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Steady-state analyses of activated sludge processes with plug-flow reactor

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ABSTRACT

Activated sludge processes (ASPs) consisting of a plug-flow reactor (PFR) and a settler are analyzed in steady-state operation using a reduced model consisting of one soluble substrate and one particulate biomass component modelling the dominating biological process. Monod biomass growth rate is assumed. Two settler models are studied. One is the commonly used ideal settler, or point settler, which is assumed to never be overloaded and to have unlimited flux capacity. The other recently published steady-state settler model includes hindered and compressive settling, and models a realistic limiting flux capacity. Generally, the steady-state concentration profiles within the PFR and the settler are governed by nonlinear ordinary differential equations. It is shown that the steady-state behaviour of the ASP can, however, be captured by equations without derivatives. New theoretical results are given, such as conditions by means of inequalities on input variables and parameters for a steady-state solution to exist. Another novel finding is that, if the incoming substrate concentration is increased from a low or moderate stationary value and the solids residence time is kept fixed, then this results in a lower effluent concentration in the new steady state. The steady-state equations are solved numerically for different operating conditions. For common parameter values, numerical solutions reveal that an ASP having a PFR, instead of a continuously stirred tank reactor, is far more efficient in reducing the effluent substrate concentration and this can be obtained for much lower recycle ratios, which reduces the pumping energy considerably.

1. Introduction

1.1. Scope

Activated sludge processes (ASPs) in wastewater treatment consist, in its basic form, of one or several biological reactors where soluble substrates are decomposed by bacteria followed by a clarification-thickening process in the secondary clarifier, or settler, from which there is a recirculation to the biological reactors. The numerical optimization and design of ASPs using detailed state-of-the-art models with high complexity can be found in many works and such are reviewed recently by Hreiz et al. [1]. The mere formulation of optimization problems delivering reliable solutions is a task in itself.

At the same time, research has been conducted from the perspective of getting a fundamental understanding of the main features of the nonlinearities of the ASP by using reduced models, i.e. models with only few constituents. Steady-state modelling and analyses of ASPs have been undertaken during decades despite the fact that a wastewater treatment plant may never be in steady state. The reasons for carrying out a steady-state analysis include that it can provide: additional insight into the overall nonlinear behaviour compared to using a more complex simulation model; simple formulas that can be used for investigating dependencies on inputs and parameters; knowledge on how to formulate control strategies; simplified design rules; and feasible initial values for numerical optimization of a dynamic process model. The hope is to obtain few equations containing the main variables and parameters.

A difficulty when analyzing an ASP consisting of a plug-flow reactor (PFR) and settler is the following. Since the concentrations in both the PFR and settler depend both on time and space, the conservation of mass yields dynamic models in terms of partial

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differential equations (PDEs). Hence, steady-state equations are ordinary differential equations (ODEs) describing stationary concentration profiles within each unit. Such equations are unnecessarily complicated for investigating fundamental relationships between plant input variables, effluent concentrations and parameter dependencies. Then only the input and output concentrations of the PFR and settler are needed. We show how the ODEs can be replaced by equations without derivatives for easier investigations.

1.2. Related works

There are several works on the steady states of reduced models of ASPs consisting of a single continuously stirred tank reactor (CSTR) coupled to a settler; see our previous publication [2] and the references therein. Among recent new publications, we mention Alqahtani et al. [3], who use Contois growth kinetics for the CSTR and investigate the stability of steady-state solutions with respect to the residence time. Alharbi et al. [4] investigate the stability of steady-state solutions for an extended biological model with four particular components and one substrate.

Most of the previous publications on reduced models use the so-called ideal settler (also called point settler or perfect settler) [3–5], where the main purpose is not to detail the settler behaviour, but to understand the overall behaviour of the ASP caused by the recirculation. The concept of ideal settler means that one assumes that the settler never experiences any overload and thickens the sludge appropriately irrespective of the load to the plant. Hence, the flux through the thickening zone has no upper limitation.

It is well known that the flux capacity through the thickening zone is limited by the nonlinear settling-compression properties and the volumetric bulk flow [6–9]. Among analyses of ASP models taking the limiting flux into account we mention [10–14].

The purpose of our previous publication [2] was to introduce a new steady-state model, here denoted the DZC settler model, and analyze its coupling to a CSTR, in which the biological processes were allowed to be modelled by any of the common growth kinetics, such as Monod, Contois, Andrews/Haldane and Tessier. The DZC settler model consists of an algebraic equation, which was derived from steady-state solutions of the dynamic Bürger–Diehl settler model [15]. The latter model is a PDE including both hindered and compressive settling; see also Bürger et al. [16], De Clercq et al. [17]. With this dynamic model the three qualitatively different states of operation (normal, under- or overloaded) are possible and more realistic concentration profiles in the settler are obtained than with models without compression; see Bürger and Narváez [8], Bürger et al. [18], Torfs et al. [19]. The DZC steady-state settler model describes the normal or optimal operating conditions when there is a sludge blanket in the thickening zone and, consequently, no overflow. Although it has been known for 30 years that the solids flux theory (hindered settling only) has not been sufficient to explain the limiting flux [20], the usage of the additional limiting flux due to compressive settling is relatively new. It is noteworthy that of all 51 reviewed ASP models for operation and design by Hreiz et al. [1], none of them includes compression and many of them use the simple ideal settler model.

Several comparisons between PFRs and CSTRs have been reported, in particular with respect to their hydraulic performance; see Tsai and Chen [21], Liotta et al. [22] and references therein. It is also known that a PFR is more efficient than a CSTR both with respect to the substrate reduction and the required reactor volume [23–25]. While there are numerous of publications on stand-alone PFRs, analyses of ASPs with a PFR are rare. Sheintuch [26] analyzed an ASP with a PFR coupled to a settler, which has a limiting flux according to the solids flux theory (hindered settling). One substrate component and two particulate components, floc-forming and non-settling filamentous micro-organisms with different growth kinetics, were modelled with the outcome of design criteria which show that a PFR enlarges the domain where the floc-forming bacteria proliferate in comparison to a CSTR; however, to the expense of a larger volume. The case PFR plus ideal settler was analyzed by Ali San [27,28], who derived several relationships and graphical solution techniques for design. Muslu [29] replaced the PFR by a series of CSTRs and presented numerical investigations. The opposite approach has been a motivation for analyzing a PFR: it can be regarded as an approximation of several CSTRs in series, which is common in many plants [25,30–35].

1.3. Purpose and contents

The purpose of this work is to present equations without derivatives and some new results for a reduced model of an ASP having a PFR instead of a CSTR. In reality, a biological tank behaves neither like a CSTR or a PFR, but in some sense in between [21]. It is therefore of interest to have results of those two extreme ideal models of a biological reactor within an ASP. The analyses here are made when the PFR is coupled partly to an ideal settler, which we denote as model ASP1, and partly to the DZC settler, which we denote as model ASP2.

We use the most reduced model with only one particulate biomass that consumes one soluble substrate component according to the Monod growth kinetics. Such a simplified model can capture the dominating process of the plant. With such a model the question arises whether the biomass decay rate b [h^{-1}] should be set to zero or a positive value. It turns out that the case $b = 0$ gives much simpler equations and it is possible to obtain some theoretical results. We do this for both ASP1 and ASP2. Of course $b > 0$ holds in reality and we cover this case for the ASP2 model, which means that the results presented here can be compared with our previous results for a CSTR coupled to the DZC settler [2]. On the other hand, $b > 0$ in a model with only two biological components means that the decayed biomass is simply ignored. The part of the dead biomass that remains particulate will of course influence the sedimentation, a fact that we neglect in this first step of analyzing ASPs containing a PFR. A more accurate model would contain two particulate microorganisms: ordinary heterotrophic organisms and undegradable organics (inert matter). As the heterotrophic organisms die, some part may be converted to particulate undegradable organics and some to (readily biodegradable) substrate. A further extension is the so-called bisubstrate model; see [36]. The fact that we only model one type of substrate (readily biodegradable), means that the influent particulate matter is assumed to be quickly hydrolyzed to soluble substrate. If the model is used for a simplified nitrification process, this assumption is not an issue. Characterization of influent wastewater is a hot research topic; see e.g. [37]. Another simplification made in our and similar models is that the dissolved oxygen concentration is assumed to be sufficiently high to fulfil the respiration need of the microorganisms.

An important concept for the operation of ASPs is the solids residence time (SRT), or 'sludge age', which is a combination of process variables giving the average time the sludge has undergone aeration in the reactor. It is well known that in real plants the SRT cannot be too small for the ASP to work properly and the control of the SRT is therefore important for the operating conditions [38,32,39–41]. In the present work, we investigate how the steady-state solution changes under the operating condition that the SRT is kept constant.

The remainder of the paper is organized as follows. The basic assumptions on an idealized ASP are presented in Section 2 together with steady-state mass balances and the two settler models. In Section 3, the equations modelling the PFR in steady state are converted to equations without derivatives containing