Cascade reactor system for methanogenic fermentation

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Methanogenic fermentation is promising method of obtaining environment-friendly energy. Moreover it can be used for disposal of sewage and other organic waste. However process complexity and susceptibility makes it difficult for application on a large scale. A new laboratory stand for studding of anaerobic digestion was developed. Three fermentation vessels and automated control system provides flexibility essential in investigation of digestion of different substrates and testing of different reactors configurations. Cheese whey is a troublesome dairy waste, potentially suitable for biogas production. Stable fermentation conditions for whey fermentation were obtained with the organic loading rate of 5 kg COD/m^3 and methane production efficiency of 0,3 m^3/kg COD. On the basis of obtained data the size of small biogas plant for average dairy was calculated.

Keywords and phrases: biogas, anaerobic digestion, whey, UASB, methane, sewage, fermentation, multi-step digestion.

Introduction

Biogas production is a multi-stage process in which organic matter is converted into methane and carbon dioxide. It is produced by mixed-cultures of micro-organisms under anaerobic conditions and can be used for organic waste treatment. The increased demand for energy from renewable resources has resulted in a growing interest in energy production from biogas. Currently, European Union countries are required to produce 20% of their energy needs from renewable sources.

The process of biogas formation is usually described in four consecutive stages [1]. In the first stage organic matter is decomposed into water soluble compounds such as carbohydrates, amino-acids, and fatty acids. In the second stage these compounds are hydrolyzed and then fermented to volatile fatty acids and alcohols. In the third stage acetogenic bacteria oxidize the fermentation products to acetate, hydrogen and carbon dioxide. Finally, in the fourth stage methane is produced by methanogenic Archaea by decomposition of acetate or by the reduction of carbon dioxide by hydrogen.

Each stage of the process is conducted by an individual assemblage of microorganisms. The optimal reaction conditions for each step differ significantly. If the entire process is carried out in a single reactor, the methanogenic step is most critical since methanogenic microorganisms are the most sensitive to any disturbances. Inhibition of their activity results in the complete collapse of the process [2].

Multi-step digestion system

In classical agricultural biogas plants complex substrates such as grass silage, animal manure, slaughterhouse waste, or oil mill wastewater are digested to produce methane. In this case the rate limiting step is the hydrolysis of organic polymers, primarily cellulose [3]. Simple products such as whey or glycerin can also be used. In these situations the biogas production rate depends on the oxidation of volatile fatty acids.

The use of a particulate substrate leads to the formation of an unique balanced microorganism population adapted to the particular culture conditions [4, 5]. Sudden changes in the composition of the substrate are usually tolerated quite poorly and often lead to process collapse [6]. For this reason individual production conditions must be optimized for each biogas plant.

The division of the fermentation steps into separate reaction vessels should theoretically improve process efficiency. In such a configuration individual processes could occur at optimal conditions, thus allowing a reduction in digester volume while also ensuring better process stability [7].

The experimental system presented in this paper is designed for studies concerning the optimization of the anaerobic digestion of different substrates, as well as investigations involving the separate fermentation processes. Our experimental model consists of a reactor system to carry on methane fermentation as well as a microchip sensor unit to collect data, as well as control system devices such as pumps, mixers, heaters, etc. The collected data are stored in a computer connected to the control system and are available on-line for analysis.

The system can work in several configuration modes. For example, the fermentation tanks can act as separate individual blocks permitting the operator to compare the digestion of different substrates in similar conditions or to test diverse treatment environments using the same substrate.

In the cascade operation mode the individual reactors are connected with each other to form a single digestion system. The conditions in the different reactors could be adjusted to produce the optimal environment for the individual digestion steps with minimal risk of process collapse. The advantage of this system is the possibility of the recovery of valuable compounds (i.e., hydrolytic enzymes) from the particular stages, compounds which would be lost during a standard digestion process.

Another possible configuration is double initial fermentation scheme. In this case one reactor serves as the final methanogenic reactor and two other reactors are used for the separate prefermentation of different substrates (e.g., plant material and whey). The fermentation products from the first stage reactors can be mixed in different proportions to ensure the optimal composition of a feed batch.

Cheese whey as a substrate in anaerobic digestion

Cheese whey is byproduct of the dairy industry. The composition of the organic component of whey is mainly lactose (about 70%) and proteins (about 12%). Whey also contains mineral salts (8%) and fats (1,5%). The high content of easily degradable organic matter (mainly lactose) results in a troublesome waste product that is very detrimental for the natural environment. However, cheese whey could be a valuable source of renewable energy.

The methanogenic fermentation of whey is difficult due to the low buffering capacity and rapid acidification of this substrate [8]. However, whey is usually utilized as an additive in biogas plants using other substrates. In this case the addition of whey increases methane yield without the risk of fermentation collapse [9]. In systems using whey as a main substrate the feedstock is usually supplemented with sodium carbonate to ensure pH stability during the fermentation process [8].

This study examined cheese whey as a substrate for the methane fermentation process. In addition, the stable fermentation conditions observed in our experimental system are compared with results from fermentation tests in other configuration designs.

Materials and methods

Fermentation vessels

A work station consisting of three Up-flow Anaerobic Sludge Blanket Reactors (UASB) which may also be used as Continuous Stirred-tank Reactor (CSTR). The reaction vessels were made of methyl polymethacrylate with a working volume of 230 liters. Reaction temperatures of 25 to 65°C were maintained with water jackets. Each unit was equipped with the following: a) temperature sensor, b) glass electrode for pH measurement, c) gas production sensor, and d) conductive fluid level sensor. The fermentation tanks could also be equipped with additional sensors such as ion selective electrodes for the analysis of sodium, chloride, sulfide, and ammonium ions.

The composition of the biogas produced was analyzed with a manual gas analyzer (GasHunter IR). Fermentation tanks can be also equipped with additional sensors such as ion selective electrodes for analysis of sodium, chloride, ion, sulfide and ammonium ions.

Mixing was maintained with low rotation stirrers equipped with a magnetic clutch, resulting in gas-tight fermentation reservoirs. The control system provided the regulation of the mixing speed (0–100 r.p.m) as well as the regulation of the stirrer working time.

Nutrient and pH regulation was maintained with 0–1500 cm^3/h duty membrane pumps. Pump function was automatically regulated. Surplus fluids were removed on an excess flow basis.

Microchip control module

A PLC SIMATIC S7-200 microchip control unit (Simens, Germany) was used to monitor and regulate bioreactor activity. System activity was maintained with an embedded touch panel or with a computer utilizing a Supervisory Control and Data Acquisition (SCADA) program. The PLC SIMATIC S7-200 control unit enabled simultaneous operation with many appliances (sensors, dosing pumps, computers, etc.).

Information exchange using integrated communication ports occurs at a speed of 1–187 kbit/s. The micro process control unit managed: a) 12 analogue input channels, b) 4 analogue output channels, and c) 27 digital channels I/O.

The system is adapted to developed communication structures of a maximum 126 attendants. The network

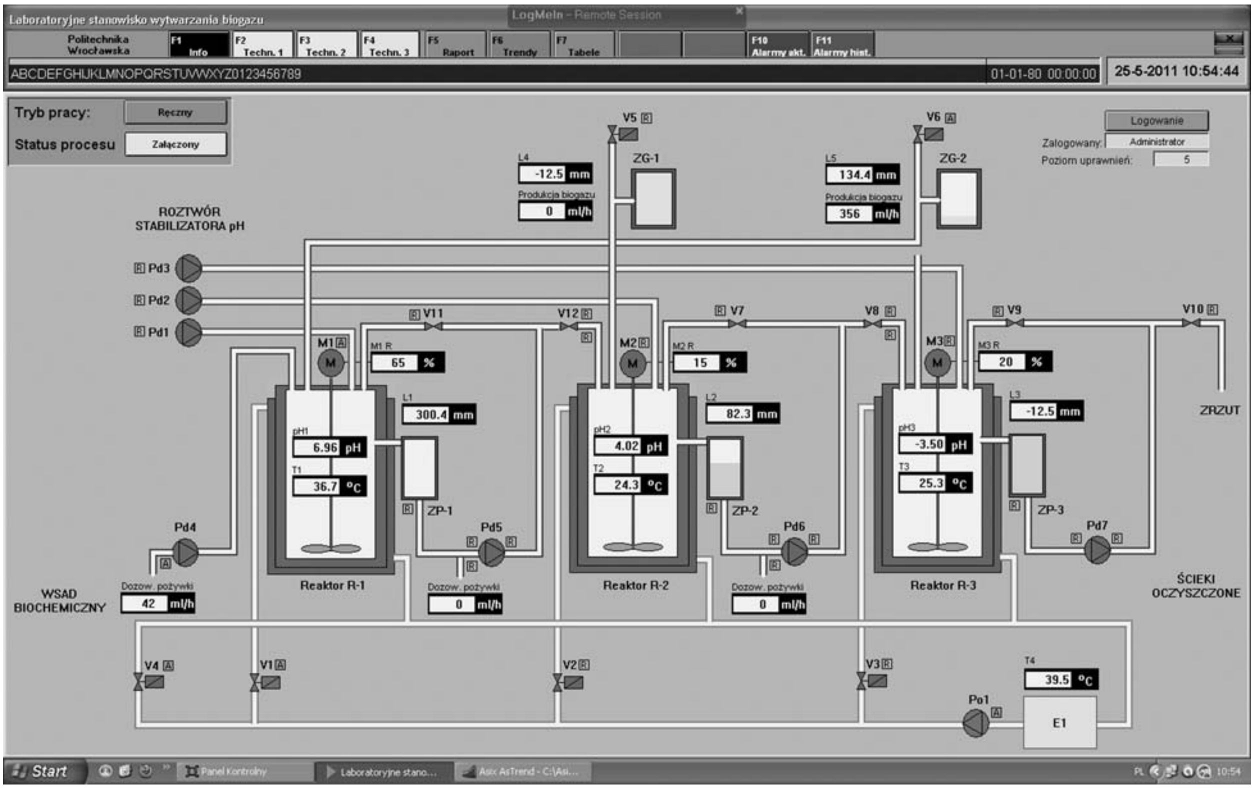

Fig. 1. Control screen from computer control system showing the configuration scheme of the reactor.

attendants can be programmer units, operation panels, computers, and other control units. The system works using both PPI and MPI (in slave mode) protocols. It allows for the co-operation with Totally Integrated Automation (TIA) system components. The communication ports work in Free Port mode with a maximum speed of 115 kbit/s. Finally, the system allows elaboration of its' own protocols using the ASCII standard to communicate with appliances like: modems, printers, computers, and bar code readers. The system can also work-together with the Modbus network.

Data storage system

Software for MS platform was computers was developed to work with Supervisory Control and Data Acquisition (SCADA) system and regulates the system from the level of the computer connected to microchip control unit. Files virtual interface is applied to record the data. It allows processing of procedures elicited from other data basis. The software development and modification is possible with the use of C and Visual Basic languages.

The software program allows data visualization, as well as system control in real time, along with historical data comparison and data storage on 2D diagrams (e.g., the simultaneous display of 16 recorded parameters). The software can also provide information on alarm and warning conditions for particular parameters thus affording a safe level of operation control during a test run. The software also offers the tools for other applications including: the application program interface (API), dynamic data exchange (DDE), and database (SQL). Finally, the program allows long-distance internet access to the process data thus allowing remote data manipulation.

Cheese whey fermentation

The composition of whey powder is as follows: lactose 70%, protein 11,8%, fat < 1,5%, ash 7,8%. The chemical oxygen demand of whey is 1000 mg O/g. The reactor was inoculated with anaerobic sludge from a sewage treatment plant in Janówek, Poland. The digestion was performed at 30°C for 100 days. In the initial period (first 2 weeks) the reactor was loaded with a low concentration of whey powder medium (1 g whey powder/liter), supplemented with 0,5 g/l of sodium bicarbonate. After first two weeks the concentration of whey powder was increased to 10 g/l and the sodium bicarbonate concentration was increased to 3 g/l. The medium was also supplemented with urea and $Na_2HPO_4 \times 12\ H_2O$ to provide an appropriate ratio of C : N : P (100 : 2,5 : 0,5). Further the organic loading rate (ORL) was gradually increased to reach a level of 5 g COD/l/d and alkali supplementation was gradually decreased to a level of 1,5 g/l of sodium bicarbonate (Fig. 2).

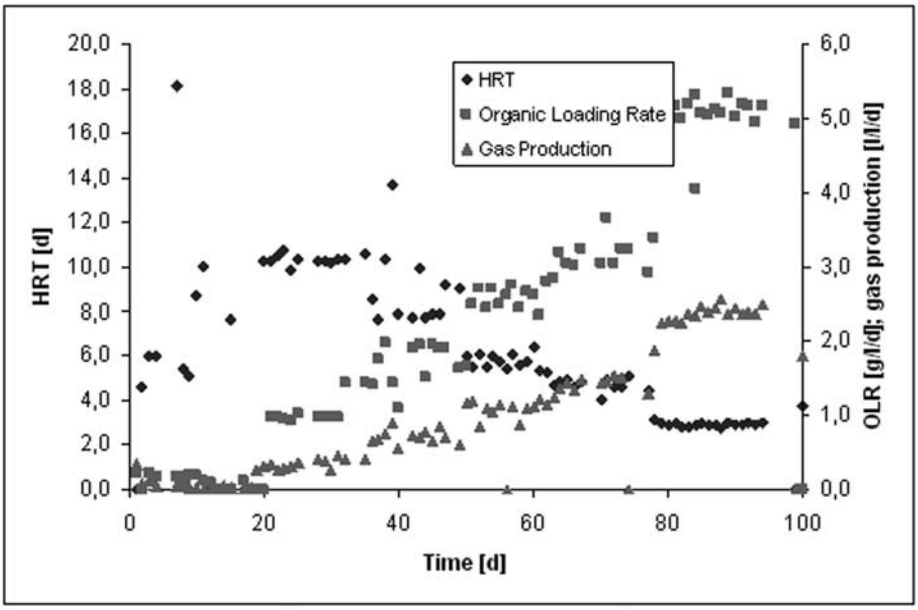

Fig. 2. Hydraulic retention time, organic loading rate, and gas production from the digestion of cheese whey.

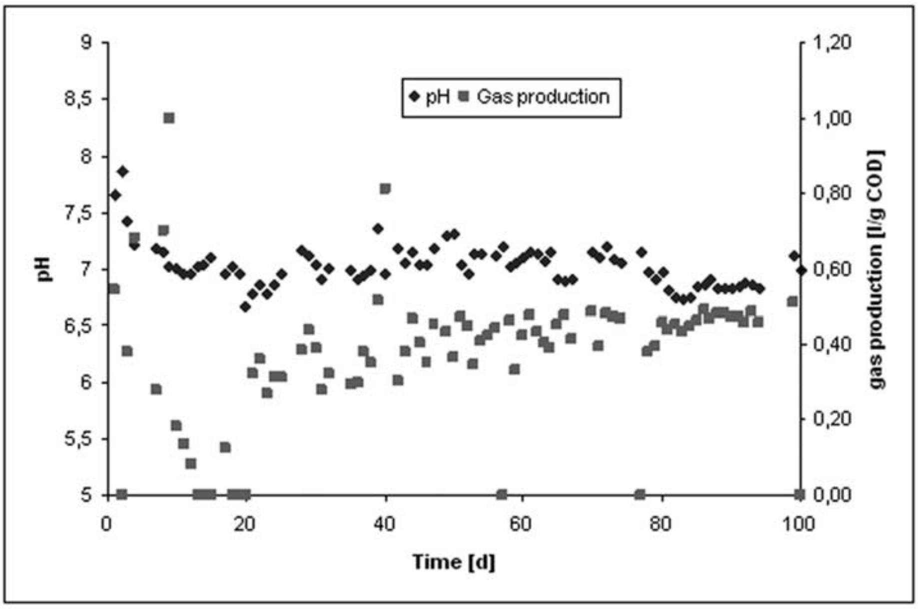

Fig. 3. The pH and the gas production efficiency during whey fermentation.

Results and discussion

During the entire experiment the pH was maintained between 6,8 and 7,5 and the production of biogas was 0,3 l/ g COD or higher (Fig. 3). Observed production efficiency was similar with that reported by other authors [10]. The amount of anaerobic sludge increased by 140% during 100 days of fermentation. The removal of organic matter was higher than 85%. The highest organic loading rate was 5g COD/l/d and 14,7% [g COD/ g VSS] of the provided substrate accumulated as biomass.

The data indicate that the fermentation trial was successful. There was no significant disturbance in process stability as a result of reduced alkali supplementation. The achieved organic loading rate, biodegradation rate, and gas production efficiency were comparable to results obtained by [11]

Using our experimental results the size and efficiency of whey utilization for an average dairy was calculated. To process 100 m^3/d of dairy sludge (organic load 12 kg COD/ m3) the digester should contain a volume of 165 m^3. Methane production would be as high as 300 m^3/d, an amount sufficient to provide the energy to power a 40 kW power generator. The generator would also provide energy in the form of heat, which could be used in the production process or to heat buildings. In this model the biogas facility would produce 2,8 m^3 of organic sludge per day. It is highly probable that is possible that the efficiency of the digestion process could be further improved thus reducing facility size and lowering operating costs.

Conclusions

Biogas production occurs on an industrial scale. However, recently there has been great interest in its optimized production, especially in smaller plants. Anaerobic digestion is a complex process which is still poorly understood. Thus, it is important to design experimental model set-ups in order to investigate the optimization of the process. To meet this requirement we have developed a very flexible set of laboratory digesters which can be easily scaled-up to industrial plant capacities. The laboratory system described in this study will allow the establishment of a database of process variables describing the fermentation of different substrates. On the basis of this data, it will be possible to identify alarm signals and create automatic emergency procedures useful in the design and operation of large-scale biogas production facilities. Additionally, the assembled data will provide important guidelines in the construction of new fermentation facilities. The collected data will be also useful in establishing computer training programs for future digester operators.

Acknowledgments

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