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Modelling the energy balance of an anaerobic digester fed with cattle manure and renewable energy crops

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ABSTRACT

Knowledge of the net energy production of anaerobic fermenters is important for reliable modelling of the efficiency of anaerobic digestion processes. By using the Anaerobic Digestion Model No. 1 (ADM1) the simulation of biogas production and composition is possible. This paper shows the application and modification of ADM1 to simulate energy production of the digestion of cattle manure and renewable energy crops. The paper additionally presents an energy balance model, which enables the dynamic calculation of the net energy production. The model was applied to a pilot-scale biogas reactor. It was found in a simulation study that a continuous feeding and splitting of the reactor feed into smaller heaps do not generally have a positive effect on the net energy yield. The simulation study showed that the ratio of co-substrate to liquid manure in the inflow determines the net energy production when the inflow load is split into smaller heaps. Mathematical equations are presented to calculate the increase of biogas and methane yield for the digestion of liquid manure and lipids for different feeding intervals. Calculations of different kinds of energy losses for the pilot-scale digester showed high dynamic variations, demonstrating the significance of using a dynamic energy balance model.

1. Introduction

Over the last few years, mathematical modelling has become very popular as a supporting tool for the design, operation and control of activated sludge systems. Particularly, the publication of the Activated Sludge Model (ASM) series can be accounted for this development (Henze et al., 2000). As it is supposed that there will be an increased application of the anaerobic treatment technology in the future, the demand for a qualified model will increase in the same way. The development of anaerobic digestion models was affected, similar to the development of the ASMs, by the progressive identification of the underlying biological conversion processes. To date, many existing anaerobic digestion models have been developed for specific applications or fermenters fed with a very specific substrate. Batstone (2000) used the information of the research work carried out before and developed a model for complex wastewaters and produced a broad set of parameters for different substrates. To extend the use of mathematical models in anaerobic digestion, it is necessary to have a model that is applicable for both different reactor types and various substrates.

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The International Water Association (IWA) task group for mathematical modelling of anaerobic digestion processes was formed in 1997 to develop a generally applicable model, the Anaerobic Digestion Model No. 1 (ADM1, Batstone et al., 2002). ADM1 is a structured model with disintegration and hydrolysis, acidogenesis, acetogenesis and methanogenesis steps. ADM1 is expected to stimulate model application for full-scale plant design, operation and optimization or generally to support an increased application of anaerobic technology in the future.

As anaerobic digestion (AD) is a complex process carried out by a consortium of highly different microorganisms (Gujer and Zehnder, 1983), a mathematical model able to describe the main single pathways and to predict biogas production will be inevitably complex. At a low degree of model complexity only the two main steps of AD, acidogenesis and methanogenesis, will be considered. Disintegration and hydrolysis steps, main process pathways of carbohydrates, proteins and lipids conversion and different forms of inhibition must be considered for a higher degree of model complexity. This is achieved by the IWA ADM1 model, though the model still has some simplifications.

Hydrogen produced by Volatile fatty acid (VFA) degradation can be transferred to sulphate reducing, homoacetogenic or methanogenic bacteria, depending on the availability of such bacteria and their respective electron acceptors (Schink, 1997). This example clarifies that the process pathways implemented in ADM1 are a simplification of reality. Kleerebezem and van Loosdrecht (2006) criticized that ADM1 contains no restrictions for thermodynamic boundaries encountered in methanogenic environments. Hoh and Cord Ruwisch (1996) e.g., proposed a model to describe hydrogen inhibition of acetogenesis by including thermodynamic limits. However, the results of Batstone et al. (2006) using ADM1 simulation at a microbial resolution, implemented in a multidimensional domain, suggest that thermodynamic inhibition compared with non-competitive inhibition only has an impact at smaller substrate field grid sizes.

AD produces products such as renewable energy, as well as a fertilizer rich in nutrients and organic soil conditioners. In Germany, about 4000 plants are currently operated for biogas generation out of agricultural substrates. New potentials for agricultural biogas technology can be expected due to the amendment of the statute for renewable energies 2004 (Erneuerbare Energien Gesetz; EEG). Usage of renewable energy sources like cultivated crops will certainly increase agricultural biogas plants in Germany. Liquid manure from livestock husbandry is used as a base substrate in most of the plants to produce a wet, pumpable mixture since dry fermentation concepts are still in testing. As the need for alternative sources of energy continues to rise, the role of AD in the treatment of organics from agricultural waste will be further increased. If a mathematical model is used to investigate an agricultural biogas reactor, the model has to be particularly able to predict the net energy yield of the plant, considering high variation of input material and its chemical, and physical characteristics as well as biodegradability.

ADM1 can be used to simulate the biogas production and thus the energy yield of fermenters digesting different kinds of substrates. However, one part of the energy produced is consumed by the digester itself. The process energy is needed to heat the fed substrate and to compensate for the irradiation loss of the digester. Stirrers together with pumps are additional energy consumers. Therefore, a dynamic energy balance model was derived in this study to allow the dynamic calculation of the net energy production of anaerobic bioreactors.

The importance of knowing the actual energy within anaerobic systems has recently been described by Lindorfer et al. (2005). In some cases, the authors reported that using energy crops in monofermentation can lead to a self-heating of the digester. Several full-scale biogas plants were cooled down in order to avoid instabilities. The authors also showed that self-heating can be explained by the microbial activity of anaerobic microorganisms. We therefore used the derived energy balance model to evaluate the self-heating potential of anaerobic reactors.

2. Material and methods

2.1. Analytical methods

Analytical methods for total solids (TS), volatile solids (VS), chemical oxygen demand (COD) and ammonia nitrogen (NH_4-N) were based on German Standard Methods for the examination of water, wastewater and sludge. VFAs were measured using an AGILENT 6890N gas chromatograph. Column: HP FFAP, 25 m, 0.32 mm. The temperature programme was as follows: initial temperature 80 °C (holding time: 1 min), 120 °C in 20 °C min^{-1} (holding time: 3 min), 220 °C in 6.13 °C min^{-1} (holding time: 20.13 min).

Determination methods according to van Soest and Wine (1967) and Weender (described in Naumann and Bassler, 1993) were performed to characterize the substrate in terms of carbohydrates, proteins and fats. The methods applied resulted in a fractionation of the organic matter between crude protein, crude fat, crude fibre and N-free extract (Weender analysis). Carbohydrates were further divided into hemicellulose (neutral detergent fibre (NDF)–acid detergent fibre (ADF)), cellulose (ADF–acid detergent lignin (ADL)) and lignin (ADL), approximately analysed by the so-called van Soest-fractions NDF, ADF and ADL.

Total biogas production was measured by the RITTER drum chamber gas meter TG5/5. Values for biogas production were normalized. Methane and carbon dioxide were quantified by means of the infrared two-beam compensation method with pressure compensation (measuring error as specified: $\pm$2%). Oxygen and hydrogen were measured by electrochemical sensors (measuring error as specified: $\pm$3%).

Experimental data were available for a period of 180 days. Biogas production, distribution of the major biogas compounds (CH_4, CO_2 and H_2), temperature and pH values were measured continuously over the whole period. TS, VS, COD and NH_4-N were measured semi-continuously for both influent and effluent. Data for VFA production (acetate, propionate, butyrate and valerate) were available for the first 65 days of the entire period.