Pilot-scale Biogas Plant for the Research and Development of New Technologies

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Received: July 31, 2012 **Accepted: September 12, 2012**

Published: September 15, 2012

Abstract: *The paper describes a new pilot-scale biogas plant of the Institute of Microbiology – Bulgarian Academy of Sciences. The equipment includes: a 100 L pilot bioreactor, a 200 L metal gasholder, sensors, actuators, a two-level automatic process monitoring and control system, a fire and explosion protection system and two web cameras. The monitoring and control system is composed on the lower level of a controller Beckhoff, and on the higher level – of a PC with specialized software (under development). The pilot biogas plant is designed to work out and scale up various anaerobic digestion (AD) technologies based on different types of feedstock. All the data will be stored on the PC for quick reference and possibly data mining, parameter identification and verification of different AD mathematical models.*

Keywords: *AD, Biogas, Sensors, Monitoring and control system.*

Introduction

Anaerobic digestion (AD) is a biotechnological process widely used in life sciences and a promising method for solving some energy and ecological problems in agriculture and agro-industry. In such kind of processes, generally carried out in continuously stirred tank bioreactors (CSTR), the organic matter is depolluted by microorganisms into biogas and digestate (potential manure) in the absence of oxygen [1]. The biogas is an additional energy source which can replace fossil fuel sources. It therefore has a direct positive effect on greenhouse gas reduction.

Unfortunately, this process is very complex and can be unstable, particularly at changes in the environment, for example following an increase in influent concentration or in dilution rate, or changes in the nature of the feedstock, and needs more studies [2].

An active research problem is to better understand the dynamics of growth and death of the different populations of the complex community of bacteria acting during AD processes. However, it is practically impossible to measure on-line different bacterial concentrations or specific growth rates [2]. Other biochemical variables important for the AD processes are too expensive to be measured. In practice, only biogas flow rate (and its composition) can be easily measured on-line [3].

The paper describes the new pilot-scale biogas plant with a computerised monitoring and control system at the Stephan Angeloff Institute of Microbiology – Bulgarian Academy of Sciences. This biogas plant will be very useful for developing new optimised technologies for anaerobic digestion and co-digestion of different organic wastes and for multidisciplinary studies of this kind of processes (microbiological and biochemical studies, mathematical modelling with parameter and state estimation, sophisticated control algorithm development, new sensor development, etc.).

Pilot-scale biogas plant

Technological scheme

The technological scheme of this pilot plant with a system for monitoring and control is shown on Fig. 1.

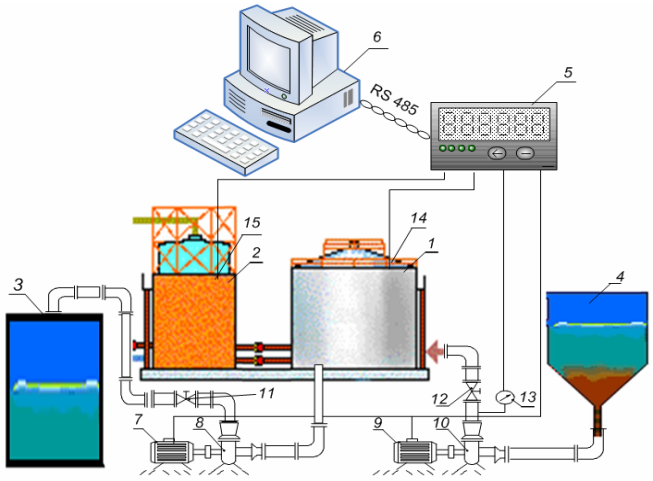

Fig. 1 Scheme of the pilot-scale biogas plant with a system for monitoring and control:
1 – bioreactor (BR); 2 – gasholder; 3 – reservoir for digestate, 4 – vessel for substrate;
5 – controller Beckhoff; 6 – personal computer; 8, 10 – pumps; 7, 9 – drives;
11, 12 – stop valves; 13, 14, 15 – sensors for t^0, flow rate of biogas (Q),
contents of CH_4, CO_2 and H_2 in the biogas.

Equipment

The substrate for the BR and the digestate taken out of it during semi-continuous operation (feeding one to six times daily) is stored in plastic cans of 50 L in the next-door auxiliary service premises of the biogas plant.

The 100 L bioreactor is designed for developing AD technologies based on standard and readily accessible types of feedstock such as diluted and suspended swine or cattle manure or chicken litter from agricultural farms, separately or in co-digestion with wasted fruits and vegetables from stock markets, finely grinded straw or restaurant wastes, activated sludge from waste water treatment plants, etc. On each substrate introduction procedure, an overflow pipe is used to drop down the culture medium level observable through a window on the corpus. The bioreactor is made of stainless steel and its upper flange is provided with magnetic coupling for the stirrer drive shaft. The drive itself is of AC type, the stirrer is of propeller type and deflectors controling the culture medium mixing are also available. The anaerobic bioreactor has been constructed with a water mantle with a compensatory reservoir and a circulation pump. An additional feature is the thermal insulation (10 cm in width) in view of economic energy studies. The insulation has been designed on creating a theoretical stationary model of the anaerobic bioreactor heat losses for two temperature modes of biogas production – mesophilic and thermophilic [4]. Thus, selected has been an effective thermal insulation of mineral wadding with a coefficient of thermal conductivity λ = 0,035 W/(m.K) and covered with aluminium foil. The bioreactor heat losses have been theoretically determined through the mathematical model at a thermal insulation thickness δ = 1, 2, ..., 10 cm. The heat losses have been established to decrease according to a parabolic dependence. Greater heat losses are found in the thermophilic mode compared to the mesophilic one. Conclusively, the uninsulated bioreactor has a high energy consumption to cover great heat losses at definite outer conditions – cold and moist weather. In this case, the bioreactor microorganisms situated near the metal wall could be at a different (lower) temperature for the given technological mode, which might affect their activity. The bioreactor thermal insulating has been performed in stages with an experimental purpose. On each stage after stationing the object (every 4 hours), photos have been taken by a thermovision camera to establish weak points of the insulation (see Fig. 2). The insulation stages are at an insulation thickness δ = 0, 5, 10 cm, respectively. On placing the first insulation layer, bioreactor surface temperatures have equalized along vertical axis, whereas the intensity of heat regulation has decreased. On placing the second layer, the small heat losses can expectedly be covered by bioreactor's own biogas production at its burning.

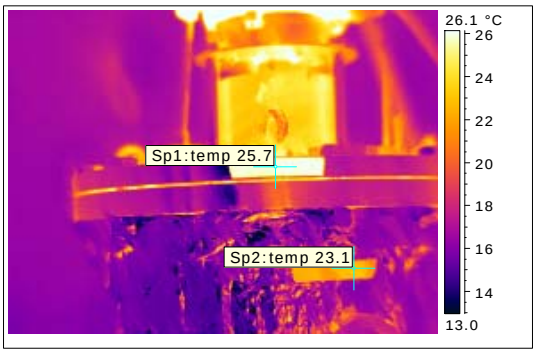

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Fig. 2 Photo of the bioreactor insulation

A biogas outlet from the upper bioreactor flange leads off the biogas to a 200 L metal gasholder (Fig. 3) operating on the water displacement principle.

Fig. 3 Gasholder

The main actuators are two feeding pumps that can be used interchangeably – of peristaltic (Fig. 4) and of progressive cavity (Fig. 5) type. The first one is self-drawing the input substrate, whereas the second one operates under substrate-submerged inlet, which requires auxiliary equipment to be built in the nearest future. On the other hand, the second pump gives the possibility to approach closely the operation mode to that of a real continuous process by apportioning the daily feed into greater number of dosages, as well as to avail of the theoretical process control algorithms [7-9] requiring multiple changes of dilution rate over a day. Other important inlet (on the substrate line) and outlet (on the digestate line and on the line from the bioreactor to the gasholder) flow control elements are the spherical valves (0 to 100%) being now manual, but some of them are provisioned to be replaced by automatic ones.

The actuator of the temperature control system is an electrical heater.

Fig. 4 Peristaltic pump

Fig. 5 Progressive cavity type pump

Sensors

Sensors for the following physicochemical variables are available:

- **temperature in the culture medium** – standard thermal resistance type Pt100 in two different points (submerged through openings on the upper flange and on the corpus);
- **pressure of the gas phase** of the bioreactor – this sensor is a produce of Comeco Systems Ltd (Bulgaria). It has a measurement range of 0-250 mbar, an indicator for the operator and a standard current output (4-20 mA) for connection with a computer;
- **pH of the culture medium** – there is no sense of placing an electrode for continuous pH measurement inside the bioreactor (as an inference from many years of experience of the authors' team from the St. Angeloff Institute of Microbiology – Bulgarian Academy of Sciences) for the following reasons:
  1. The electrode's membrane very quickly gets "overgrown" with microorganisms and organics and the measurements are not precise, whereas the periodic draw-out of the electrode from the bioreactor for cleaning is undesirable in view of preserving hermeticity and hence the bioreactor anaerobic conditions.
  2. The pH changes in the bioreactor are relatively slow and a measurement period of day is completely sufficient.

  Therefore, pH measurement in the bioreactor is performed by a standard laboratory pH-meter (with thermal compensation) in the sample taken once daily.

- **biogas flow rate** (through transformation of the linear shift of the gasholder into a normalized electrical signal). This sensor has been developed by our team (see Fig. 6). It operates on the capacitive principle and consists of a primary transducer, an electronic measurement block and a digital indication device to visualize the measured value. The primary transducer transforms the change in the gasholder level (in the float position) in a variable capacity and its construction is based on a metalized polypropylene tube with an externally insulated metal layer. The tube has been hermetically fixed on the upper surface of the gasholder float and immersed in the water in the outer vessel. Changing the immersion depth changes tube's capacity with respect to the water. One of the electrodes of the variable capacitor is the metal layer in the tube, the tube's outer insulation is the dielectric, and the second electrode is the water around the tube. This water should not be distilled, i.e. it must contain a certain amount of salts in order to be conductible. The capacity of the variable capacitor changes linearly as a function of the measured level.

The electronic measurement circuit transforms the capacity of the primary transducer in an electrical signal – voltage (0-5 V) or current (4-20 mA), depending on its further processing.

Fig. 6 Sensor for biogas flow rate

– **content of methane, carbon dioxide and hydrogen in the biogas** (see Fig. 7). These sensors are produces of MSR (Germany) with the following characteristics for the separate sensors:
  a) sensor for CH_4 content – infrared sensor with a measurement range of 0-100 %/vol., a measurement precision of ±1%, a monthly drift of ±1%, a linear output signal of 4-20 mA, a transient process time of less than 30 s and a lifetime greater than 5 years;
  b) sensor for CO_2 content – infrared sensor with a measurement range of 0-70 %/vol., a measurement precision of ±1%, a monthly drift of ±1%, a linear output signal of 4-20 mA, a transient process time of less than 30 s and a lifetime greater than 5 years;
  c) sensor for H_2 content – catalytic bead sensor for combustible gases with a measurement range of 0-100 LEL %, (corresponds to 0-4 %/vol.), a measurement precision of ±1 LEL %, an annual drift of ±5 LEL %, a linear output signal of 4-20 mA, a transient process time of less than 10 s and a lifetime greater than 3 years.

The sensors are situated consecutively to each other and to a pump creating the biogas flow through them which gets out of and back into the gaseous phase of the bioreactor. The measurements are visualized on the display of an electronic module GC-4 and are recorded on a PC.

Various data on important standard AD model variables or specific metabolites are acquired from chemical, physicochemical and microbiological analytical methods performed regularly off-line, such as those for concentrations of total and volatile solids, volatile fatty acids, glucose, reducing sugars, total sugars, total fats, total and soluble proteins; for enzyme activities – cellulase, xylanase, etc. These data are enregistrated manually in the computer and form a database for development of mathematical models and optimisation of the operation of the biogas plant.

Fig. 7 Sensors for CH_4, CO_2 and H_2 into the biogas

Monitoring and control system

The monitoring system consists of two web cameras (see Fig. 8a and Fig. 8b) and software sensors [5, 6] (under development) for video observation, control, recording video images on a server at system failures or gas leak, automatic sending of snapshots on controller's signalling (at reporting parameters beyond admissible ranges) and for presenting experiments and remote (through internet) training in methods for biofuel production.

The web camera SONY IPELA SNC-RZ25P on Fig. 8a has been installed in the biogas laboratory. The camera features an intelligent monitoring software with possible monitoring of images, different modes of recording, motion detection, filtering the raw data, sound from a microphone or other audio input device, etc. Fig. 9 shows a camera taken photo of the laboratory.

The web camera on Fig. 8b has been installed in the auxiliary premises for observing the pretreatment operations on the influent substrates.

Fig. 8a SONY IPELA network camera SNC-RZ25P

Fig. 8b Camera NDH210-3A

Fig. 10 shows a board containing measurement and control devices – frequency converters for the AC drive control, an electrical protection device, different electrical supplies and an electrometer taking account of the energy consumption.

The control system is composed on the lower level of a Beckhoff controller receiving the sensor information (see Fig. 10 with the Beckhoff controller in the top), and on the higher

level – of a PC (see Fig. 11) with specialized software (under development). For the future, some of our theoretical achievements in the field of software sensor and control algorithm design [3-9] will be realised and tested on this pilot biogas plant.

Fig. 9 Camera-taken photo of the laboratory

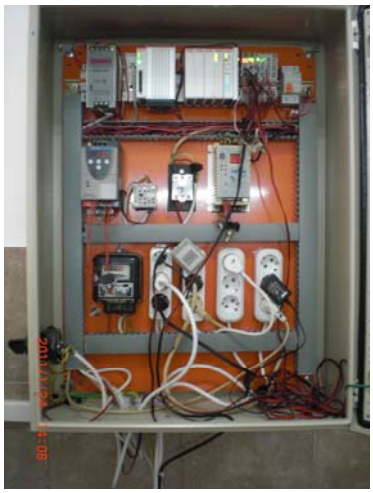


Fig. 10 The board containing measurement and control devices

Fig. 11 General view of the system

A fire-and-explosion protection system has been installed in the pilot-scale biogas laboratory (Figs. 12, 13 and 14).

Fig. 12 Light and sound signalling of the protection system

Fig. 13 Light signalling of the protection system

Fig. 14 Fan for removing excessive biogas in the lab

Experimental studies

The pilot anaerobic BR has been started and operated in continuous mode with cattle manure and different values of dilution rate (D) and of the concentration of dry matter in the influent (S_{in}).

Experiment 1. Some experimental data from a very particular experiment with cattle manure and pulse-wise changes of D for different values of S_{in} (described in Table 1) are presented on Fig. 15a (with averaged data due to rarer measurements) and 15b.

The daily biogas flow rate per 1 dm^3 of the working volume of the BR has been denoted by Q_{sp}: $Q_{sp} = Q/V$– specific daily biogas yield [L biogas/L liquid.day], where Q – daily biogas yield [L/day], V – working volume, [L].

Table 1. Pilot-scale data for D and S_{in}

Time [day]	D [day^{-1}]	S_{in} [g/dm^3]
0	0.001	69
1	$Pulse_1 = 0.025$	69
9	$Pulse_2 = 0.02$	69
16	$Pulse_3 = 0.0225$	86
30	$Pulse_4 = 0.025$	40

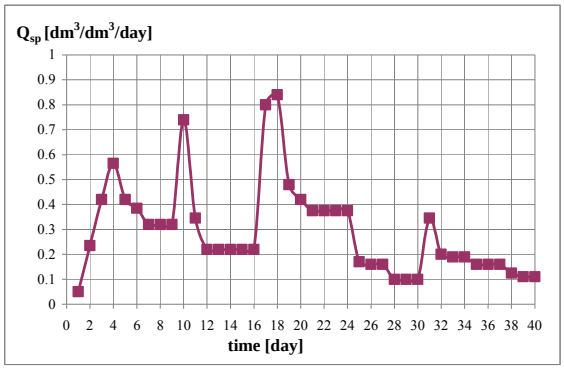


Fig. 15a Specific daily biogas flow rate evaluation during the experiment described in Table 1

From the specific daily biogas flow rate (Q_{sp}) evaluation, presented on Fig. 15a, one may conclude that the community of microorganisms in the BR reacts immediately on pulse-wise changes of the control input (D) and different values of the concentration of dry matter in the influent (S_{in}).

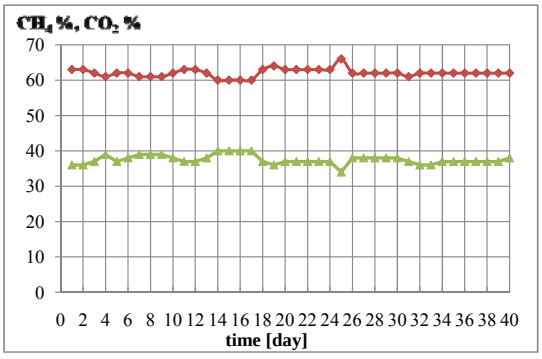
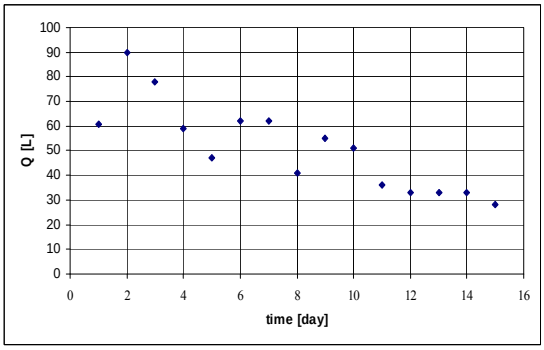


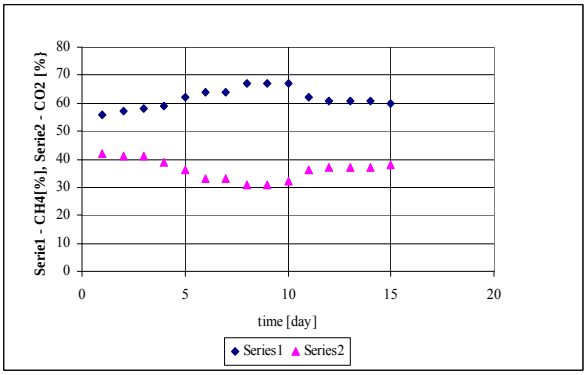
Fig. 15b Evaluations of CH_4 and CO_2 in the biogas during the experiment described in Table 1

From the evaluations of CH_4 and CO_2 concentrations in the biogas, presented on Fig. 15b, one may conclude that the ratio CH4:CO2 in the biogas for the above described experiment is practically not sensible to pulse changes of the control input (D) and different values of the concentration of dry matter in the influent (S_{in}).

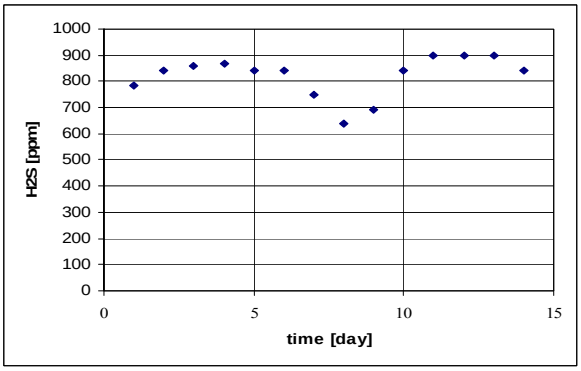
Experiment 2. AD of wasted fruits and vegetables (WFV) with different D.
A lot of experiments with WFV in mesophilic and thermopholic conditions have been performed [10] with ratio was WP:WC:WT:WA = 40:20:20:20, where WP – wasted potatoes, WC – wasted cucumbers, WT – wasted tomatoes and WA – wasted apples. Some results concerning the transient behaviour of the main variables for a change of D from 0.025 [day^{-1}] to 0.0125 [day^{-1}] are shown on Fig. 16. The average values for the daily biogas yield (Q) and the specific daily biogas yield (Q_{sp}) for these values of D are presented in Table 2. Measurements of H_2S (in ppm) in the biogas have been done using a Draeger device.



a) transient behaviour of Q



b) transient behaviour of CH_4 and CO_2 (in %/vol)



c) transient behaviour of H_2S (in ppm)

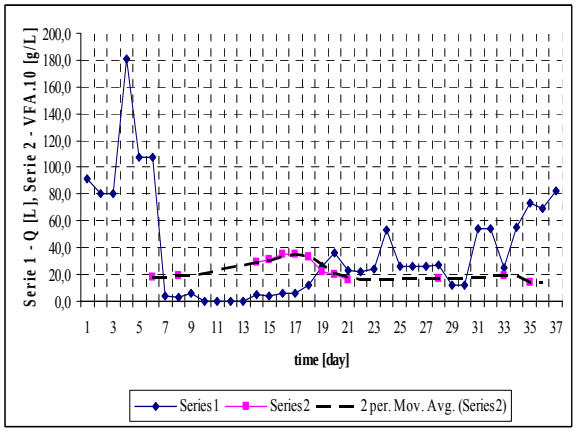
Fig. 16 Change of D from 0.025 [day^{-1}] to D = 0.0125 [day^{-1}] in t = 2

Table 2. Q and Q_{sp} for different values of D

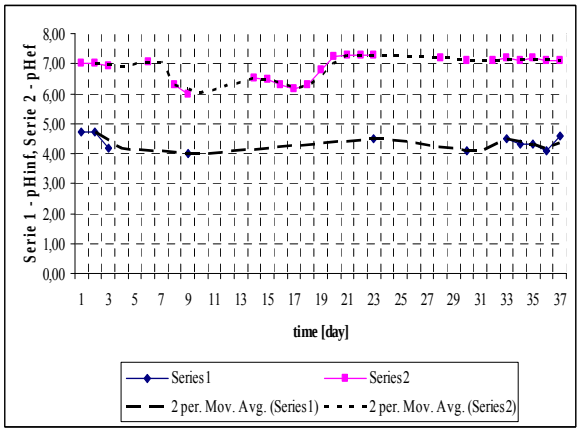
D [day^{-1}]	Q [L.day^{-1}]	Q_{sp} [L biogas/L medium.day]
0.025	80	1.0
0.0125	30	0.375

It is evident from Table 2 that the dependence $Q_{sp} = f(D)$ is nonlinear.

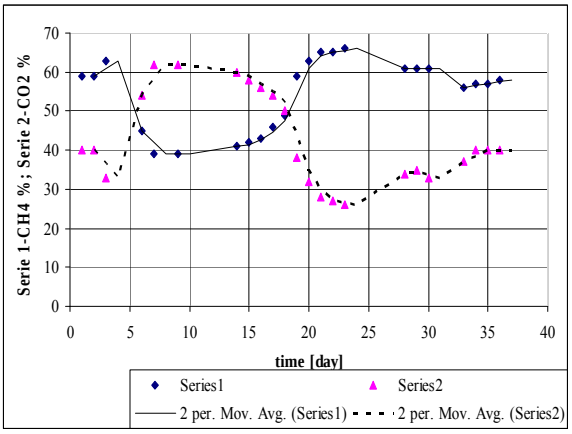
Experiment 3. Organic overloading of AD of WFV.
In an appropriate moment, after a long period of stable operation in semi-continuous mode with D = 0.025 day^{-1} and total solids of 43 g/L and organics of 40 g/L of the influent, an organic overloading of AD of WFV was done as follows: organic load (OL) = 240 g/L in day 3, and 160 g/L in day 4. This overloading provoked a break-down of the process – the biogas yield (Q) decreased briefly (from 180 L in day 4 to 2.9 L in day 8), pH of the anaerobic digester medium dropped from 7.0 to 6.0 and volatile fatty acids (VFA) concentration (measured with the Ripley method) increased from about 1.8 g/L to 3.5 g/L in day 16. The transient behaviour of Q (L/day) and VFA concentration (×10 g/L) are shown on Fig. 17a, transient behaviour of pH of the influent and of the effluent – on Fig. 17b, and transient behaviour of CH_4 [%] and CO_2 [%] – on Fig. 17c. After a period of two weeks the process recovered slowly and a new feed started as follows: in day 23 – 1.5 L, in day 30 – 3.5 L with OL = 40 g/L, in day 33 – 2.5 L.



a) transient behaviour of Q (L) and VFA concentration (x10 g/L)



b) transient behaviour of pH of the influent and of the effluent



c) transient behaviour of CH_4 [%] and CO_2 [%]

Fig. 17 Organic overloading
(in day 3 – 6 L, in day 4 – 4 L; in day 23 – 1.5 L,
in day 30 – 3.5 L with OL = 40 g/L; in day 33 – 2.5 L)

Conclusion

A new pilot biogas plant has been designed to work out and scale up various AD technologies based on different types of feedstock. All the data will be stored on the PC for quick reference and possibly data mining, but certainly for the parameter identification and verification of different AD mathematical models. Some data are further processed to produce some unmeasurable AD process variables or optimized control parameters on the basis of various estimation and control algorithms under development and testing.

Some experiments have been performed. They have proved the good performances of the presented biogas plant.

Acknowledgements

This work has been supported by contract No. ДО 02-190/08 of the National Science Fund of Bulgaria.

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