Bioresource Technology 245 (2017) 698–705

Contents lists available at ScienceDirect

Bioresource Technology

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

Optimal conditions for flexible methane production in a demand-based operation of biogas plants

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ARTICLE INFO

Keywords:
Flexibility
Demand-based
Biogas
Overloading
Limits

ABSTRACT

The aim of the presented work was to study the methane production limits and to determine optimal conditions for flexible operation of an anaerobic reactor in order to set up an operational strategy. Punctual overloads were conducted in a laboratory-scale anaerobic reactor with readily biodegradable solid substrates, and the influences of overload intensity, baseload value and substrate used were investigated. A maximal daily value around 1000 mL/L of reactor for methane production has been assessed. This value did not evolve significantly during experiment time, and conditioned the persistence of overloads as well as the flexibility margin on the reactor, which ranged from +25% to +140% on daily production. Results highlighted the fact that for a maximum flexibility, low organic loading rates are better to work with on this type of reactors.

1. Introduction

The energy sector is going to face the issue about future fossil energies shortage. Techniques for extraction of oil and gas are getting more expensive. To keep providing power to a growing population without worsening environmental problems, it is necessary to switch to a renewable-based energy mix. In the last years, power from renewable energies as wind and solar PV have been developed at a high rate all over the world: they presented an annual growth rate of respectively 23% and 51% between 2004 and 2014. In 2015, they represented 6.2% of the total global electricity supply. However, a power supply mix composed of a high share of solar and wind energy sources can have a high degree of variability due to the dependence on the weather and there might be some problems in infrastructures supplying electricity. The current infrastructures are indeed not designed for an electricity supply which may vary to such an extent, seasonally, weekly and daily (World Energy Council, 2016).

Biogas can soften these variations of power supply and act as buffer energy (Szarka et al., 2013). Production of biogas is now a widely used process in Europe: there are more than 17,000 anaerobic digestion plants in 2015, with a total capacity of 8293 MW_{el} (European Biogas Association, 2015). Biogas is mainly (more than 60%) burned into CHP, to obtain electricity and heat (Biogas Baromete 2014, 2014). The majority of anaerobic digesters are operated in stable conditions, mainly because of the complexity of the biological and physico-chemical processes involved, to avoid failures that lead to money losses for the plant owner. To ensure a buffer effect, the biogas production should, however, be flexible. Literature has proven that microbial communities can adapt to organic shocks, and functional long-term stability is seen even with high disturbances (De Vrieze et al., 2013). Renewable energy supply policy in Germany, which is the first producer of biogas in Europe, now supports flexible electricity generation from renewable energy sources with the *Renewable Energy Act*. Besides limiting the amount of agricultural crops in reactors, it promotes small decentralized biogas plants and sets up some incentives for demand-driven power production (Boettcher, 2014). This implies that flexible ways of production would be valorized in the near future. There are several ways to achieve flexible supply of biogas, split in two main strategies: biogas storage and flexible production.

Biogas storage is the most common solution and the easiest way to make biogas supply flexible. It is mostly designed to balance small variations in biogas production (4–6 h) in the case of internal biogas storages. It can be low or high-pressure, made from various materials (plastic layers or steel), storing from 10 to 16,000 m^3, and often with some biogas losses (1–5% daily), (Liebetrau et al., 2010). However, on-site biogas storage is subject to legislation limiting the volume of methane which can be stored on-site, thus limiting the flexibility of this solution.

Another method for biogas storage is to inject biogas into the natural gas grid after upgrading raw biogas to the legal requirements in terms of methane content and pressure. Upgrading up to a methane content of 94–96% can be achieved by physico-chemical processes

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http://dx.doi.org/10.1016/j.biortech.2017.09.013
Received 22 June 2017; Received in revised form 1 September 2017; Accepted 2 September 2017

(Ryckebosch et al., 2011) or biological methanation (Reuter, 2014). Nevertheless, some investments in both energy (one physical process as water scrubbing costs 0.2–0.3 kWh/m^3_{biogas}) and money (operator can pay up to 250,000 € for connection pipes) are mandatory. This is not suitable for small agricultural plants.

Biogas plants may be designed to produce biogas on-demand: these are generally double-stage reactors. Some processes such as ReBi ("Regalbare Biogasanlage") or IFBB biogas plant (designed for lignocellulose rich biomass) can achieve an intraday flexibility of biogas production up to 800% (Hahn et al., 2014b), but these solutions can only be used in the case of new projects.

One simple way to achieve flexible biogas production on existing farms is to apply substrates management, i.e. feed a variable amount of organic degradable matter to the reactor. The principle is to have a base biogas production and to add biodegradable substrates for some peak-production periods. Coupled to biogas storage, it does not require further investments in equipment because of the reduction of storage volume which reduces both environmental and financial costs (Hahn et al., 2015, 2014a). This can be coupled to biogas storage for a maximum efficiency (Mauky et al., 2014). However variable feeding raises the problem of reactor response. With the ADM1 model (Batstone et al., 2002) it is possible to foresee the effects of varying organic load (Weinrich and Nelles, 2015), but a good knowledge of both the reactor's maximum organic charge removal and of the substrates characteristics is necessary. These knowledges can also be a step towards a simpler model for reactor control.

Biogas production flexibility is a barely discussed subject in the literature. Lately, some articles assessed the feasibility of flexible feeding in various reactors (Terboven et al., 2017). Most of researchers have done experiments trying to raise at a maximum the organic load of digesters, seeking a higher production thus profitability for biogas plant (Ganesh et al., 2013; Steyer et al., 1999). However, when coming to the flexibility topic, experiments in the literature were conducted at a lower constant organic loading rate (OLR), and overloads were only punctual. In (Mauky et al., 2014), three different substrates were chosen, with different degradation kinetics to achieve flexibility. Sharp responses were assessed, but production was limited to the same maximal value even when applying different daily charges, even in the same day, and regardless of base production. In fact, one hour after the feeding, the biogas production was the same (8 L/h) even when the organic added load was doubled (corresponding to the quarter or the half of daily feeding). This phenomenon was also noticeable in (Linke et al., 2015) in a two-phase leach bed reactor: on the LBR of 35 L, methane production was limited to the same value (around +50% compared to baseload) when feeding the reactor from two to seven times its daily baseload. Plus, VFA accumulated in LBR in highest overloads (until 5 g/L). Immediate daily response in biogas was limited and not proportional even when raising the OLR, i.e. applying a charge 7 times higher in the same time.

The aim of this work was to find the methane production limits of an anaerobic reactor and find how it could affect a flexible operation of methane production. Methane content in the biogas produced could vary with operation conditions, so this value was closely followed during flexible operation. Operation of anaerobic digesters with punctual overloads is still a barely discussed topic in the scientific literature. The novelty of the work lies in the fact that flexibility potential was assessed on the methane production in continuously stirred tank reactors (CSTRs) fed with different mixes of solid substrates (corresponding to standard configurations of existing plants), during a year and a half. Evaluation of flexibility potential and identification of parameters which influences it makes it possible to set up guidelines for an efficient flexible operation of biogas plants, following electricity needs in the grid.

2. Material & methods

2.1. Experimental setup

One double-walled stainless steel reactor of 15 L, with an effective sludge weight of 10 kg, was used. The temperature inside the reactor was kept at 37 °C by an electric resistance located in the double wall. The reactor was equipped with a paddle-shaped stirrer powered by a 1 HP motor. The volume of biogas produced by the reactor was measured every two minutes by a Ritter gas flow meter (Milligascounter MGC-1 V3.1) and stored in the computer memory. This volume was corrected by the current temperature in the experiment room (one acquisition every 15 min) and by the daily atmospheric pressure to work with a value in normal conditions (T = 0 °C, P = 1 atm).

2.2. Base substrates

The reactor was fed with a base mixture of grass and carrots. These two substrates were chosen for their fast degradation kinetics. The base mixture was composed of 30% of grass and 45% carrots in mass approximately corresponding to 60% grass and 40% carrots based on volatile solids (VS). The rest (25% in mass) was added tap water for keeping total solids content around 12%. The substrates were shredded and kept at −20 °C until the week before their use. After defrost, they were kept at 4 °C for maximum 1 week. During all the experiments, three different batches of substrates have been used. Their characteristics are shown in Table 1. For each substrate, biomethane potential (BMP) was measured with a method using near-infrared spectroscopy developed by (Lesteur et al., 2011) on freeze-dried and shredded samples.

2.3. Reactor operation

The reactor was inoculated with 10 kg of sludge from an Up-flow Anaerobic Sludge Blanket reactor (UASB) from a sugar factory treatment plant in Marseille, France. Total and volatile solids concentrations were 9.6% and 4.5%, respectively. The reactor was operated at a base OLR of 1.5 gVS/L.d for 354 days and then at a base OLR of 2.5 gVS/L.d, for another 196 days, then fed again at a base OLR of 1.5 gVS/L.d during 36 days. Hydraulic retention times (HRT) were respectively of

Table 1
Characteristics of substrates batches used in the experiment.

	Carrot batch 1	Grass batch 1	Carrot batch 2	Grass batch 2	Carrot batch 3	Grass batch 3
TS (%)	9,2 ± 0,2	53,8 ± 1,1	9,5 ± 0,6	24,1 ± 0,8	10,4 ± 1,7	26,0 ± 2,0
VS (% TS)	92,2 ± 1,2	80,9 ± 0,7	93,3 ± 1,4	80,9 ± 0,7	93,3 ± 1,3	85,2 ± 1,8
COD (mg/gVS)	1300	1318	–	–	–	–
BMP (mLCH_4/gVS)	333 ± 30	245 ± 30	250 ± 30	231 ± 30	229 ± 30	251 ± 30
Biodegradability (%)	73	54	–	–	–	–
	Mixture batch 1		Mixture batch 2		Mixture batch 3	
Total solids (%)	12 ± 2					
Volatile solids (% TS)	94 ± 2					
Calculated BMP (mLCH_4/gVS)	279		238		242	