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Innovative Biogas Multi-Stage Biogas Plant and Novel Analytical System

First Project Experiences

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Abstract

The here presented applied research and development project is targeted to the development and application of new and improved techniques in plant design, performance analysis and process control. Hereto following the required steps are illustrated and the goals are outlined. The project covers the development of a previously patented anaerobic digestion process, adaption of flow cytometry as an analytical instrument and investigation of innovative ways of disposal of solid fermentation wastes. The preliminary experiences with a newly built research plant employing a novel anaerobic biogas digestion technique are discussed. In this paper the first outcomes concerning the construction and operation are discussed. A novel method of disposal of the fermentation wastes is also discussed and first results are shown.

Biogas, multi-stage, flow cytometry, respirometry, disposal of fermentation wastes

1. Introduction

A research network formed by Renergia, Metalinox (project leader), University of Trento and University of Trier has been established in order to build and operate a multi-stage type research fermenter system to explore the potential of a multi-stage fermentation system in which the single phases of the biological process are broken down into well separated steps allowing for higher specific gas yields and faster digestion. The findings will be applied to full size plants. The overall project is financed by the Autonomous Province of Trento.

To further improve the digestion efficiency and obtainable gas yields a novel process efficiency and control analytical system based on flow cytometry (FCM) will be developed (Foladori, Bruni and Tamburini, 2010 [1]). The lack of rapid and continuous quantitative and qualitative analytical methods for the determination of the efficiency of the digestion process is a major drawback in the operation of a

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biogas plant. The traditional analytical methods mostly allow only for a retroactive assessment of eventual problems that had occurred. The rapid analysis by the use of flow cytometry, to be developed within this project, will allow for a proactive response to many possibly arising problems. The application of this particular analytical process will require substantial research efforts in order to achieve the desired goals, i.e. an almost real-time analysis of the microbiological process. The multi-stage fermentation system is particularly adapted to the use of flow cytometry as analytical tool as substrate can be drawn at the point of passage from one fermenter to the other, of the substrate. The spatially separated cascade will allow, based on the results of the flow cytometric analysis, to eventually adjust flows from one reactor to the other or support decision making about introduction of eventual additives like, for example, enzymes.

Novel ideas of disposal of the fermentation wastes are explored and tested.

1. Multi-stage anaerobic fermentation

The multi-stage anaerobic fermentation system (Gasser, Binnig and Moedinger, 2004 [2]) consists of a series of stainless steel vessels set in a cascade in which the substrate flows semi-continuously from one vessel to the other (initial feed → hydrolysis → acidification → multi step methane generation).

The multi stage biogas digestion process (Figure 1) is based upon the spatial separation of different phases of the biological process into well-defined spaces that allow, when compared to traditional fermentation systems, for a specialization of the various stems of Achaea involved resulting, under controlled and analyzed conditions, in a higher biogas yield and better digestion.

The spatial separation allows furthermore a complete control of the bacterial activity as the flow between the single vessels can be analyzed and hence the necessary steps taken. The single vessels do not need to be of the same size but can be of different size in order to best adjust duration of the specific process stage.

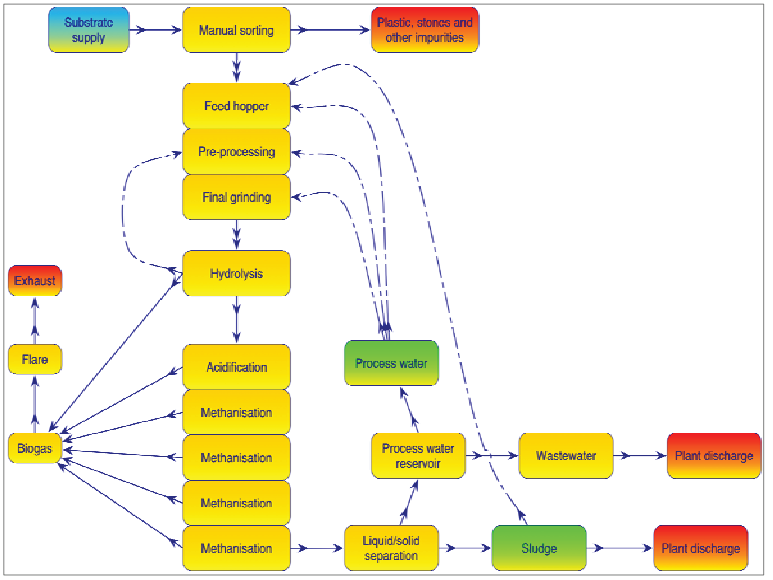

Figure 1: Process flowchart

The substrate is, prior to be fed to the system, ground or crushed to a particle size of less than 5 mm. It is then fed, after eventually having been heat treated for hygiene, to the hydrolysis vessel. The loading level of this temperature controlled vessel can change according to process needs.

The feed to the subsequent acidification vessel can either be continuous, semi-continuous or batch. From the acidification vessel the substrate is fed in continuous to the first of the methane generators.

In the first stage of the methane generating process, organic matter is decomposed by mainly acetogenic strains of bacteria at a pH value of between 6.5 and 7. The pH value in this first stage is controlled accurately by the feed rate.

In the second stage methane generation occurs to a lesser extent by acetogenic and to a larger extent by hydrogenotrophic bacteria. In the subsequent stages the hydrogenotrophic Achaea strains become more and more predominant and the pH values slowly rise to neutral or slightly above. Bacterial activity is controlled by temperature, eventual addition of, for example, enzymes, and temperature.

Size and process conditions (temperature, pH value, duration of residence, mixing) of each vessel can be varied according to substrate requirements and operational data. The relatively small size of the single vessels allows for relatively rapid changes of the most important process parameters giving room for substantial efficiency improvements. Mixing of the substrate is optimized with continuous loop mixers.

2. Process comparison

The main difference between the novel cascade fermentation process and the conventional ones are illustrated in Table 1.

Table 1. The main differences between the various biogas generation technologies offered on the market today

	Conventional		Novel
	Single stage fermentation	2 stage fermentation	Cascade fermentation
Characteristics	Biochemical process takes place in the same vessel and partially in competition between each other. Poor mixing and hence poor phase separation. Biogas contains between 35 and 60% of methane. Up to 20% of dry substance and hence very high COD values in the effluent. Long duration of the process.	Rough separation of the biochemical process phases. Improved has yield and most of the times biogas featuring a higher methane content. Improved mixing but still insufficient phase separation. Lesser COD and dry substance content in the effluent. Shorter duration of the process.	Complete separation of the biochemical process phases improving further on methane content. Individual temperature control of the various stages and phases. Individual flow rate control of the various stages and phases. Very low COD and dry substance content in the effluent. Very efficient mixing and hence good phase separation. Expected duration of the process between 12 and 40 days.
Investment	Low investment.	Average investment.	Higher investment.
Suitability	Best suited to plants in an agricultural environment where the effluent is to be used as fertilizer and the main objective is manure odour treatment.	Mostly used for energy crops.	Accepts wider choice of substrates. Works well with monosubstrates.

The higher investment required for a cascade fermentation system certainly targets the possible application to installations where somewhat more stringent requirements exist - like for example in the case of organic household waste as mono-substrate. In this case the higher investment and greater complexity is offset by the higher commercial yield of the plant.

Another possible advantage of the cascade system is a higher operational safety and process reliability compared to a traditional plant because of the separation of the phases and the single, relatively modest sized, vessels. Due to this design in case of contamination of the incoming substrate not the entire plant is affected but only a limited portion of the overall digestion volume. The analytical method furthermore allows for a quick and efficient designation of the eventual problem and hence finding of a solution.

3. Plant design

The objects and goals of the pilot plant (Figure 2) are manifold: they range from mechanical, flow and sensor optimization to optimization of the analytical methods.

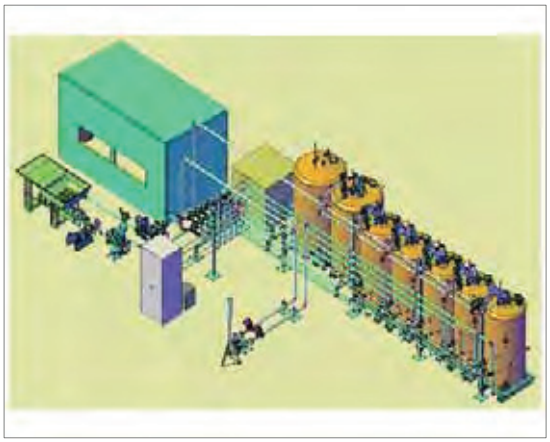

Figure 2. Multi stage fermentation pilot plant

The design parameters of the pilot plant are:

Table 1. Main design parameters of R&D plant

Design	Transportable, modular
Required space for operation	ca. 200 m^2
Overall height (ready for operation)	3.2 m
Overall usable digester volume	ca. 10 m^3
Process water storage	2.5 m^3
Substrate input	ca. 200 kg per day via semi automatic feed hopper
Expected biogas output	ca. 1 Nm^3/h

The plant will consist of a preparation unit, a storage tank and several fermentation vessels.

4. Analytical methods

The state of the art in analytical methods used in the management of biogas plants regarding substrate composition is actually represented by a more or less frequent determination of dry substance, organic dry substance and fatty acids. Sometimes a nitrogen / potassium mass balance is made as well and the ammonium content assessed. pH values and temperatures are usually recorded. Such analysis might be sufficient in the case of corn and/or manure co- or mono-fermentation. They are certainly not sufficient in the case more difficult substrates, such as organic household waste, are used as mono-substrates.

Bacterial activity is estimated as a consequence of the concentration and presence of fatty acids but never measured directly. But as well for the analysis of the substrate there is much room for improvements. The lack of rapid and continuous quantitative and qualitative analytical methods for the determination of the efficiency of the digestion process is a major drawback in the operation of a biogas plant. The traditional analytical methods mostly allow only for a retroactive assessment of the problems that may have occurred. The rapid microbiological analysis using FCM, which will be applied in this project, seems to be very promising to allow for a proactive response to any possibly arising problems. The application of this particular analytical approach will require substantial research efforts in order to achieve the desired goals, i.e. an almost real time analysis of the microbial activity during the process.

Furthermore the degree of biodegradability of the substrates applied in the cascade fermentation system is assessed by using respirometry which can be applied both under aerobic and anaerobic conditions (Andreottola, Dallago and Ragazzi, 2005 [3]). The cascade fermentation system is particularly suitable for a monitoring approach based on FCM because the bacteria population of the single fermentation vessels can be easily collected and substrate can be drawn at the point of passage from one fermenter to the other.

The preliminary evaluation of substrate biodegradability will allow, based on the results of respirometry, to predict and to decide the most suitable fermentation process, aiding to decide how many stages have to be used. Again, the spatially separated cascade will allow, based on the results of the FCM analysis, to eventually adjust flows from one reactor to the other or support decisions about changes in operational conditions or introduction of eventual additives like, for example, enzymes.

FCM permits a quantitative and qualitative almost real time analysis of the number and the activity level of individual bacteria in a suspension. It is used in science mainly in medical related applications such as DNA determination but also in various fermentation processes, such as cyder and beer production. The industrial importance as control and optimization tool for biotechnological processes is constantly growing.

Given the diversity of important cell characteristics that can be measured by FCM and the speed at which these assays can be performed, FCM will certainly be a valuable tool for process control of a biogas plant because it can better describe bacterial characteristics.

In FCM, single cells or particles are stained with specific fluorescent probes and pass in front of a laser beam in a directed fluid stream. Scattering and fluorescences are monitored for each single cell. The commercially available flow cytometers consist mainly of a light source, flow cell, optical filters and the appropriate detection and data processing equipment.

The functional principle of a flow cytometer is pictured in Fig. 3. below.

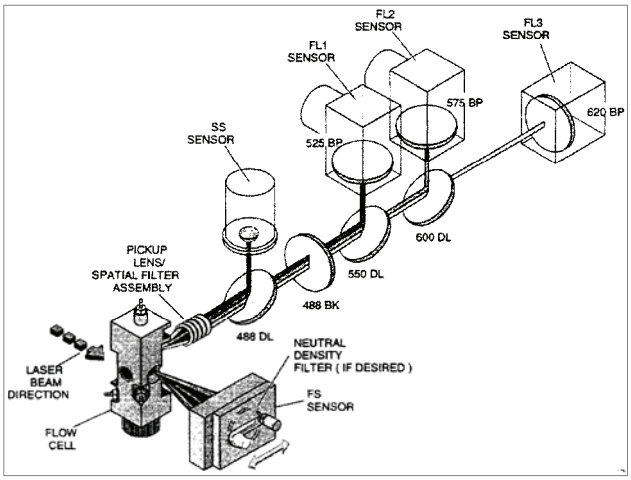

Figure 3: Schematic diagram flow cytometry (Coulter, 1996 [4])

The main difficulty of adopting FCM to an application in the biogas sector is the appropriate dilution of the test samples to get a specimen without cell agglomerates and turbidity or other hindering particles in the stream trough the flow cytometer. An adequate pre-treatment of the sample to separate bacterial cells from other abiotic debris has to be developed as well as the right fluorescent probes have to be chosen to detect specific cell functions and bacteria groups.

5. Use of fermentation wastes

Fermentation wastes are used in agriculture as fertilizers. This use conflicts in many ways with the ever more stringent rules and regulations about nitrate concentrations in soils making it necessary to dispose of ever larger spreading areas.

In case of plants running exclusively on manure the problem might even result in making the operation of the plant ultimately impossible.

With the digestate generated by the cascade process new utilization possibilities arise. Due to the chemical – physical property of the digestate it can be used in brick production as a density reducing agent without any major influences on the quality or chemical composition of the fired bricks (see Grehl, 1995, for a comprehensive study on the use of waste materials as an addition to the brick feed [5]).

The following tests, see Table 2 below, have been made by adding a 20 % in volume of the solid fraction of the fermentation of organic household waste from a major city in The Netherlands to the standard feedstock of a brickyard (all data in mg/kg and rounded to the nearest 0):

Table 2. Chemical composition of bricks and limit values recycling

		Production	20% Fermentation wastes	Limit values law 152/2006/Encl. 5/Table 1 / A	Limit values law 152/2006/Encl. 5/Table 1 / B
Arsenic	As	20	20	20	50
Cadmium	Cd	<1	<1	2	15
Chrome	Cr	160	115	150	800
Mercury	Hg	1	2	1	5
Nickel	Ni	100	74	120	500
Copper	Cu	41	41	120	600
Selenium	Se	<2	<2	3	15

The brick manufactured with the addition of the fermentation wastes will hence fulfill, at the end of its lifecycle, the requirements of current Italian legislation concerning recycling and reuse of building materials. It is expected that the solid fermentation residues of the cascade fermentation system will even perform better.

Leaching behavior has been investigated as well and found to be within the limits.

6. Results and discussion

The expected results of this project are clearly targeted at improving the specific gas yield, introducing, for the biogas sector, new analytical methods and novel methods of disposal of the solid fermentation wastes. The project as presented here will hence be a substantial contribution to new knowledge and know- how.

The first operational results of the R&D plant are, at the time of writing of this paper, not yet available for publication. Too few data have been collected due to a late start of the project. The collected data will be source for later publication.

Building R&D scaled plants in the anaerobic digestion sector as proof of concept is a rather uncommon approach for the sector: Almost always laboratory results are transferred directly to full size plant level. Many times this approach results in failure as the operational conditions under which data are obtained are not comparable. Many times novel substrate, as an addition or substitution of the existing substrate, are tested experiencing a drop in the production of biogas and hence generation of energy.

With the R&D plant it will also be easier to test, verifiy and improve the novel analytical methods. In a full size commercial plant it would be unthinkable to establish certain operational conditions, intentionally presumably wrong density and temperature of the substrate for example, that are required and necessary to fine tune the analytical method and verify the operational parameters that result from the analysis.

Scaling up the experiences made with the R&D plant will help in avoiding mistakes both in design and process control.

The R&D plant will also be a valuable asset once a full scale plant has been built as a test bed for certain substrates that might be deemed to be used in the full size plant in order to optimize and determine process parameters before the new or additional substrate is fed to the commercial size plant. Even from a

purely financial point of view such a novel approach will certainly be, in a period of time where public incentives are decreasing, important and highly desirable.

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