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Energy evaluation of anaerobic digesters

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Abstract: - A method is developed for the energy evaluation of anaerobic digesters. It incorporates a model for the calculation of the energy flows to and from the digester and an algorithm to identify the parameters of the model. Application of the method is demonstrated in a pilot-plant that processes diluted poultry manure at 35^{o}C and 20d hydraulic retention time. The plant is initially proved to have a strongly negative energy outcome, due to its small size and its design philosophy, the last being based on environmental rather than energy saving principles. Nevertheless, if we replaced existing electric heater with a gas burning one, and slightly enhanced the insulation of the reactor (to decrease heat losses by 30%), the energy outcome would become marginally positive. Furthermore, if we decreased hydraulic retention time to 10 days, increased reactor temperature to 40^{o}C and applied 50% heat recovery, the net energy outcome would significantly increase and the waste to energy conversion efficiency would approach the value of 20%. Design parameters and operating conditions that present major impact to the energy efficiency of this specific plant, proved to be the volatile solids content of the feed, the reactor heat losses coefficient and the hydraulic retention time.

Key-Words: - Anaerobic digestion; Evaluation; Energy efficiency; Net biogas; Identification; Optimization;

1 Introduction

Anaerobic digestion is advantageous from the energy point of view, when is for instance compared to aerobic process, as it consumes less energy, leads to the production of less sludge and among its final products a fuel, biogas, is included. Furthermore, anaerobic digestion is unique in combating high load polluted waste, succeeding satisfactory removal efficiencies (Mata-Alvarez et al., 2000). This is not exactly the case however with the energy results of the process, despite the fact that it is generally considered as a mean to produce renewable fuel; its energy requirements may become comparably high and even exceed its energy outcome (Chen, 1983), depending on several parameters and requiring so a specific investigation for each case.

To this aim, a simplified method has been developed for preliminary energy evaluation of anaerobic digesters. The method incorporates (i) a model for the calculation of energy flows and for the lay down of the energy balance, and (ii) the algorithm for the estimation of the parameters that are required in the model. It allows (a) the energy evaluation of a digester (b) the identification of the major design parameters or operating conditions that mostly impact its energy results and (c) it helps the designer to find out modifications to the improvement of the energy efficiency of the unit. The application of the method is demonstrated in an existing pilot-scale digester, which is fed with diluted poultry manure.

2. Problem Formulation

2.1 Criterion for energy evaluation

Various criteria have been suggested for the evaluation of anaerobic digesters as the specific biogas production (energy criterion), the organic matter in the effluent (environmental criterion) or a combination of above two criteria (Simeonov et al., 1996). In energy evaluation, either the use of combustion heat or the use of exergy can be alternatively used, although the application of the second consideration is not mature yet, due to the numerous data needed for such calculations (Claassen et al., 1999). Life cycle evaluation, which constitutes a more recent approach (Berglund and Boerjesson, 2006), is applied when the energy requirements of other relevant processes (as collection of raw material, transportation, disposal of effluent etc.) must be accounted for, too. Net biogas production constitutes also an important indicator, and may characterize the process if reduced to an appropriate reference quantity. As such a quantity we introduce here the energy content of the waste, and define so the *waste to energy conversion efficiency WECE,* defined as the ratio:

$$WECE = \frac{Energy\ of\ net\ biogas\ production}{Energy\ content\ of\ waste} \quad (1)$$

The energy quantities in eq. (1) correspond to a complete calendar year, in order to take into account ambient temperature variations and the consequent changes caused to the – usually high - heating requirements of the plant.

2.2 Estimation of energy flows

The model is based on a simplified lay-out of an anaerobic digester, as presented in fig.1. The feed line (1), the reactor (2), the re-circulation pump (3), the heater (4), the biogas line (5), the rejection line (6) and the heat exchanger (7) are noticed.

Three categories of energy flows are distinguished: (a) energy from the incoming flows (waste) (b) energy flows of the effluents (c) energy needs of the process (including heat and electricity). The following equations (2) to (7) are used for the estimation of the various energy flows to and from the system (in J/yr), namely E_W (energy content of the incoming waste), E_P (preheating load of the feed), E_R (heat losses of the reactor), E_A (agitation requirements), E_E (heat recovery), E_B (energy content in biogas):

$$E_W = F \cdot t_Y \cdot VS \cdot HHV_{GL} \quad (2)$$

$$E_P = F \cdot \rho \cdot C_P \cdot DD(T_R) \quad (3)$$

$$E_R = 86{,}400 \cdot V_R \cdot K_{V,R} \cdot DD(T_R) \quad (4)$$

$$E_A = 86{,}400 \cdot V_R \cdot W_{A,R} \cdot t_Y \quad (5)$$

$$E_E = \varepsilon \cdot F \cdot \rho \cdot C_P \cdot DD(T_R) \quad (6)$$

$$E_B = t_Y \cdot G_{MET} \cdot HHV_{MET} \quad (7)$$

where F is the volumetric flow rate of the waste (m^3/d), V_R is the reactor volume (m^3), Θ is the hydraulic retention time ($=V_R/F$, in d), t_Y is the operation time within a year (d), VS is the volatile solids of the influent waste expressed as equivalent in glucose (kg/m^3), HHV_{GL} is the high heating value of glucose (J/kg), ρ is the density of the waste (kg/m^3), C_P is the specific heat of the waste (J/kg-^oC), $DD(T_R)$ are the heating degree-days (^oC-d) based on T_R, $K_{V,R}$ is the volumetric heat loss coefficient of the reactor (W/m^3-^oC), $W_{A,R}$ is the mean electric power consumed by the agitation system per reactor volume (W/m^3), G_{MET} is the methane production rate (m^3/d), HHV_{MET} is the high heating value of methane (J/m^3) and ε the effectiveness of the heat exchanger (dimensionless). Last quantity equals $N/(N+1)$, where N is the number of heat transfer units of the heat exchanger.

The energy content of the liquid and solid effluents of the digester is ignored, as we especially focus on the conversion of waste to fuel.

Introducing conversion efficiencies of biogas to heat n_H and to electricity n_E, respectively, the ratio *WECE* gets the form:

$$WECE = \frac{E_B - \{E_P + E_R - E_E\}/n_H - E_A/n_E}{E_W} \quad (8)$$

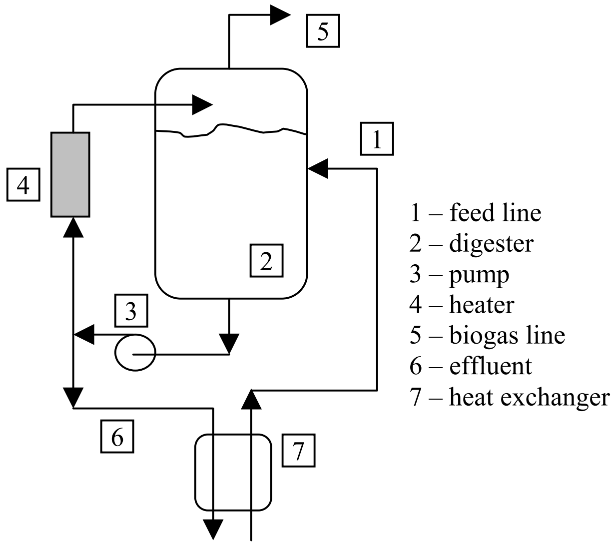

Fig.1. Simplified lay-out of the system

2.3 Identification of parameters

The application of eq. (8) pre-supposes the knowledge of several parameters, that are distinguished to three categories: (a) parameters concerning thermal behavior of the system (b) parameters relevant to the biochemical processes and (c) parameters dealing with engineering aspects. To identify these parameters, systematic experiments are required.

2.3.1 Heat losses coefficient

Volumetric heat losses coefficient of the reactor can be identified by monitoring heating needs during a time period when waste is not entering the reactor (e.g. the time between two successive batches). In that case, total heating needs are given by eq. (4) only, which can be written in the following integrated form:

$$\Sigma Q_H \cdot \Delta t_H = K_{V,R} \cdot \{\ V_R \cdot \Sigma \Delta T \cdot \Delta t\ \} \quad (9)$$

where Δt is the time step used for the numerical integration (s), Δt_H is the time the heating system operates within the above time step (s), Q_H is the capacity of the heating system (W) and ΔT is the temperature difference between the reactor and its environment (°C). As a consequence, the volumetric heat loss coefficient $K_{V,R}$ can be easily identified by monitoring the thermal behavior of the reactor and applying linear regression analysis to the results.

2.3.2 Biochemical parameters
A number of biochemical processes take place in the digester, in a successive, simultaneous or even competitive manner. Notwithstanding the complicated of the processes, experience has indicated that a simplified first order kinetic model may give a good description of anaerobic digestion. In that case, two major parameters may describe the system, namely the kinetic constant K (in d^{-1}) and the refractory fraction of volatile solids R (dimensionless) that determines the non biodegradable material. It is easily proved that methane production G_{MET} (m^3/d) is approximated by the expression:

$$G_{MET} = 0.35 \cdot V_R \cdot K \cdot S_O \cdot \frac{1-R}{1+K \cdot \Theta} \{1-e^{-(D+K)t}\} \qquad (10)$$

where S_O is the influent volatile material expressed in COD (kg-O_2/m^3), D is dilution ($=1/\Theta$, d^{-1}), R is the refractory fraction of volatile solids, t is time (d) and factor 0.35 stands for m^3-CH_4 produced per kg-COD removed. According to eq. (10), the time constant is $\{1/(D+K)\}$ and equilibrium production is $G'_{MET} = 0.35 \cdot V_R \cdot K \cdot S_O \cdot (1-R)/(1+K \cdot \Theta)$. A non-linear least squares regression analysis of production history may lead to the identification of these parameters, K and R.

2.3.3 Engineering parameters
Determination of minimum energy requirement for agitation can be estimated by decreasing stepwise the rate of agitation (actually by decreasing the frequency with which agitation is applied) until some indication of instability appears (increase of volatile fatty acids in relation to alkalinity, or decrease of biogas production).

3 Case study
As a case study we evaluated the pilot-scale digester of our Institute. This pilot plant consists of (fig. 2, from left to the right) the waste feed tank, the continuously stirred tank reactor with a capacity of 100 L, the sludge separation unit, a biogas cleaning and upgrade arrangement, the control panel and the methane storage tank.

The plant was operating at mesophilic conditions (T_R=35°C) with 20d hydraulic retention time, and was supplied with diluted poultry manure having COD=95g/L and equivalent VS=79.8g-glucose/L (other characteristics as per table 1). After reaching steady state, the unit was producing 150L-biogas/d; at the same time the re-circulation pump and the electric heater of the plant were consuming 370W_e and 1kW_e, respectively, both of them being however intermittent loads.

The model can be applied for the evaluation of the plant, provided that all parameters are known. Consumption of control systems (control panel, electro-pneumatic valves) is ignored here, as in general this load is of minor importance in commercial systems.

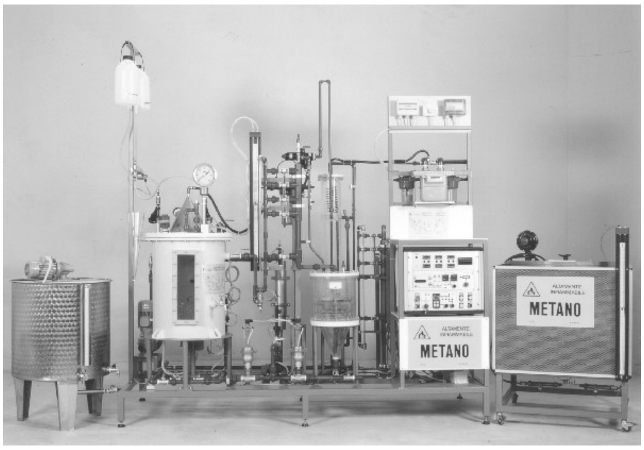

Fig. 2. Picture of the pilot plant unit

Table 1 Main characteristics of diluted poultry manure, used as feed in the experiments

pH	7.4 (at 22°C)
Total Solids, % w/w	5.6
Volatile Solids, % w/w	3.3
COD, kg-O_2/m^3	92.4
Oil and grease, % w/w	2.4
Proteins, % w/w	0.7
Carbohydrates, % w/w	0.2

3.1 Identification of the parameters
The thermal behavior of the reactor and the operation of its heating system were monitored. By applying linear regression analysis to the data collected (as per fig. 3), we found – according to eq. (9) - the reactor heat losses coefficient $K_{V,R}$ to be equal to 11.92W/m^3-°C.

Afterwards, we applied non-linear least squares regression analysis to production data (simulation shown in fig.4) and identified the biochemical related parameters at K=0.18d^{-1} and R=0.343.

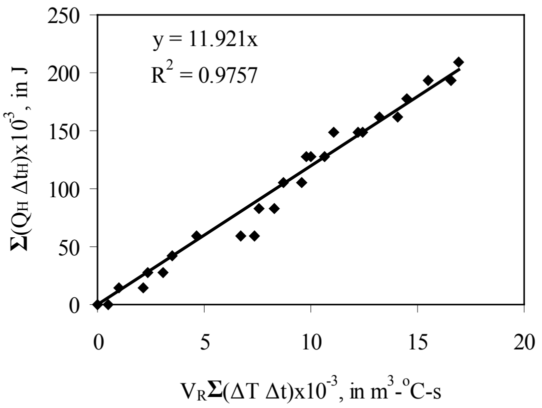

Fig.3 Thermal behavior of the reactor and simulation results, to identify $K_{V,R}$

Last, by testing various agitation rates (fig. 5), we found out that when the mean power consumed for agitation reached 30 W/m^3 the biogas production dropped rapidly. We increased agitation rate and confirmed that the value of $W_{A,R}$=40W/m^3 is a safe limit, allowing at the same time minimization of the energy requirements for the agitation in the digester.

The degree-days were estimated according to hourly temperatures of Athens (Gelegenis, 1999). All data and parameters used in the model are presented in table 2.

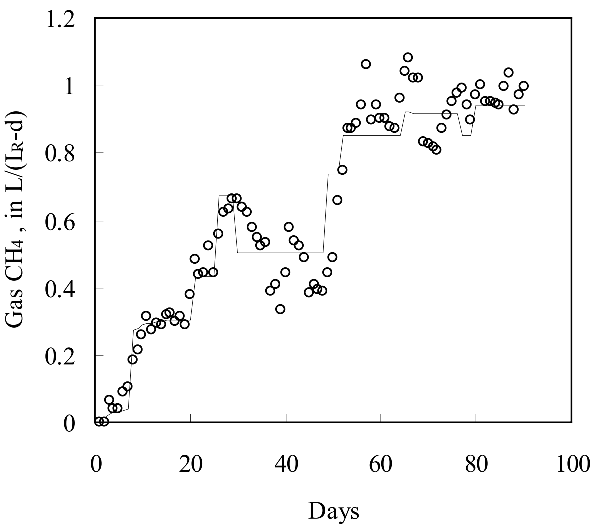

Fig.4 Production history and relevant simulation to identify *K, R.*

Table 2 Data used for the application of the method to the pilot plant of T.E.I. of Athens

VS	79.8kg/m^3	$W_{A,R}$	40W/m^3
COD	95kg/m^3	*K*	0.18d^{-1}
V_R	0.1 m^3	*R*	0.343
F	5x10^{-3}m^3/d	$DD(T_R)$	6187^{o}C-d
Θ	20d	t_Y	365d
T_R	35^{o}C	HHV_{GL}	1.4x10^{7}J/kg
$K_{V,R}$	11.92W/m^3-^{o}C	HHV_{MET}	3.4x10^{7}J/m^3

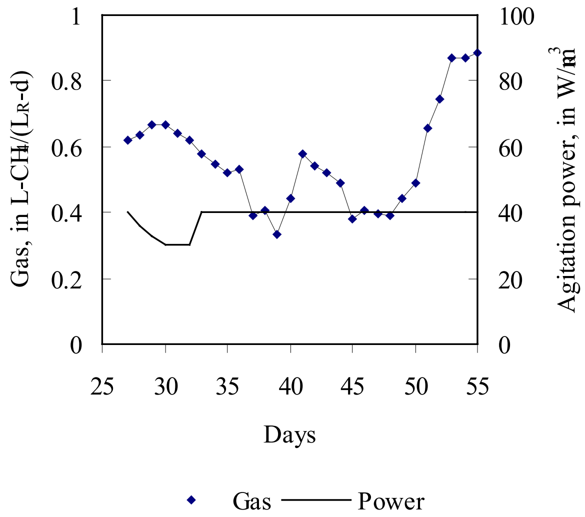

Fig.5 Determination of agitation requirements

3.2 Evaluation of the pilot plant

Based on the design characteristics of the pilot plant, the operating conditions and the parameters identified, we proceeded to the energy evaluation of the unit. Applying eq. (2) to (5) and (7) (the plant does not include a heat exchanger) we estimated the annual energy flows as shown in table 3. To estimate the net biogas production we considered efficiency of conversion of biogas heating value to electricity n_H=35%.

A negative outcome resulted, which is justified by the following reasons:

(a) insufficient insulation of the system
(b) long hydraulic retention time
(c) use of electricity for heating purposes
(d) small size of the reactor
(e) large size of the circulation pump
(f) no application of heat recovery.

The conditions under which the specific plant could lead to a positive energy outcome are further investigated.

Table 3 Energy flows in the pilot plant

	Energy (kJ/yr)	Equivalent from biogas (kJ/yr)
E_W	2,039,657	
E_P	-129,930	-371,229
E_R	-637,531	-1,821,517
E_A	-126,144	-360,411
E_B	1,060,783	1,060,783
	Net production	-1,492,374

3.3 Sensitivity analysis

3.3.1 Modification of the design of the system

According to table 3, the major energy consumption deals with the reactor losses (E_R) because of above mentioned reasons (a) to (c) (para. 3.2). However, there are possibilities to modify the design of the system and amend these factors to a more efficient operation. If a gas heater (with efficiency n_H=85%) was used in the place of the electric heater, biogas equivalent energy needs would decrease to about E_R=750,000 kJ, which is almost 40% of the present value.

When the reactor heat losses coefficient $K_{V,R}$ is expressed per external surface of the reactor, a value of $K_{A,R}$=1.0W/m^2-^{o}C arises. However, a 30% lower value ($K_{A,R}$=0.7W/m^2-^{o}C) is still a realistic heat losses coefficient, and can be relatively easily attained by adding another insulation layer. In that case $K_{V,R}$ would be 8.35W/m^3-^{o}C and reactor losses would decrease by other 30%.

Last, the application of a heat exchanger with an effectiveness as low as 0.50 could be easily realized. However, this would have a minor effect due to the long hydraulic retention time; indeed, this results to low preheating needs and consequently the energy saving potential from the corresponding effluent is restricted.

By modifying accordingly the data in eq. (2) to (8) (using the values n_H=85%, $K_{V,R}$=8.35W/m^3-^{o}C, ε=0.50) we re-estimate the efficiency at 4.8%. Hence, with some modifications in the design of the unit, it may become energy efficient as it is shown in table 4. It is worthwhile that even without the addition of the heat exchanger, but only by replacing electric with gas heater and adding an insulation layer to the reactor, the net energy outcome in the digester becomes marginally positive (*WECE*=1.1%).

Table 4 Energy flows in case of better insulation, use of gas heater and application of heat recovery

	Energy (kJ/yr)	Equivalent from biogas (kJ/yr)
E_W	2,039,657	
E_P	-129,930	-152,859
E_R	-446,271	-525,025
E_A	-126,144	-360,413
E_E	64,965	76,429
E_B	1,060,783	1,060,783
	Net production	+98,915
	Efficiency of conversion	4.83%

3.3.2 Change of operating conditions

In order to investigate alternative operating temperatures, we consider that kinetic constant follows Arrhenius equation:

$$K=K_o \cdot exp(-E/RT) \quad (11)$$

where E is the activation energy (6.3x10^{4}J/mole), R is the ideal gas constant (8.316 J/mole-K) and temperature T is introduced in degrees Kelvin.

We kept biochemical conversion efficiency almost unchanged (about 70%). Modifying T_R and Θ to the increase of energy efficiency of the conversion, we concluded to the values of T_R=40^{o}C and Θ=10d. In this case *WECE* becomes 18.0%. Higher efficiencies can even be reached (up to 25%) if a lower retention time is allowed. Indeed, due to the small size of the reactor and consequently the high heat losses via its relatively extended surfaces, optimization leads to small retention times. The last however may not be allowed, in order to avoid wash-out of the microorganisms but also to succeed acceptable COD removal efficiency.

3.3.3 Detailed sensitivity analysis

Based on the above optimum conditions we performed sensitivity analysis, by varying operating conditions and design characteristics from –25% up to +25% of their nominal values. The results are shown in fig. 6. The nominal values applied were VS=79.83g/L, $K_{V,R}$=8.35W/m^3-^{o}C, T_R=40^{o}C, Θ=10d, $W_{A,R}$=40W/m^3. Reactor volume and effectiveness of heat exchanger are not included in this diagram, as proved to have – for this specific unit – minor effect to the energy efficiency of the plant.

From fig.6 it is concluded the dramatic drop of efficiency with use of diluted waste (low VS), but also the noticeable increase at lower retention times.

The selected reactor temperature T_R was a local optimum, while both $K_{V,R}$ and $W_{A,R}$ significantly effect the efficiency of the plant, with the first being even more important.

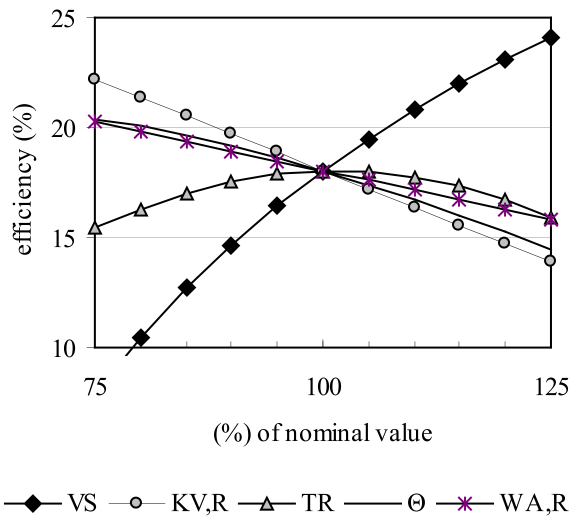

Fig.6 Sensitivity analysis

4 Conclusion

A method was developed for the energy evaluation of anaerobic digesters. The method is based on the effectiveness of the energy conversion of waste to biofuel, and may lead to the improvement of the energy efficiency in digesters, by modifying their design and/or the operating conditions.

The method was applied for demonstration purposes to a pilot plant unit operating with poultry manure at mesophilic conditions and showed that the unit has a negative energy outcome. Various reasons were recognized for this, including the small size of the unit and its educational and environmental rather than energy orientation; this fact justifies energy inefficient practices as insufficient insulation, electric heating and over-dimensioning of pumping equipment.

The application of the model allowed furthermore to find out measures to succeed a positive energy outcome, while keeping almost unchanged the biochemical conversion efficiency. Energy efficiency proved for this plant to be more sensitive to the volatile solids content of the waste and to the heat losses coefficient of the reactor. The hydraulic retention time, the reactor temperature and the agitation requirements also have a major impact, while the reactor volume and the effectiveness of heat recovery may have a minor effect only. Although demonstrated in a pilot-plant, the method can be easily adapted to commercially operating digesters.

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