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A simple model to describe the performance of highly-loaded aerobic COD removal reactors

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ABSTRACT

Highly-loaded aerobic chemical oxygen demand (COD) removal reactors (also known as A-stage) include two main processes, COD removal by heterotrophic biomass and adsorption of COD on the activated sludge. A simple model to describe highly-loaded aerobic COD removal reactors has been developed. A one-year-set of measured data from a full scale wastewater treatment plant has been used to calibrate the efficiency of the adsorption and to evaluate the ability of the mathematical model to describe the measured data in both steady state and dynamic conditions. The approach lumped the efficiency of the settler and the adsorption with a simple but powerful approach which includes the use of the measured sludge retention time (SRT) and the settling efficiency. The effects of dynamics in terms of (i) seasonality (for water temperature, flow rate and concentration of pollutants), and (ii) daily variations in flow rate were investigated. Results showed how during winter the low water temperatures negatively impacted the efficiency of the A-stage, producing a higher COD concentration in the effluent, which eventually could impact the performance of the nitrogen removal in the B-stage. General guidelines for the application of the model to similar highly loaded A-stage reactor systems were provided.

1. Introduction

Biological removal of organic material representing a given chemical oxygen demand (COD) by activated sludge is associated to the growth of heterotrophic bacteria. Heterotrophic bacteria take-up the (biodegradable) COD, a fraction is mineralized to CO_2 and water, another fraction can be stored as intracellular biopolymers for later use and the rest is used for biomass synthesis, increasing the amount of bacteria. In the 1970s a simple configuration emerged in Europe for the treatment of wastewaters with a high fraction of industrial effluents: the so-called Adsorption-Belebungsverfahren (AB process), a two-stage wastewater treatment plant (WWTP) [1–3]. This process features a very high food-to-microorganism (F/M) ratio in the first stage (Adsorption or A-stage) at a short hydraulic residence time (HRT, about 30 min), and a short sludge residence time (SRT, 3–12 h). The second stage (Belebungs or in English Biooxidation, B-stage) is an aeration stage with a low F/M ratio. The F/M ratio in the adsorption stage typically ranges from 2 to 10 g BOD/g VSS/day (where BOD stands for biological oxygen demand and VSS for volatile suspended solids) [4]. In the second stage, biological oxidation takes place at a much lower F/M ratio of less than 0.1 g BOD/g VSS/day [4]. The adsorption stage is operated at a low oxygen concentration (close to zero) [4]. The A-stage was considered to be of key importance against the effect of toxic shock loads for the nitrifying bacteria in the B-stage activated sludge process, while simultaneously being able to collect a high fraction of COD as sludge and use it for biomethanation [4].

The treatment configuration was developed and introduced in the 70-ies, but got in disuse in the past decades due to efforts to reduce total nitrogen in the treatment plants. Nowadays, there is still a fraction of the WWTP in operation in Europe that retained the AB process configuration. The A-stage achieves a high removal efficiency, typically removing 70–80% of total COD and 80–95% of suspended solids [5]. The production of biogas out of the excess sludge is enhanced because of the short SRT imposed; thus the digestion characteristics of the sludge improve considerably [6]. Due to this highly efficient energy production to energy consumption ratio, the A-stage has been identified as a convenient option for COD removal to be combined with the use of nitritation/anammox

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(anammox stands for anaerobic ammonia oxidation), for nitrogen removal, with the aim to achieve energy neutral or even energy producing WWTP [7–9].

The high performance obtained with the A-stage is due to a simultaneous conventional removal of COD by heterotrophic bacteria together with the adsorption of an important fraction of the COD, including particulate solids and colloidal particles. This COD adsorbed onto the sludge can be removed in the settler without having been metabolized by bacteria, allowing for short HRT and SRT. This adsorption, also named biosorption, is a process taking place in a short period of time, in the order of minutes [10,11]. The efficiency of adsorption is known to be linked to complex process that drive the sludge characteristics, like type and fraction of extracellular polymeric substances (EPS), presence of storage compounds and even dissolved oxygen (DO) levels in the reactor [10–12]. In fact, the DO concentration was identified as a key operating condition, since it negatively affected the adsorption due to poor aeration intensity [10,12].

Because the A-stage has been considered as an old process, researchers paid little attention to the modelling of this process. Haider et al. [13] presented general guidelines for the selection of kinetic parameters for heterotrophs in AB processes (mainly a higher maximum specific growth rate and lower half-saturation coefficient for COD compared to those in conventional activated sludge models). Moreover they proposed a particular fractionation of the soluble COD, to allow for a none complete conversion of soluble COD in the A-stage due to the use of a higher specific growth. Their modelling approach focused on describing the removal of soluble COD but not on how to model the fraction of COD adsorbed in the A-stage. A detailed model was presented by Nogaj et al. [14]. In that model, getting insight in the process was the main driving force during model development. The strategy yielded a rather complex mathematical model, in which new state variables were added to the generally accepted activated sludge model No. 1 (ASM1 [15]) stoichiometry matrix, including concentrations of colloidal biodegradable organics, colloidal non-biodegradable organics from the influent, extracellular polymeric substances (EPS) and particulate storage compounds. The model would require a set of measurements that are usually not available in the regular operation of WWTP. To date, there is no simple model available to describe the main processes in a highly loaded aerobic COD removal reactor. Such a model would aid in the current research and development effort devoted to improve the efficiency of A-stage systems [12,16–20]. The core of the energy production and therefore the success of an energy neutral WWTP lies on the efficiency of the A-stage [9]. Even more, the performance of the subsequent nitritation/anammox stage might depend on the capacity of A-stage to remove COD and solids efficiently [21,22].

In the WWTP of Dokhaven (Rotterdam, The Netherlands) an AB process is operational since 1987 [23]. The use of anammox for nitrogen removal in the mainstream is under consideration [24]. Therefore, a model able to describe the performance of the current A-stage can be used as a tool for the simulation of the future scenario in which the A-stage is followed by nitritation/anammox for nitrogen removal. In addition, this model may help practitioners to better understand and apply this technology.

Here, we developed a simple mathematical model, based on the use of the habitual measurements in a WWTP and ASM1. The goal was the mathematical description of the COD removal in a highly-loaded aerobic COD removal reactor with a minimal complexity. The model predictions at steady state and under dynamic conditions are compared to a measured data set covering a period of one year. The model provides a simple description of the performance and presents general guidelines that could be followed to model other similar highly loaded A-stage reactor systems.

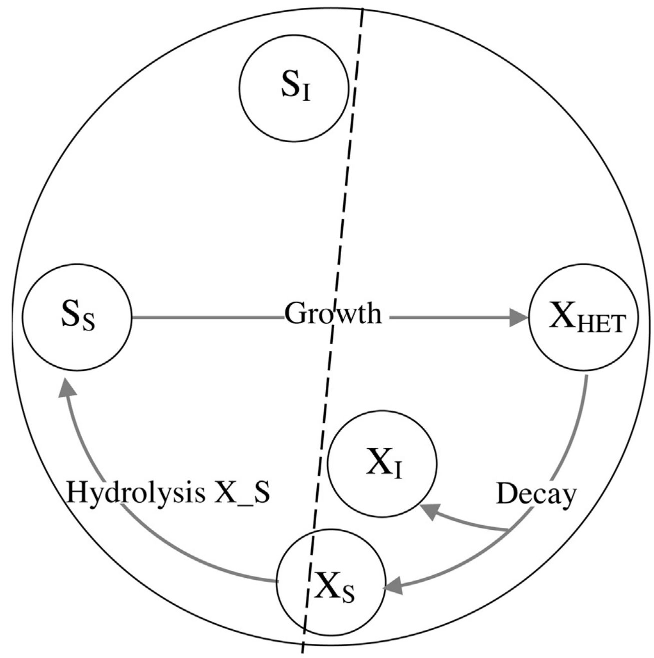

Fig. 1. Different state variables used in the model of the A-stage for organic compounds and their conversions. The dashed line separates the soluble and particulate COD in the figure. Since slowly biodegradable organics (X_S) are potentially partly soluble, the line crosses there. Particulates included: Heterotrophic bacteria (X_{HET}), inert non-biodegradable organics (X_I), and a fraction of X_S. Soluble organic compounds included: biodegradable organics (S_S), a fraction of X_S, and soluble inert non-biodegradable organics (S_I).

2. Model description

2.1. State variables, and general modelling approach

The model is based on ASM1 [15] but nitrite concentration was considered as an additional state variable as it will be further detailed in the Section 2.4. Kinetics and stoichiometry. The different state variables used to describe the different organic compounds concentrations were the following: biodegradable organics (S_S), soluble inert non-biodegradable organics (S_I), slowly biodegradable organics (X_S) and particulate inert non-biodegradable organics (X_I). Heterotrophic bacteria (X_{HET}) were considered the main bacterial population. A more extensive distribution of the biodegradable organics, as well as different variables for storage polymers (like in ASM2 [15]; or like used in Nogaj et al. [14]) were considered unnecessary for the purpose of this model. A schematic overview of the model showing the main processes under consideration can be found in Fig. 1. The S_S was used as substrate for heterotrophic growth. Since the slowly biodegradable organics (X_S) can be soluble or particulate [15], a 40% soluble and 60% particulate was assumed (see Section 2.5 for details). A large fraction of the X_S (independently if they are soluble or particulate) and X_I would be adsorbed in the A-stage, for details regarding the modelling approach to adsorption see below Section 2.2). Furthermore X_S can be hydrolysed to S_S [15]. The decay of X_{HET} produces X_S and X_I. Colloidal COD has not been included as a separate variable, to avoid unnecessary complexity. Also storage COD and a difference between faster or slower biodegradable soluble COD were not used in this model. It was assumed that a fixed percentage of X_S is adsorbed in the A-stage and later separated in the settler. Therefore the exact composition of the particulate COD was less important.

For simplicity it was assumed that there would be no biological activity or buffering capacity in the settler. This is in line with operation of the settlers in Dokhaven WWTP where only very