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Influence of different substrates on the performance of a two-stage high pressure anaerobic digestion system

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HIGHLIGHTS

- Two-stage high-pressure digestion is a novel approach for the production of biogas.
- Digestion under elevated pressure leads to decreasing pH-values in the digestate.
- Influence of the nitrogen content on the performance of the system has been tested.
- Higher NH_4 contents led to higher methane concentrations of the produced gas.

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ABSTRACT

The two-stage autogenerative high-pressure digestion technique is a novel and promising approach for the production of gaseous fuels or upgraded biogas. This new technique is described in the patent DE 10 2011 015415 A1 and integrates biogas production, its upgrading and pressure boosting in one process. Anaerobic digestion under elevated pressure conditions leads to decreasing pH-values in the digestate due to the augmented formation of carboxylic acid. Model calculations carried out to evaluate the two-stage design showed that the pH-value in the pressurized anaerobic filter has a major influence on the methane content of the biogas produced. Within this study, the influence of the nitrogen content as one of the most important buffering substances on the performance of the system has been tested. The results show that higher NH_4 contents lead to higher pH-values in the digester and as a consequence to higher methane contents.

1. Introduction

Removal of CO_2 from biogas allows instead of direct, local conversion into electrical energy and heat, the injection of the produced biogenic gases in natural gas grids, thus enabling a spatial and temporal separation of the gas production and utilization. By that the overall efficiency of biogas production and utilization can be increased. So far, this technology is only being applied in about 1.5% of the installed biogas systems in Germany, since the treatment is relatively complex and const intensive (DENA, 2013).

The anaerobic conversion of biomass into biogas is a complex sequence composed of four major microbial steps (hydrolysis, acidogenesis, acetogenesis and methanogenesis) (Khanal, 2008). In terms of nutrient requirements, physiology, nutrient uptake and required environmental conditions (pH-value, etc.) acidogenic microorganisms differ substantially from the methanogenic ones (Pohland and Ghosh, 1971). Therefore, Pohland and Ghosh (1971) suggested dividing the process into two reactors to provide optimal environmental conditions for each group of microorganisms. In the first reactor the formation of volatile fatty acids takes place, whereas in the second step methanogenic microorganisms convert these volatile fatty acids into methane and carbon dioxide (Anderson et al., 1994; Ueno et al., 2007). Cohen et al. (1980) as well as Fox and Pohland (1994) found that this leads to an increase in process stability. According to some literature sources, the specific bioenergy production in two-phase systems during the digestion of organic waste and household waste was up to 24% higher than in single-phase systems (Schievano et al., 2012; Luo et al., 2011; Liu et al., 2006; Cohen et al., 1980).

Zielonka et al. (2010) as well as Schönberg and Linke (2012) described two-stage digestion systems for energy crops based on anaerobic leach-bed reactors combined with anaerobic filters. They found that the two-stage and two-phase digestion of energy crops led to an exhibited stable digestion behavior. But high degradation

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rates were only achieved when the hydrolysis reactor was operated in a thermophilic range. Fei-Baffoe and Busch (2010) suggested using such a system consisting of a leach-bed reactor and an anaerobic filter for the treatment of unsorted municipal solid waste.

Up to now, biogas production by anaerobic digestion, its upgrading to the quality of natural gas and the necessary pressure boosting for the injection into national gas grids are three separate procedures, which are connected in series. In 2011 Lindeboom et al. described a new digestion technique integrating these three different steps in one process: the autogenerative high pressure digestion (AHPD). While conventional one or two-stage biogas reactors are run under atmospheric pressure the novel technique was based on reactors with a working pressure of up to 90 bars. In these reactors the pressure increase was only based on the biogas production by the microorganisms. Since CO_2 has a higher solubility in water or liquids with similar physical properties than CH_4, proportionally more CO_2 is dissolved in the liquid. Therefore, AHPD biogas is characterized by a high CH_4 content, reaching equilibrium values above 90% at pressures up to 90 bar (Lindeboom et al., (2011)), whereas biogas produced under atmospheric pressure has a much lower calorific value. The results were based on experiments with 8 L closed fed-batch digesters fed with acetate as substrate. Lindeboom et al., (2011) concluded that the proposed AHPD process is a highly promising technology for the production of so called "green gas" in one step.

A process with a similar approach is currently being developed by the University of Hohenheim (Stuttgart) and DVGW Research Institute (Karlsruhe). In contrast to the AHPD technology this novel method is based on the continuous two-stage process with an anaerobic filter run under elevated pressure.

This process has already been described by Chen et al. (2014a). They examined the effects of different fermentation pressures in the methane reactor on the biological process parameters as well as on the quality of the produced gas. Running the anaerobic filter at 8.91 bar the pH-value dropped to 6.5 as a result of the increased formation of hydrogen carbonate. With the pressure increasing the methane content raised up to 75% thus being much lower than the methane content of the biogas described by Lindeboom et al. (2011). Further researches of Chen et al. (2014a,b) showed that these systems can be run up to $OLR_{(COD)}$ of 17.5 kg m^3 d^{-1} achieving the best performance at 12.5 kg m^3 d^{-1}. Hence, $OLR_{(COD)}$ achieved were comparable to upflow anaerobic filters run under atmospheric conditions (5–15 kg according to Khanal (2008)). However, at a working pressure of 9 bar the reactor performance seemed to be limited by the low pH-value (approximately 6.5) induced by the high CO_2 partial pressure. Based on the trials of Chen et al. (2014a,b) a mathematic model for indentifying the optimization potential in pressurized anaerobic filters was developed by Wonneberger et al. (2014). According to these simulation calculations it became obvious that the pH-value in the methane reactor had the strongest impact on the methane content of the produced gas. An increase of the pH-value in the methane reactor will lead to a significantly higher absorption of carbon dioxide in the liquid phase and a lower desorption of this gas into the gaseous phase. Therefore, Wonneberger et al. (2014) suggested controlling the pH-value in the pressurized anaerobic filter by adding buffering substances.

Based on the literature reports two-stage high pressure digestion seems to be an interesting new technique for the production of high calorific biogas. Nevertheless, up to now the methane content of the produced gas is quite low compared to the gas gained with the AHPD technique. Modeling calculations showed that the pH-value in the methane reactor has an important impact on the quality of the produced gas. Therefore, the aim of this study was to test the influence of the ammonium buffer capacity on the performance of the two-stage high pressure digestion system. Higher crude protein contents of the initial substrates should lead to a higher buffer capacity of the leachate and thereby to higher pH-values in the pressurized methane reactor resulting subsequently in higher methane contents of the produced biogas.

2. Methods

2.1. Set up of experimental unit

The fundamental set up of the two-stage high pressure fermentation unit has been described by Wonneberger et al. (2014) and Chen et al. (2014a). The first stage is an anaerobic leach-bed hydrolysis/acidogenesis in which the fed silage is degraded and mainly converted into organic acids and alcohols. It consists of six parallel-operated, 50 L leach-bed reactors run in a batch mode at atmospheric pressure. Every week, two of these digesters were opened, unloaded and re-filled with the silage. Also 10 L of tap water were added. Micro nutrients were added according to the recommendations of Vintiloiu et al. (2013) to avoid biological process disturbances due to an undersupply. An internal circulation of the liquid was used to volatize and leach out the produced organic acids from the silage. By that, a liquid rich in organic acids and alcohols is formed. The aim of the chosen set up was to provide a leachate with a constant and reproducible composition over the entire experimental series. At the same time this induced a minor degradation of the added silages which had been taken to be a necessary consequence of providing ceteris paribus conditions for the high pressure methane reactors the study is focusing on.

Twice a week, around 40 L of liquid from the leach-bed reactors were pumped into a storage tank (B2G1T-1 in Fig. 1). Every 6 h, a certain amount of the leachate was pumped from this tank into the high-pressure methane reactors where the organic fractions were converted into biogas. The feeding amount was only dependent on the influent COD concentration and hence, the organic loading rate of the methane reactor remained unchanged. For keeping the working volume constant the same amount of liquid was eluted from the methane reactor and either removed from the process or re-circulated into the leach-bed reactors.

The two high pressure methane reactors of the laboratory system were designed as upflow anaerobic filters. Both reactors were constructed identically, except slight differences in the process water management. For instance, one of the methane reactors (B2G1-MR-1) has a separate circulation pump, while the circulation in the second methane reactor (B2G2-MR-1) is realized by the substrate pump (B2G2 P-4). Despite these differences the flow rate in the fixed bed was identical in both reactors. The fixed bed consisted of randomly packed sintered glass fillers (Sera Siporax), which have an effective settlement area of 270 m^2 L^{-1} and a porosity of 70%. Thus the active biomass was enriched in the reactor as a biofilm on the surface of the packings.

The aim of the high-pressure fermentation system is to reach an autogenerative increase of the reactor's working pressure. In order to control the pressure of the reactor the produced biogas did not immediately leave the methane reactor, but accumulated therein, until the desired pressure in the methane reactor was reached. At that point, the automatic control opened the valve of the gas outlet and the produced biogas was injected into a gas bag. As soon as the gas was released and the pressure of the methane reactor started to drop slightly the gas outlet was closed again, allowing the autogenerated biogas pressure to increase up to the desired value again. This system was controlled automatically with very short opening periods so that the release of the gas led only to slight changes in the aimed working pressure.