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RESEARCH ARTICLE

Development of velocity sensor to optimize the energy yield in a biogas plant

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ABSTRACT

The number of biogas plants has increased worldwide making the energy from Biomass one of the main renewable energy resources. Along with the increase of number of biogas plants, the prices of the substrates have been increased. Therefore, the optimization of the energy efficiencies in biogas plants has become a crucial subject. An option to improve the efficiency of the biogas plants is by optimizing their stirring system, where up to 51% from the internal energy consumption in biogas plants might be caused by the stirrers. The evaluation of the current mixing performance is done by performing velocity testing with a reliable technology - the bending beam-. The main advantages of this sensor in advance to the simple technology are the cost reliability, accuracy, resistivity against foul and ability to be installed inside the fermenters. The results showed the efficient use of the sensor and an inaccuracy of the range (4-6) %. The effect of the Total Solids content (TS) of the digestate on the mixing inside the fermenter was determined; at higher TS values, the flow of the substrates becomes more uniform than at lower TS values.

Keywords: Bending beam, biogas, optimization, sensor & velocity

1. INTRODUCTION

Worldwide the importance of renewable energy resources has increased over the recent years; the generated power by renewable energies (including hydropower) share of global energy production by the end of 2015 reached around 24% [1]. In Europe, the installed biogas plants by the end of 2015 reached 17,358 biogas plants, 10,846 of them were installed in Germany. The total capacity reached around 8,728 MW_{el} [2]. To reach the targets of the Kyoto protocol, Germany set a reduction aim of at least 40% of CO_2 emissions by 2020 and up to 80 to 90 percent by 2050 in comparison with 1990. These targets shall be achieved by supporting new renewable energy systems and the optimization of the energy efficiency for the installed systems [3].

The increasing substrate costs leads to difficulties in the economic operation of biogas plants. It is necessary for operators to achieve higher gas yields with lower internal energy consumption. One approach to increase the profitability is optimizing of the stirring performance. The reason for this is stirrers have a significant share of the internal energy consumption in biogas plants; the share of the stirrers might reach up to 51% from the internal energy consumption in biogas plants [4].

The reduction of the consumed energy by the stirrers is not always a good factor in the optimization of the energy yield; this has been noticed from the experience. In case of insufficient mixing, sinking layers and floating covers might be formed. That will prevent the anaerobic microorganisms from having the ability to get in contact with the substrates. Thus, the biogas production will decrease or stop entirely [5], [6], [7] and [8]. On the other hand, the aggressive stirring (the high velocities of the stirrers or long operation times) might form high shear forces. These forces can affect the acetic and methane producing bacteria negatively. Therefore, it is important to find the most suitable mixing conditions to avoid the formation of sinking layers and the floating covers as well high shear forces [9].

This project takes place in a biogas plant near to Hamburg – Germany. The biogas plant consists of two fermenters with a volume of 2659 m^3 each. Every fermenter has two submersible agitators and one Hydro-mixer agitator. In addition, inside the mixing tank and digestate storage one submersible and three

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submersible agitators are assembled respectively (status March 2015). As substrates for the fermentation process dairy and swine manure, poultry manure and maize silage are used.

2. MATERIALS AND METHODS

To develop the velocity sensor and check its reliability, different technologies were evaluated according to several criteria. Then the sensor was tested in a biogas plant.

2.1. Methods

The choice of the concept to be used for the velocity sensor was done with attention on the needs of the sensor. Mechanical and chemical measurement concepts were chosen to be evaluated with regards to the cost, resistivity against foul, place requirements and the accuracy. The concepts doubling of ultrasonic, doubling of laser, X-Ray and tracer particles were excluded due to the available budget and the fact the measurements will be done inside a fermenter that has a concrete thickness of around 20 cm.

2.2. Mechanical Measurement Methods

The focus here is on the methods in which the forces or the effects of the forces are measured. The evaluation for the mechanical measurements method was done for two main concepts; the anemometer and the bending beam. Anemometer has been developed for measuring the flow field velocities. The main anemometer concepts, which were studied, are: Vane wheel anemometers, in which the speed of the rotating of the vane wheel is determined by the angle of the vane and the speed of the fluid flow [10]. Pitot tube anemometers rely on measuring the variances between the static pressure values and the dynamic pressure values to obtain the velocity of the fluid flow [11]. The rotating cup anemometer was the third type of anemometers that have been evaluated. This principle (rotating cup) is considered as a simple one and depends on counting the number of revolutions that the cups are having during the flow of the fluid [12]. The bending beam concept depends mainly on measuring the absorbed and forwarded forces which are applied by the flow hitting the plate, where a strain gauge (DMS) is assembled.

2.3. Chemical Measurement Methods

These methods focus on the differences of the substrates concentrations, the calorific properties or chemical concentrations between different points in the flow to measure the velocity. Three concepts can be used are: pH value and the Redox potential differences as well as calorimetric measurements. Based on the pH value measurements (the technology of ISFET array), a sensor for flow velocity measurements was designed and implemented [13], it depends on measuring the difference of the pH value at two different points. The measurements of velocity depending on the Redox potential values follow the same principle in the previous mentioned technology.

After carefully evaluating the mentioned concepts previously according to their costs, accuracies, resistivity against fouling and their suitability to fit inside the fermenter, the choice was made to use the bending beam concept. Table 1 summarizes the evaluation of the concepts.

Table 1. Summary of the evaluation of the main methods for velocity measurements

Method	Place requirement	Resistance Against fouling	Accuracy	Cost
Doubling of Laser	-	+	+	-
Doubling of Ultrasonic	-	+	+	-
X-rays	-	+	+	-
Tracer particles	0	+	+	-
Vane wheel anemometer	0	-	-	0
Pitot pipe impeller	0	0	+	+
Rotating cup anemometer	0	0	0	+
Bending beam	+	0	+	+
pH value difference	-	0	0	+
Redox potential difference	0	+	0	+
Calorimetric measurements	+	+	0	0

where:
- : Not or low competent,
0 : Medium competent,
+ : Very competent.

2.4. Materials

The test of the sensor took place at a commercial size biogas plant locates near Hamburg – Germany. This biogas plant consists of two fermenters and digestate container. The fermenters have identical sizes (2659 m^3) and three stirrers; two movable submersible mixers (TMRW) and one Hydro mixer (GFRW) in each. The operating time for the mixers was five minutes every half an hour. The digestate container has a volume of 6514 m^3 with three submersible mixers. There is a possibility to insert the velocity sensors in the fermenters at twelve different locations; every 90° at the levels of 1, 3 and 5 m (normally at the level of 5m, there is just gas). Fig 1 represents the design of the fermenters (1 and 2 are identical) and the meaning of the levels (heights), angles and the depth.

The materials used for the measuring device were designed to last for the expected speed inside the fermenters; it was provided by the biogas plant operator that is in the range (0 – 0.4) ms^{-1}. The measuring device consists mainly from two parts; the measuring rod and the measuring sensor. Their design was done to fit to the gauge size at the chosen biogas plant. In this biogas plant, the operator designed gauges to simplify the sampling and the velocity measurements. The radius of the gauges is 38.5 mm.

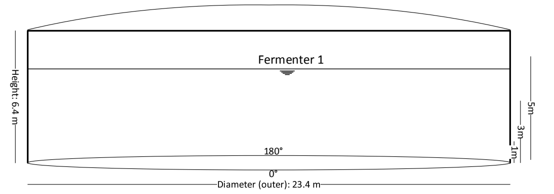

Fig 1. Design of fermenter 1 representing the possible sampling (measurements) points

2.5. Measuring Rod

The rod was designed to sustain the conditions in the fermenters with different substrates; Total Solids contents (TS), pH values, densities and velocities. For the conditions of the chosen biogas plant, the maximum reached TS value was around 10.5% (w/w), the rod designed to handle at least a velocity of 2 m s^{-1} at this value. The used material is stainless austenitic chromium – nickel steel (1.4301). The rod specifications are summarized in Table 2. Fig 2 represents the measuring rod connected to the fermenter.

Table 2. Specifications of the measuring rod

Parameter	Unit	Value
Length	m	1.5
Outer radius	m	0.019
Inner radius	m	0.014
Density	kg m^{-3}	7900

Fig 2. Measuring rod used for the velocity measurements

2.6. Measuring sensor

A plate from Aluminum alloy was used to build the sensor that can sustain bending corresponding to the velocity of 1 m s^{-1} at TS of 10.5% (w/w), its main specifications can be represented as following:

Table 3. Specifications of the measuring sensor

Parameter	Unit	Value
Length	m	0.200
Width	m	0.030
Thickness	m	$0.5 * 10^{-3}$
Density	Kg m^{-3}	2670

A resistance strain gauges (DMS) was built at Hamburg University of Technology. In this sensor, the resistance changes with the expansion. DMS consists from a carrier film and a meander inductor measurement grid. The carrier material is glued onto the surface of the aluminum plate. If the DMS stretched in the direction of measurement, the electrical resistance of the conductor increases, and it can be measured at constant amperage a change in voltage. The strain is proportional to the voltage change and enables the calculating of the force applied by the flow. This strain has a full bridge circuit consists of four units. It also has a resistance of 320 Ω. Thereafter, the terminals are electrical connected and to a 7-pole plug cable. Subsequently, the components have been sealed with clay. Fig 3 shows the measuring sensor.

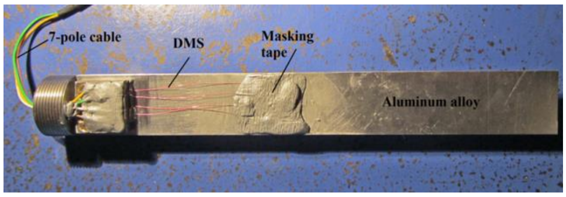

Fig 3. The velocity sensor designed at TUHH

The calibration of the sensor was done at The Hamburg Ship Model Basin (HSVA), where the measurements of the voltage generated were taken at different times and different velocities. A quadratic approximation (equation 1) can be used to show the relationship between the voltages (y) and fluid velocity (x).

$$y = 2.8219x^2 + 8.7681x \quad (1)$$

The sensor was used to measure the velocity inside a cylindrical fermenter. It could measure for around 75 seconds, but it started to show noise due to the high velocities exceeding 1 m s^{-1} and the aggressive environment inside the fermenter, which destroyed the DMS. Therefore, further improvements were needed. A new sensor from Aluminum alloy was developed has same specifications as the previous one, except increasing its thickness to 1.5 mm.

The sensor was isolated by using masking tape so-called ABM 75. This sensor operated for short time due to the insufficient isolation. Following further another sensor was designed, this sensor has a size of (180 mm * 20 mm * 1.5 mm) from the same material.

Then it was coated by a layer of masking tape ABM 75. After that and before any measurement, the sensor is coated with 3 layers from the insulation material Plasti Dip liquid rubber. The calibration was done at HSVA as before. The calibration curve can be seen in Fig 4 and the relationship between the voltage and flow velocity from equation 2.

$$y = 0.9887x^2 + 0.1088x + 0.0007 \quad (2)$$

y: the voltage in V

x: the flow velocity in m s^{-1}

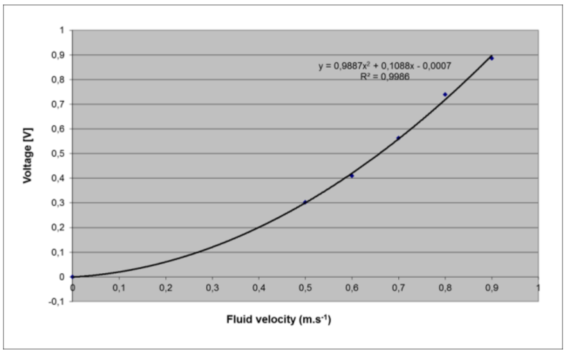

Fig 4. Calibration of the velocity sensor done at HSVA

The measuring rod was improved as well, by using a 6 m of rod of stainless austenitic chromium – nickel steel (1.4571). This rod was divided into three parts of 1m, 2m and 3m with the ability to be connected to allow further measurements at deeper points inside the fermenters with more flexibility in the measuring depth.

3. RESULTS AND DISCUSSION

The frequency of the measurements per second was decided after experimental trials; it was done for three different frequencies (two measurements per second, one measurement per second and one measurement every two seconds). The conclusion was to run the measurements with a frequency of one measurement per second. Fig 5 represents measurements of the flow velocity inside fermenter 2 in a biogas plant at a height of 1m, depth of 0.75 m. An example of the measurements of the velocity and its relationship with the measured voltage (the relationship can be seen from equation 2) can be seen from Fig 5. The harmonies and avoidance of the noise can be noticed as well. The changes of the measured voltage were not occurring dramatically within very short period (up to 10 seconds).

The velocity sensor has been used for the measurements at different points (heights 1m and 3m, depths of 0.75m, 1.25m and 1.75m, and angles of 0°, 90°, 180° and 270°) in two fermenters (fermenter 1 and fermenter 2). It showed stability and flexibility for the measurement at different depths inside the fermenters without any difficulties. The values of velocity inside the fermenter were changing for the different measuring locations according to the distance from the stirrers and the wall. The points next to the walls showed higher velocity values and longer time to reach the non-movement velocity after switching the stirrers off. The effect of the distance from the wall appeared stronger at lower TS values.

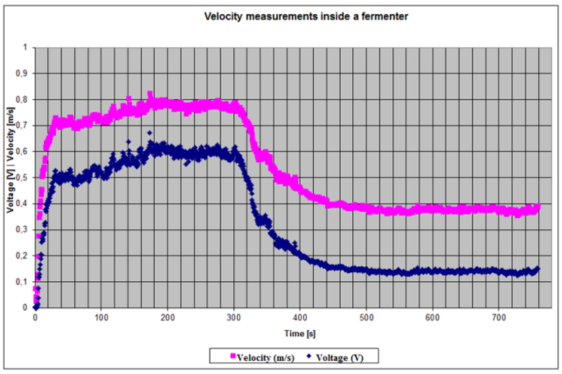

Fig 5. The velocity measurements at a biogas plant after the calibration [8]

A comparison was done for the velocities inside fermenter 2 at the same point (level 1 m and depth 0.75 m) at different times (different feeding scenarios), where the values of the Total solids content were different, refer to Fig 6. The measurements were done while the stirrers were on for 300 seconds, and while the stirrers were turned off. The Total Solids content played a big role in the changes of the velocity; at higher TS values the velocities were more stable and following a more uniform shape.

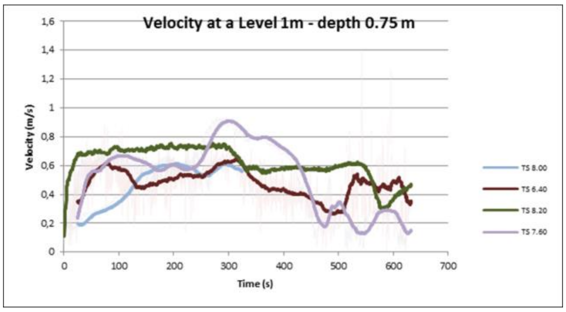

Fig 6. Velocity at different TS values

The TS value could be considered as one of the main factors controlling the mixing inside the fermenters. TS value is the main factor controlling the viscosity of the digestate. Therefore, it has an effect on creating foaming layers or causing an inadequate mixing or even breaking down the stirrers [14]. Brehemer studied the effect of the TS value on the viscosity and its effect on the mixing. He concluded that the viscosity is highly affected by the feeding substrates (TS values). To avoid the dead zones formation, increasing the viscosity can be chosen as an option, this increase leads to a strong reduction in the mixing time. At the same time if the viscosity increases too strongly, a stall and cavities are formed [15].

The results of the measurements showed that at higher TS values, the stability of the flow of the digestate is increasing and also the velocities are higher. Furthermore, it takes longer time to reach the phase of non-movement and starting the creation of dead-zones after turning off the stirrers, at higher TS values. The effect of the TS values on the velocity of digestate flow is comparable with the effect of the viscosity on the velocity flow from other studies [16], [17] and [18].

4. CONCLUSION

The principle of bending beam might be used in velocity measurements inside fermenters, where it is cost reliable, accurate and can be installed in any biogas plant. This only requires the adaption of the size of the gauges at the biogas plants. The resistivity against fouling can be improved by using isolation materials such as Plasti Dip liquid rubber. The inaccuracy of this sensor is dependent on the flow velocity, where it is in the range of (4-6) %. The relationship between the velocity of the flow and the sensor accuracy is proportional. As a result, this accuracy is satisfactory for the improvement of the mixing performance in biogas plant.

In the measurements done at the biogas plant, the stability of the velocity and the changes were highly dependent on the TS value due to the changes these values on the viscosity. Therefore, it is recommended to do further measurements in different biogas plants with different substrates and TS values. This will highly help in finding optimum conditions for the mixing in biogas plants and avoid the creation of floating layers and sedimentations.

The improvement of the mixing performance can be achieved by the help of simulation programs such as Computational Fluid Dynamics (CFD) and practical part using the flow sensor. This improvement and evaluation should consider the feeding substrates, the hydraulic retention time as well the stirrer models and their locations in the fermenters. The evaluation can be based on examining the homogeneity of the digestate from different locations in the fermenter and the effect of mixing on the energy yield and the consumed energy.

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