Applied Energy 116 (2014) 409–415

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

The pressure effects on two-phase anaerobic digestion

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HIGHLIGHTS

- The pressure effect on anaerobic digestion up to 9 bar was examined.
- Increasing pressure decreased pH value in the anaerobic filter.
- Increasing pressure increased methane content.
- Increasing pressure decreased specific methane yield slightly.
- The pressurized methane reactor was very stable and performed well.

ARTICLE INFO

Article history:
Received 26 February 2013
Received in revised form 2 September 2013
Accepted 3 November 2013
Available online 27 November 2013

Keywords:
Anaerobic digestion
Pressure
Two-phase
Substitute natural gas
Biogas
Biomethane

ABSTRACT

Two-phase pressurized anaerobic digestion is a novel process aimed at facilitating injection of the produced biogas into the natural gas grid by integrating the fermentative biogas production and upgrading it to substitute natural gas. In order to understand the mechanisms, knowledge of pressure effects on anaerobic digestion is required. To examine the effects of pressure on the anaerobic digestion process, a two-phase anaerobic digestion system was built up in laboratory scale, including three acidogenesis-leach-bed-reactors and one pressure-resistant anaerobic filter. Four different pressure levels (the absolute pressure of 1 bar, 3 bar, 6 bar and 9 bar) were applied to the methane reactor in sequence, with the organic loading rate maintained at approximately 5.1 kgCOD m^{-3} d^{-1}. Gas production, gas quality, pH value, volatile fatty acids, alcohol, ammonium-nitrogen, chemical oxygen demand (COD) and alkaline buffer capacity were analyzed. No additional caustic chemicals were added for pH adjustment throughout the experiment. With the pressure increasing from 1.07 bar to 8.91 bar, the pH value decreased from 7.2 to 6.5, the methane content increased from 66% to 75%, and the specific methane yield was slightly reduced from 0.33 l_N g^{-1}COD to 0.31 l_N g^{-1}COD. There was almost no acid-accumulation during the entire experiment. The average COD-degradation grade was always more than 93%, and the average alkaline buffering capacity (VFA/TIC ratio) did not exceed 0.2 at any pressure level. The anaerobic filter showed a very stable performance, regardless of the pressure variation.

1. Introduction

Anaerobic digestion is a biological process, in which organic wastes and energy crops can be degraded and converted into biogas, mainly containing CH_4 and CO_2 [1]. The most common practice in Germany is to transfer biogas into a local combined heat and power plant for electricity and heat production. However, with the exception of digester thermal control and heating purposes at the biogas plant, a great amount of cogenerated heat is dissipated into the air and wasted. Alternatively, biogas can be injected into the gas grid as substitute natural gas after desulfurization, CO_2-removal, drying and pressurization [2]. Since it temporally and spatially separates biogas production from utilization, the overall energy utilization efficiency is largely increased. In addition, the existing gas distribution and storage infrastructure can be used without modification. Therefore, this application has received increased attention in recent years [3]. Nevertheless, biogas purification and upgrading is usually energy demanding [4]. Two-phase pressurized anaerobic digestion is a possible solution. It is intended to directly remove CO_2 and H_2S in the digester, making use of their high gas solubility under pressure. Thus, biogas production, purification and pressurization are integrated in one system, and the expenses involved in the subsequent treatment can be considerably reduced.

Abbreviations: COD, chemical oxygen demand; ODM, organic dry matter; SBP, specific biogas production; SMY, specific methane yield; TAN, total ammonia nitrogen; TIC, total inorganic carbon; VFA, volatile fatty acid.

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http://dx.doi.org/10.1016/j.apenergy.2013.11.012

To better understand pressurized anaerobic digestion, it is essential to first gain knowledge of how pressure affects the process. Although various operational parameters (e.g. temperature, pH, hydraulic retention time, organic loading rate and mixing mode) have been thoroughly studied and reviewed [5–8], there have been few discussions on the effect of pressure. The pressure variable is not given enough recognition in anaerobic digestion, mainly due to the limitations in the available techniques and facilities suitable for experimental investigation on pressure effects [9]. In addition, pressure change induces complicated interactions among operational conditions and microorganism activity in a reactor. For the sake of easy management, the total gas pressure in a common anaerobic digester is maintained slightly above atmospheric pressure (up to 0.02 bar overpressure) [10]. Compared to other operational parameters, pressure is a constant, rather than a variable, in actual application. In order to improve anaerobic digestion performance, efforts are primarily focused on the optimization of more adjustable and controllable parameters, and as a result, the investigation of pressure effects on anaerobic digestion has been overlooked.

As a matter of fact, anaerobic digestion for methane production under pressure is not rare in natural ecosystems or in the wastewater treatment industry. It is common in marine sediments, hundreds of meters deep [11], in landfills [12] and at the lower part of anaerobic digestion towers or biogas tower reactors [13] that are used in wastewater treatment to save ground space. Based on the pressure adaptability, microorganisms can be divided into three categories: piezosensitive, piezotolerant and piezophilic microbes. Piezosensitive microbes have optimal growth at atmospheric pressure and stop reproduction around 500 bar [14]. Both piezotolerant and piezophilic microbes are bacteria that are able to grow and proliferate up to a pressure of 1000 bar [15]. The optimal growth rate of piezotolerant microorganisms, however, occurs at atmospheric pressure [16]. Since most microbes in anaerobic digesters are inoculated from sewage slurry, excrement or wastewater treatment sludge under atmospheric pressure, they are normally not piezophilic. That means, their growth rates are hardly inhibited by pressure up to 10 bar, according to the research summary of Abe and Horikoshi and Abe [16]. This offered a theoretical basis for the experiment of anaerobic digestion under pressure.

This study examined the effects of pressure on anaerobic digestion by testing four different pressures (the absolute pressure of 1 bar, 3 bar, 6 bar and 9 bar) in a two-phase anaerobic digestion system. Gas production, gas quality, pH value, volatile fatty acids (VFAs), chemical oxygen demand (COD) degradation grade, buffer capacity and ammonium were analyzed and compared.

2. Materials and methods

2.1. Reactors

The flow diagram of the two-phase anaerobic digestion system is shown in Fig. 1. The hydrolysis-acidification was performed in three parallel-operated acidogenesis-leach-bed-reactors at 55 °C. Each reactor had 50-liter volume, and was alternately fed with 10 kg (fresh mass) maize silage from the Field-test station of the University Hohenheim (Unterer Lindenhof, Eningen, Germany) at a time interval of seven days. In order to avoid the deficiency of the nutrients necessary for microbial growth and biological process disturbances, micronutrients were also added once a week. The dosage and the composition of the micronutrients was based on the recommendation of Vintiloiu et al. [17]. The maize silage was loosely stacked on a perforated grate. In the acidogenesis-leach-bed-reactors, the substrate was gradually decomposed and a leachate rich in organic acids, as well as alcohols was produced. Every week, approximately 20 l of leachate from each acidogenesis-leach-bed-reactor was introduced into a tank (Tank 1 in Fig. 1) for storage and homogenization. Every six hours, a certain amount of the leachate was pumped from the tank into an anaerobic filter, which was operated under pressure for further degradation. The feeding amount was only dependent on the influent COD concentration, since the organic loading rate of the methane reactor remained unchanged. For the stable working volume, the same amount of liquid was eluted from the methane reactor to the other tank (Tank 2 in Fig. 1) for storage under atmospheric pressure. Due to the pressure difference, the dissolved CO_2 could be released, and the liquid in Tank 2 was distributed evenly to the three acidogenesis-leach-bed-reactors once a week. A liquid level sensor (Endress + Hauser, Liquicap T FMI21) constantly controlled the working volume of the anaerobic filter.

The upflow-operated anaerobic filter was running at 37 °C. The reactor was composed of a fixed bed, a three-phase separator and a gas chamber at the top. The 20 l fixed bed was packed with sintered glass (Sera Siporax) as a carrier material. With 270 $m^2\,l^{-1}$ biologically effective surfaces, the sintered glass helped the microorganisms' immobilization and biofilm development. Despite the fixed bed, there was still a certain amount of biomass suspended in the fluid. The three-phase separator prevented the suspended biomass from leaving the anaerobic filter with the effluent. In addition, the gas bubbles formed in the process could also be collected without significant foaming by the separator.

The produced biogas did not immediately leave the anaerobic filter, but accumulated therein, till the desired pressure in the anaerobic filter was reached. At that point, the valve of the gas outlet automatically opened, and the produced biogas was injected to a gasbag. As soon as the gas was released, the pressure of the anaerobic filter started to drop, and the gas outlet was closed again, allowing the auto-generated biogas pressure to increase to the desired value. By this means, the anaerobic filter could be set under a certain operating pressure. The entire process was controlled by a pressure sensor (Endress + Hauser Ceraphant T PTC31) and a control valve (Bürkert 2712).

In addition to the anaerobic filter, the acidogenesis-leach-bed-reactors also had gas outlets. The gas outlet of each reactor was connected to a gasbag for gas-quality and -quantity measurement. Furthermore, both the anaerobic filter and the acidogensis-leach-bed-reactors were equipped with pumps for internal circulation (about 1.5 l min^{-1}), mixing for five minutes every ten minutes.

2.2. Experiment procedure

The anaerobic filter was seeded with the effluent from another fixed-bed anaerobic reactor, which had been fed with leachate of grass silage [18]. The reactor start-up period and preliminary tests lasted approximately four months. After that, the reactors reached a steady state, and the experiment on the pressure effects on two-phase anaerobic digestion began.

The experiment was divided into four runs. With the exception of the working pressure of the anaerobic filter, all the operating parameters were maintained at a constant. The influent COD concentration stayed at 23 ± 0.9 g l^{-1}. The organic loading rate of 5.1 ± 0.1 kgCOD $m^{-3}\,d^{-1}$ was applied to the anaerobic filter. Four different working pressures on the anaerobic filter were tested (Table 1). No additional caustic chemicals were added for pH adjustment throughout the experiment, so that the pressure effects on anaerobic digestion could be clearly examined.

2.3. Analytical methods and data acquisition

In this study, pH, pressure and temperature of the anaerobic filter were monitored in real-time (pH-sensor: Endress + Hauser