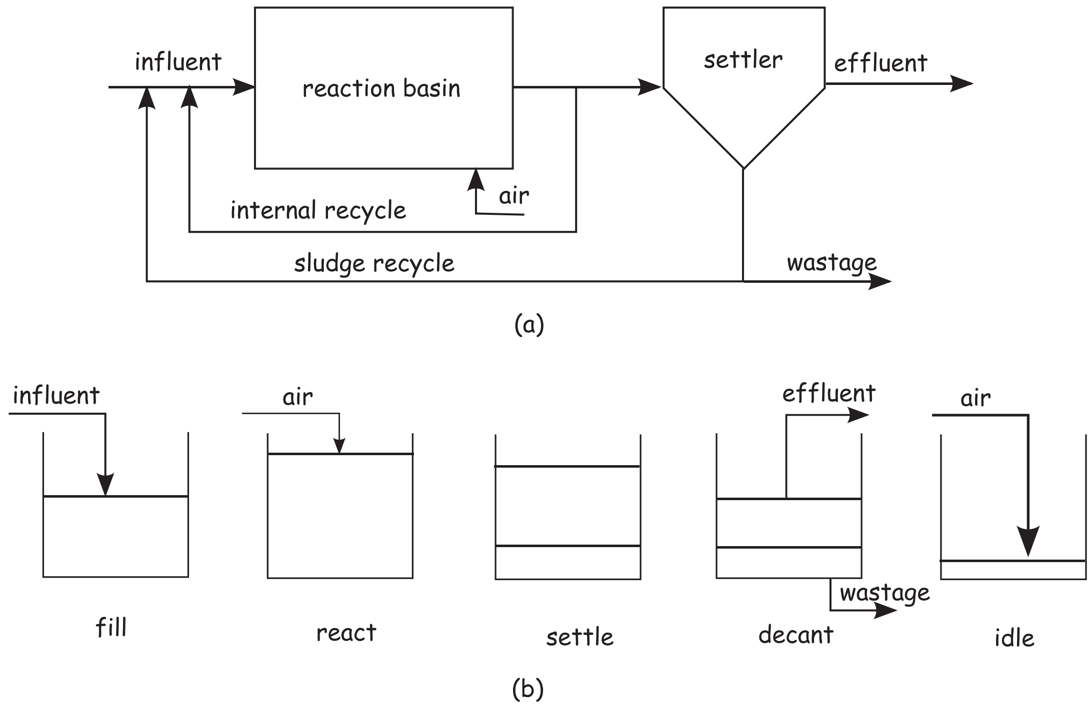

Fig. 1. (a) Continuous activated sludge process, (b) sequencing batch reactor.

Taken from Hopkins et al. (2001).

as unsteady-state activated sludge processes. In SBR systems the reaction and settling operations take place within the same tank. Hence, aerobic and anoxic stages are also required for meeting effluent quality. As shown in Fig. 1b, the operation of the SBR system comprises the filling, reacting, settling, decanting and idling operation stages in sequence. Moreover, flexibility is one of the main advantages invoked when dealing with either batch or semibatch operating systems (Rippin, 1993; Biegler et al., 1997). In this context flexibility means that the underlying system is capable of meeting target product requirements even when the processing conditions (i.e. feed stream composition, flowrate, etc.) are different from the ones for which the system was originally designed (Hopkins et al., 2001). However, in Hopkins et al. (2001) no important differences in flexibility were found for similar CAS and SBRs systems for nominal operating design conditions. Among all operating conditions that can be modified in SBR systems, the aeration profile is one of the more important control variables (Spagni and Marsili-Libelli, 2009). This is so because the consumption of biodegradable matter and ammonia strongly depends upon adequate switching between aerobic and anoxic operating stages. In fact, proper aeration profiles can reduce both operating time and chemical oxygen demand (Antonio Delgado et al., 2014). However, finding optimal aeration profiles turns out to be a complex task due to the presence of nonconvexities and nonlinear behavior in the underlying models used for optimization purposes.

In Coelho et al. (2000) organic matter and nitrogen removal in a SBR was undertaken considering both the filling and reacting phases. The underlying optimal control problem considered as decision variables the feed rate profile, filling time and aeration time. As objective function the authors proposed the minimization of the total batch time. Experimental implementation of the results was also sought. In Fikar et al. (2005b) and Chachuat et al. (2005) an optimal aeration profile for a small scale continuous sludge activated process was obtained. Although the authors successfully computed those aeration profiles, and derived a set of heuristic rules for the practical calculation of the aeration profile, they needed to set the number of switching events between the aerobic and anoxic phases to avoid solving a mixed-integer nonlinear programming problem. In Holenda et al. (2007) optimization based on the deployment of genetic algorithms was applied in a continuous wastewater treatment plant to find the optimal sequence of aerobic/anoxic operating stages such that energy consumption of the aeration process and the pollution load in the effluent are minimized. In Souza et al. (2008) the authors used an optimal feed operating policy for removing organic matter and nitrogen from wastewater streams. The optimization problem was cast as non-linear programming problem where the authors fixed the number of aerobic and anoxic stages and treating the flowrate of pollutants and switching times between aerobic/anoxic phases as the decision variables. During the aerobic phase the flowrate of air was set to a value such that maximum dissolved oxygen concentration was obtained. They concluded that a single aerobic/anoxic strategy was enough to obtain optimal target values of water quality. In Kim et al. (2008) the authors used a dynamic programming approach for solving the underlying optimal control problem for finding optimal operating policies regarding the dissolved oxygen during the aerobic phase and the amount of external carbon source during the anoxic phase using as objective function the minimization of the batch operating time. In Balku et al. (2009) the authors used a control vector iteration approach for handling the solution of an optimal control problem of a small scale continuous activated sludge wastewater treatment plant. The control variable consisted of computing the time length of both the aerobic and anoxic operating periods, whereas the objective function was the minimization of the operating time in a effort to reduce the main cost in wastewater treatment plants related to the energy used in the aeration devices. The authors also compared their results against similar results obtained using a genetic algorithm. In Cruz et al. (2013) the authors state that the right way of computing optimal aeration profiles in SBRs under partial denitrification is by allowing that both the number of aeration intervals and the duration of each one of the aeration intervals to be treated as decision variables. However, the authors recognized that treating the number of aeration interval as decision variables would lead to a