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Monitoring of full-scale hydrodynamic cavitation pretreatment in agricultural biogas plant

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ABSTRACT

The implementation of hydrodynamic cavitation (HC) pretreatment for enhancing the methane potential from agricultural biomasses was evaluated in a full scale agricultural biogas plant, with molasses and corn meal as a supplementary energy source. HC batch tests were run to investigate the influence on methane production, particle size and viscosity of specific energy input. 470 kJ/kgTS was chosen for the full-scale implementation.

Nearly 6-months of operational data showed that the HC pretreatment maximized the specific methane production of about 10%, allowing the biogas plant to get out of the fluctuating markets of supplementary energy sources and to reduce the methane emissions. HC influenced viscosity and particle size of digestate, contributing to reduce the energy demand for mixing, heating and pumping. In the light of the obtained results the HC process appears to be an attractive and energetically promising alternative to other pretreatments for the degradation of biomasses in biogas plant.

1. Introduction

Various pretreatment technologies have been developed in recent years to ensure flexibility and stable biogas production from agro-industrial biogas plant (Patinvoh et al., 2016; Ward et al., 2008), where lignocellulosic biomass, such as agricultural residues and energy crops, together with livestock manure are used for biogas production. Biodegradation of lignocellulosic biomasses is difficult for the highly crystalline structure of cellulose, which is embedded in a matrix of polymers – lignin and hemicellulose (Hendriks and Zeeman, 2009; Ravindran and Jaiswal, 2016). Thus, pretreatment strategies should aim to disrupt the crystalline structure of cellulose and to separate the cellulose and hemicellulose from lignin.

Among pretreatments, hydrodynamic cavitation (HC) process has been recently reported as a challenging technology to increase the biodegradability of lignocellulosic biomasses, i.e. wheat straw (Patil et al., 2016), and diluted brewery spent grain (Montusiewicz et al., 2017). The effectiveness of the HC treatment of lignocellulosic biomass has been further studied in improving the bioethanol production from sugarcane bagasse (Hilares et al., 2016) and reed (Kim et al., 2015), and in accelerating the delignification of wheat straw in the paper manufacturing process (Badve et al., 2014; Iskalieva et al., 2012). In contrast with other pretreatment methods like ultrasound, that operate between 1,000 and 16,000 kJ/kg TS (Carrere et al., 2015), or thermo- alkaline up to 130,000 kJ/kg TS (Gonzállez-Fernálndez et al., 2012), HC needs less energy and provides a high and more stable increase in biogas production (Habashi et al., 2016; Lee and Han, 2013). However, while HC has been extensively applied in wastewater treatment plant for sludge processing as means to produce particular matter disintegration (Petkovšek et al., 2015), minimize sludge production (Hirooka et al., 2009), increase the aerobic biodegradability (Langone et al., 2015; Mancuso et al., 2017) and the methane production (Lee and Han, 2013), few studies are reported on agricultural residues.

Cavitation is generally defined as a sequential phenomenon of formation, growth, and collapse of cavities, within a liquid, resulting in very high local energy densities. HC occurs in a dedicated reactor, which geometry causes velocity fluctuations in a liquid flow, and thus a local drop of pressure. During cavities collapse very high temperatures (500–15,000 °K) and pressures occur (100–5,000 atm) for a very short time, but with the overall environment remaining equivalent to process conditions (Gogate, 2011).

The intense turbulence as well as conditions of high shear result in an intensification of mechanical effects with a reduction of the degree of polymerization of cellulose in lignocellulosic biomass and an increase of the specific surface area (Hendriks and Zeeman, 2009). Further, the high local temperatures lead to the formation of radicals (predominately $OH^{\cdot}$ and $H^{\cdot}$) from the homolytic cleavage of water molecules, which are very much reactive and could be responsible for the

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oxidation of main components of lignocellulose (Badve et al., 2014).

Different HC reactors have been developed, based on orifice plate (Habashi et al., 2016; Lee and Han, 2013), venturi (Stoop et al., 2015), swirling jet reactor (Mancuso et al., 2017), rotor-stator assembly (Patil et al., 2016) and two rotating disc pair systems (Petkovšek et al., 2013), usually installed in a closed-loop circuit, which limits the number of implemented full-scale systems. HC effectiveness depends on a significant number of parameters (Ozonek, 2012), among them technological process parameters, such as the pressure at the inlet to the HC system or the speeds of rotation of the rotor, are strongly dependent on the specific energy transmitted to the unit mass by the HC reactor. As a general trend, it is usually accepted that specific energy input has a positive effect in most HC applications taking advantage of either chemical or physical effects. Nevertheless, a very high intensity may be detrimental, and its effect on agricultural residuals should be evaluated. In the case of wastewater treatment, when the speed of rotation/pressure is increased beyond a certain value, super - cavitation may occur. The generated cavities do not collapse and do not produce the required pressure pulse to destroy the molecules and, thus, there is a decrease in the destruction rates (Mancuso et al., 2016; Mishra and Gogate, 2010). Further, the compounds formed during severe pre-treatment processes of lignocellulosic biomasses may prove inhibitory to enzyme activity, microbial growth and metabolism (Bolado-rodríguez et al., 2016; Hendriks and Zeeman, 2009; Ravindran and Jaiswal, 2016).

To date, research is mainly focusing on lab – or pilot – scale research, while full - scale experience is missing in the literature. This paper for the first time summarizes key data on a full-scale application of an HC system in an agricultural biogas plant. Further, the “one shot treatment”, without recirculation, was investigated. The effects of the HC treatment on methane production, particle size distribution, viscosity, residual methane production, and energy consumption in the full scale biogas plant are analyzed and discussed. The effects of increasing specific energy input are further addressed.

2. Materials and methods

2.1 Description of the investigated full-scale biogas plant

In this study, one HC reactor was implemented at full scale in an agricultural biogas plant located in Emilia Romagna region (Piacenza, Italy). The biogas plant was operated at 42 – 43 °C to produce electrical energy and heat by two combined heat and power (CHP) units (725 kW_{el} = 525 + 200 kW_{el}) and an exhaust gas energy recovery system based on Organic Rankine Cycle (OCR) (36 kW_{el} = 2 × 18 kW_{el}).

The produced electrical energy was sold to the public power grid and the thermal energy was used to heat the biogas plant. The biogas plant had three stirred anaerobic digesters (AD1, AD2, AD3) in series, with an overall hydraulic retention time of 30 – 35 days; the nominal volume of each digester was 1400 m^3 and they were filled at 97.5 %. Digesters were covered by a gasometer. Mixing system, provided by two mixing units (15 kW_{el} each) in the first and second digesters, and by one mixing unit (30 kW_{el}) in the third digester, operated in an automatic on/off mode.

During the investigation period the biogas plant was fed with pig slurry, energy crops (maize silage and triticale silage), and agricultural by-products (beet molasses, and corn meal) as supplementary biomasses. The results of biomass characterization are shown in Table 1. Solid feedstocks were loaded to AD1 by means of a loading system running on regular interval time during the day, whereas the pig slurry was fed by a pumping station in both AD1 and AD2. Two pumping systems were used to pump the digestate effluent from AD1 to AD2 and from AD2 to AD3. About 96% of the digestate from AD1 was pretreated with a mechanical shredder (Rotacut RCQ-33 Vogelsang, 2.2 kW_{el}) to protect the biogas plant from clogging. In the present layout, produced digestate from AD3 was not recycled back to the digestion process.

Table 1
Biomasses characterization.

Substrate	Total Solids g/kg	Volatile Solids g/kg	VS/TS %	Standard BMP[a] Nm^3 CH_4/t VS
Pig slurry	38.8 ± 7.5	24.1 ± 6.3	62.1	300
Maize silage	348 ± 31	332 ± 30	95.4	355
Triticale silage	286 ± 45	266 ± 44	93.0	340
Beet molasses (high density)	805 ± 23	640 ± 20	79.5	400
Beet molasses (low density)	550 ± 10	384 ± 15	69.8	380
Corn meal	850 ± 5	833 ± 7	98.0	380

[a] Standard Biochemical Methane Potential (BMP) values evaluated at the beginning of the monitoring period for each substrate by means of batch digestion tests.

Approximately 125 m^3/day of fresh digestate was discharged from AD3.

2.2. HC equipment

The HC reactor used for the generation of cavitation was a stator and rotor assembly (BioBANG®, Three-ES – Italy, 20 – 40 kW_{el}). The rotor was a solid cylinder attached to a gear assembly which was connected to a variable frequency drive (VFD). This VFD controlled the speed of rotation of the rotor and thus the energy input provided to the system and the cavitation intensity as well described in literature (Patil et al., 2016). The inlet pressure to the HC reactor was 2.0 bars. An open-loop circuit had been applied, where the effluent was treated only once, in an operational setup called “one shot treatment”, without any recirculation. Outlet and inlet flow rates were the same as there was no accumulation in the HC reactor. The flow rate and the electrical power could be set through a control software.

2.3. Effect of the HC specific energy input

The effect of the HC process on the anaerobic biodegradability was investigated at increasing electrical power of the HC reactor, and consequently increasing speed of rotation of the rotor. Batch experiments at full-scale were run at 20, 30 and 40 kW_{el} treating the digestate effluent from the AD1 (TS = 82.1 ± 2.1 g/kg, VS/TS = 78.3 ± 0.9 %). The corresponding specific energy input (E_{SPEC}), defined as the amount of energy acting on 1 kg of total solids (TS), was approximately 470, 740, and 954 kJ/kg TS, respectively. The HC reactor was installed downstream of the mechanical shredder and the mohno pump (Wangen KL30, 2.2 kW_{el}, 1.0–6.0 m^3/h). Each treatment was performed in triplicate. The untreated and HC treated digestate samples were analyzed and compared for BMP, viscosity and granulometry. The obtained results in batch experiments were used to select the most suitable configuration of the HC reactor at full-scale.

2.4. Effect of the HC process on the full-scale biogas plant

The HC reactor was installed after the first digester of the agricultural biogas plant. Almost 96 % of the effluent from AD1 was HC treated during its transfer to AD2. A schematic representation of the installation of the HC reactor at the full-scale biogas plant is reported in Fig. 1. The full-scale biogas plant was investigated prior to the installation of the HC reactor for 3-month reference monitoring period, without any biomass pretreatment (days 1 – 96), and after the HC reactor installation for nearly 6-months (days 97 – 277). Samples of digestate from AD1, AD2 and AD3 were taken and analyzed in the reference period for volatile organic acids/total inorganic carbon ratio (VOA/TIC).

The HC reactor absorbed power and flow rate were set up at