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Modified ADM1 for modelling an UASB reactor laboratory plant treating starch wastewater and synthetic substrate load tests

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ABSTRACT

A laboratory plant consisting of two UASB reactors was used for the treatment of industrial wastewater from the wheat starch industry. Several load tests were carried out with starch wastewater and the synthetic substrates glucose, acetate, cellulose, butyrate and propionate to observe the impact of changing loads on gas yield and effluent quality. The measurement data sets were used for calibration and validation of the Anaerobic Digestion Model No. 1 (ADM1). For a precise simulation of the detected glucose degradation during load tests with starch wastewater and glucose, it was necessary to incorporate the complete lactic acid fermentation into the ADM1, which contains the formation and degradation of lactate and a non-competitive inhibition function. The modelling results of both reactors based on the modified ADM1 confirm an accurate calculation of the produced gas and the effluent concentrations. Especially, the modelled lactate effluent concentrations for the load cases are similar to the measurements and justified by literature.

1. Introduction

Anaerobic digestion processes are state of the art for the treatment of industrial wastewaters and UASB reactors are commonly used in case of mainly soluble wastewaters (Lettinga and Hulshoff Pol, 1991). However, these plants do often not operate at their optimal levels as the anaerobic processes are rather sensitive in regard to variations of boundary conditions like pH, temperature, nutrients, loading rates (Austermann-Haun et al., 1999) and flow conditions (Vavilin et al., 2007). Thus, different load tests were carried out with two UASB reactors in this study to observe their impact on the gas yield and the effluent concentrations.

In addition to the operation of laboratory reactors, the development and use of reliable models is reasonable to avoid disadvantageous boundary conditions in anaerobic reactors. Such models can also be used for process optimization, in order to improve the process understanding and to evaluate different control strategies. With the aim of providing a common modelling platform, the Anaerobic Digestion Model No. 1 (ADM1) (Batstone et al., 2002) was developed considering the main relevant processes and at first it was focusing on anaerobic sludge digestion. Therefore, in most of the

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publications in recent years, ADM1 is applied for the simulation of sludge digesters (Blumensaat and Keller, 2005; Parker, 2005; Shang et al., 2005; Batstone et al., 2009) and for modelling the anaerobic solid degradation of energy crops and organic wastes (Lübken et al., 2007; Schön, 2010; Esposito et al., 2011; Zhou et al., 2011). However, some important process steps have to be included to use the ADM1 for the simulation of anaerobic industrial wastewater treatment plants: For instance, Batstone et al. (2004) and Ramsay and Pullammanappallil (2005) included the degradation of ethanol to ADM1 in order to simulate the treatment of winery and brewery wastewater. Fezzani and Cheikh (2009) extended the ADM1 to simulate the processes of phenol compounds and homologues in olive mill wastewater. Moreover, Taruyanon and Tejasen (2010) implemented a model of the sulphate reduction process for the simulation of a laboratory plant treating distillery wastewater.

Furthermore, lactate accumulation in the effluent was found for easily degradable wastewaters with high sugar concentration by Romli et al. (1995) and for impact loads (Costello et al., 1991). Thus, the ADM1 must be modified to consider lactate as a by-product of sugar degradation for the simulation of glucose and starch wastewater load tests. At first, Costello et al. (1991) and Batstone et al. (2000) described the lactic acid fermentation processes and the rate equations in anaerobic models generally. In addition, a bioreaction network that describes the typical pathways for the degradation of glucose and also the formation of lactate was proposed by Rodriguez et al. (2005). However, the prediction of the lactate formation by pyruvate uptake was not possible at the current stage of the developed model even though it was observed in experiments. Then, Peiris et al. (2006) included the intermediates lactate and ethanol into an extended ADM1 for simulating bio-hydrogen production and compared batch experiment results of pH, biomass yield and hydrogen production with their modelling output. Additionally, Penumathsa et al. (2008) modified the ADM1 by implementing dynamic glucose degradation depending on the total concentration of undissociated acids and they also considered lactate production. However, the lactate yield was only calculated and not verified by experimental data. Moreover, Soda et al. (2011) included lactate and ethanol into the ADM1 and compared their simulation results with data from experiments over 370 days using organic waste with total solid concentration to 8–10%. Thamsiriroj et al. (2012) assessed lactic acid to their modified ADM1 for modelling the mono-digestion of grass silage. Thus, the anaerobic degradation via lactate had been implemented to the ADM1 in several studies focusing on batch experiments or solid substrates.

Whereas, the focus on this study was to operate two laboratory UASB reactors treating wastewater from starch industry as substrate that has a total suspended solid (TSS) concentration of less than 5 g/L. The principal aim of this work was to simulate both reactors that are continuously operated for 212 days in the steady-state operation period with constant loading rates and exposed to load tests with starch wastewater and synthetic substrates (glucose, acetate, cellulose, butyrate and propionate). The main objective of the load tests was to observe their impact on gas yield and effluent quality and to describe the reactor performances sufficiently. For the simulation of all processes and especially of the detectable lactate concentrations in the reactor effluent during the load tests with glucose and with starch wastewater the lactic acid fermentation had to be included into the ADM1. In conclusion, the motivation for this work was the development of a new modified model that is able to simulate UASB reactor plants treating glucose or carbohydrate rich wastewater, to predict the effects of load tests accurately and to be used for the optimization of anaerobic processes.

2. Material and methods

2.1. *UASB reactor laboratory plant set up and operation*

The laboratory plant consisted of two identical double walled UASB reactors and each had a reactor volume of 12.5 L and a height of 1.5 m. The influent was pumped by peristaltic pumps from the storage tank into each reactor (influent volume flow: 0.06–0.15 L/h). Two recirculation pumps (flow: 8.5 L/h) were used for mixing and for setting up the upflow velocity to about 1.1 m/h. In the upper part of the reactor, the three-phase separator split the gas-, water- and solid-phase and retained the biomass in the reactor. Biomass of an EGSB (expanded granular sludge bed) reactor, which was operated at mesophilic conditions (about 32 °C) for treating distillery wastewater, was used as inoculum. The TSS and volatile suspended solids (VSS) concentration of the inoculum was about 30 g/L and 25 g/L respectively.

Reactor temperature was set to mesophilic conditions (around 33 °C on average). Besides reactor start-up period, which took three times the hydraulic retention time (HRT) until the biomass was adapted to the new environment (Koch et al., 2010), no acids or bases were added to the influent. During plant operation, the pH in both reactors was about 6.6.

The reactors were continuously operated for 212 d. For Reactor 1, the HRT and the volumetric loading rate (VLR) were set to 8.3 d and 1.5 kg COD/(m^3·d) respectively (steady-state operation). Reactor 2 was operated at double load nearly (HRT = 4.8 d, VLR = 2.6 kg COD/(m^3·d)).

Different load tests were carried out with both reactors. In these tests, the influent flow was increased to 3.6 L/h for 30 min. These rates were around 24 and 60 times higher than the influent rates during the steady-state plant operation for Reactors 2 and 1 respectively. Additionally, the substrate in the influent was changed for most load tests and all tests were characterised in Table 1. The COD in the load test influent was adjusted to the COD in the influent during steady-state conditions (12 kg COD/m^3 on average). The period between two load tests comprised always more than 2 d, in order to achieve stationary conditions and thus obtain comparable results.

2.2. *Measuring methods*

During steady-state plant operation, influent and effluent samples were taken and analysed three times a week. Additionally, one influent sample and five effluent samples were taken 1 h, 3.5 h, 6 h, 8.5 h and 23.5 h after the end of each load test.