Self-heating of anaerobic digesters using energy crops

H. Lindorfer *, R. Kirchmayr, R. Braun
BOKU - University of Natural Resources and Applied Life Sciences, Vienna
Department for Agrobiotechnology, IFA-Tulln, Institute for Environmental Biotechnology,
Konrad Lorenz Str. 20, 3430 Tulln, Austria
* Corresponding author, E-mail: harald.lindorfer@boku.ac.at,.

Abstract

With the increasing application of energy crops in agricultural biogas plants and increasing digester volumes, the phenomenon of self-heating in anaerobic digesters appeared in some cases. Until now this development was just known from aerobic systems. To get an idea of the thermodynamics inside an anaerobic digester, a detailed analysis of all heat fluxes in a full scale agricultural biogas plant was carried out. Several experiments were realised to quantify the influences of different internal and external energy sources. To estimate the impact of self-heating in anaerobic systems, data of other full scale agricultural biogas plants in Austria were collected. Alternatives to the cooling of the digesters are discussed basing on individual experiences of several plants. A connection between carbohydrate rich substrates, especially with high starch contents, and the self-heating could be shown. But from the results it can be assumed that heat enthalpy due to anaerobic microbial metabolism plays a key role in self-heating, which is in contrast to the current thermodynamic knowledge.

Key words: Anaerobic digestion, digester thermodynamics, energy crops, heat fluxes, self-heating

Introduction

In Austria the number of agricultural anaerobic digesters using energy crops is increasing considerably. This is to a certain extent the result of governmental promotion of renewable energies. On the other hand, the use of crops for biogas production seems to be a promising alternative for farmers in regions with sufficient agricultural land available.

Although anaerobic digestion is a quite experienced technology, some new technical problems in the anaerobic process performance appeared with the application of new substrates. One of these problems is the self-heating of digesters. This phenomenon appears mainly in digesters using energy crops, especially grains from maize or wheat, and in plants with mesophilic process performance.

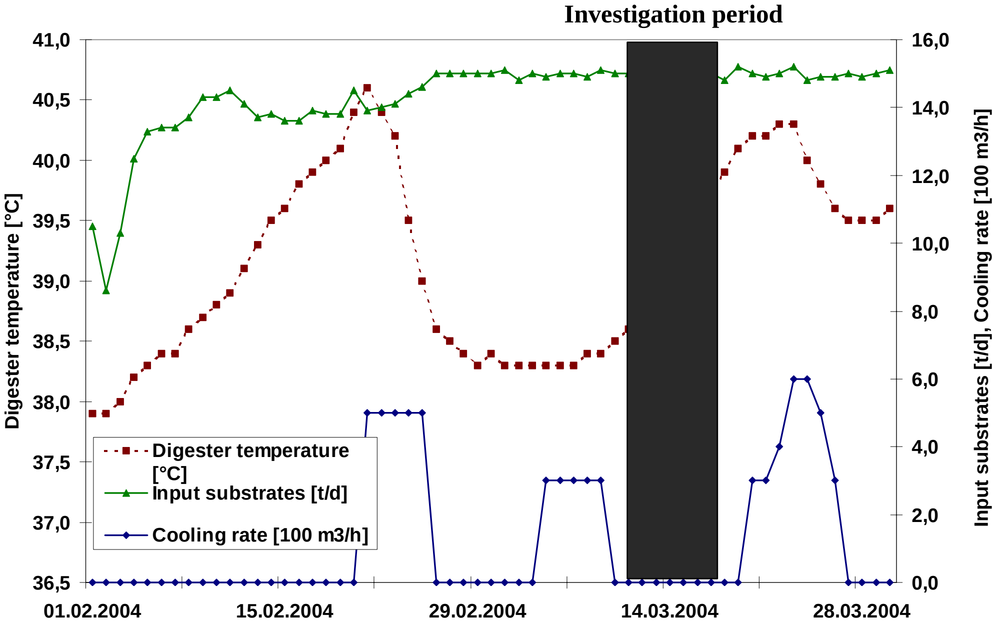

Figure 1: Digester Temperature, loading and cooling rate of the energy crop digester in Reidling (Austria), representative period march 2004.

In Austria, approx. 40 % of the interviewed operators of agricultural biogas plants report that phenomenon. In figure 1, the initial problem leading to this work is demonstrated. A continuously rising temperature curve leads to a process breakdown connected to immense drops in the biogas yield, due to thermal inhibition of the microbial community. The usage of cooling systems, usually with water, results in an immense consumption of fresh water. The construction companies still do not provide economic cooling systems in their new plants, since the effect of self-heating in anaerobic digestion processes is in contrast to the current thermodynamic knowledge.

To investigate that phenomenon, a detailed analysis of the heat fluxes was carried out in an agricultural digester situated in Lower Austria. All heat energy in- and outputs were recorded and quantified. Furthermore, several tests were realised, e.g. to investigate the influence of oxygen input via solid substrates loading and the role of different substrates. Further research on the influence of the prevailing microbial community and on microbial metabolism is still conducted.

Material and methods

The period in which the thermodynamic calculation was carried out is shown in figure 1, marked in grey. It was fixed in a phase without digester cooling or heating and with a continuous rise of the temperature of 0.15 K daily. In the following part the different heat fluxes in anaerobic full scale digesters are quantified. To follow the balance, the way of calculation is presented as well. The digester in which the research was realised is a mesophilic, continuous stirred tank reactor (CSTR) with a main digester volume of 2000 m^3, a second digester step (1850 m^3) with gas storage and an open storage tank (6000 m^3) for the residual manure. The substrates applied were pig manure (50 %) and solid energy crops (50 %) like silages from maize and rye, grinded grains from maize and wheat, Corn-Cob-Mix (CCM) and residues from vegetable processing. The mean process temperature was 39 °C, the mean content of total solids was 7-8 %.

Most of the data used for calculations was provided by the owner of the plant (substrates, input, temperature, cooling and gas data) and the constructing company AAT, Bregenz, Austria (insulation data, heat transfer from stirring). Most formulae were taken from LANGHANS (2000) and LESCHBER & LOLL (1996).

To exclude the influence of oxygen supply via solid substrates input, the solid substrates were added in a CO_2 atmosphere during two periods, each one of 5 days. For that purpose, a gas supply with a continuous CO_2-flow was installed at the lower end of the spiral pump which transports the solids into the digester. To estimate the influence of different substrates on the digester temperature, defined changes of the substrate mix and the loading rate were realised during 2004.

Results and discussion

Total energy content of the input substrate

Based on calorimetric results from HARTMANN & LEWANDOWSKI (1999) and OECHSNER (2005), the energy content of energy crops can be estimated at 17 $MJ.kg^{-1}$ TS. The average content of volatile solids in the used substrates was 96 % of the total solids content. The input of total solids, composed of manure and energy crops, averaged out at 8.35 t $TS.d^{-1}$. Therefore the total calorimetric energy content of the input substrates results in 141950 $MJ.d^{-1}$ of which 94183 $MJ.d^{-1}$ were converted into 2632 $Nm^3.d^{-1}$ of methane. This corresponds to 73 % of the total energy content. The residual sludge contains about 10.5 % of the energy in the form of non degradable organic substances like lignin or cellulose or bacterial biomass. The rest of the energy are probably heat losses.

Heat energy consumption/losses

Substrate warming-up. The energy to warm up the input substrates (Q_S) was calculated using formula (1). The daily input of substrates (M_S) in the investigated period was 30 t, the temperature difference (ΔT) between the substrate and the digester content was approximately 22 K (input substrate 290 K, digester 312 K) . The other factors are concerning the conversion of the unit (kcal to kJ). This results in an energy consumption to warm up the input substrates (Q_S) of 2764 MJ.d^{-1}.

$$Q_S = M_S * \Delta T * 1000 * 4.1868 \qquad [kJ*d^{-1}] \tag{1}$$

M_S: Mass of the substrate [t]
ΔT: temperature difference [°K]

Radiation. The heat energy which is lost through radiation (Q_A) was calculated using formula (2). The surface of the investigated digester was 584 m^2 (above ground) and 660 m^2 (subterranean). The specific heat transfer coefficient was 0.383 [$kcal*m^{-2}*h^{-1}*K^{-1}$] (Fa. AAT), the temperature inside the digester was 312 K, the average outside air temperature was 277 K and the subterranean temperature was estimated as 279 K. This results in an energy loss through radiation (Q_A) of 1625 MJ.d^{-1}.

$$Q_A = A * k * (T_R - T_U) * 4.1868 \qquad [kJ*h^{-1}] \tag{2}$$

A: Surface digester [m^2]
k: Heat transfer coefficient [$kcal*m^{-2}*h^{-1}*K^{-1}$]
T_R: Temperature digester [K]
T_U: Temperature surrounding [K]

Heat discharge connected to the produced biogas. The heat discharge connected to the output of hot, water saturated biogas (Q_{gas}) from the digester to the gas storage was calculated using the formulas (3) and (4) and approximated values (5) – (7) from LANGHANS (2000). In the investigated period the average gas production was 6030 m^3 (312 K) with an percentage of approximately 50% CH_4, which result in 7070 kg of daily produced dry biogas. The proportional mass of water with 100 % steam saturation in the biogas (x_{H2O}) at 312 K is 0.03988 kg $_{H2O}$.$kg_{biogas,dry}^{-1}$ (48.65 g.m^{-3} steam, 1171 g.m^{-3} biogas). The loss of heat energy due to the discharge of hot biogas (Q_{gas}) results in 4545 MJ.d^{-1}.

$$Q_{gas,wet} = m_{biogas,dry} * \left(c_{P,biogas} * (T + 273) + x_{H2O} * h_{steam}\right) \qquad [kJ.d^{-1}] \tag{3}$$

$$c_{P,Biogas} = \psi_{CH4} * c_{P,CH4} + (1 - \psi_{CH4}) * c_{P,CO2} \qquad [kJ.kg^{-1}.K^{-1}] \tag{4}$$

Ψ : Volume of CH_4 / CO_2 in the biogas [m^3]
C_P : Specific heat capacity [$kJ.kg^{-1}.K^{-1}$]
T : Temperature of the biogas [K]
h_{steam} : Enthalpy of evaporation [$kJ.kg_{H2O}^{-1}$]
m_{Biogas} : Mass of the dry/wet biogas [kg]
x_{H2O} : Steam fraction[kg $_{H2O}$.$kg_{biogas,dry}^{-1}$]

With (LANGHANS, 2000):

$$C_{P\,CH4} = 0.0097 * t + 2.1659 \qquad [kJ.kg^{-1}.K^{-1}] \tag{5}$$

$$C_{P\,CO2} = 0.0037 * t + 0.8161 \qquad [kJ.kg^{-1}.K^{-1}] \tag{6}$$

$$h_{steam} = 2505 - 2.388 * T \qquad [kJ.kg_{H2O}^{-1}] \tag{7}$$

Heat discharge connected to the residual sludge. The hot digester sludge discharged into the residual storage tank has to be regarded as a loss of heat energy as well. In the investigated digester 77 % of the mass input was discharged from the digester. This results in a daily output of 23.1 t. The difference of the temperatures is calculated using the same temperature levels as in the calculation of the input energy demand, 312 K inside and 290 K in the surrounding. The energy loss due to the residual sludge (Q_R) was calculated using formula (8) and results in 2183 MJ.d^{-1}.

$$Q_R = M_R * \Delta T * 1000 * 4.1868 \qquad [kJ*d^{-1}] \tag{8}$$

M_R: Mass of the residual sludge [t]
ΔT: Temperature difference [K]

Heating up of the digester sludge. During the investigated period there was still an additional self-heating inside the digester of 0.15 K per day. This means another energy release (Q_{SH}) which can be calculated using formula (9). The sludge volume in the investigated digester was 2000 m^3.

$$Q_{SH} = V_D * \Delta T * 1000 * 4.1868 \qquad [kJ*d^{-1}] \qquad (9)$$

V_D: Sludge Volume in the digester [m^3]
ΔT: Daily temperature difference caused by the heating up [K]

Heat energy supply

Heat generation due to stirring. Due to the stirring of the digester there is a heat energy release from the engine which could be transferred through the axis inside the digester. The constructing company (Fa. AAT) specified this energy as 7.6 kW per hour. This results in a daily heat energy input from the stirrer (Q_{ST}) of about 657 $MJ.d^{-1}$.

Biological desulphurisation. To reduce the H_2S in the biogas produced during the fermentation process, fresh air is pressed into the headroom of the digester. The H_2S is oxidised in an exothermic reaction (10) to elementary sulphur. The amount of the fed air is connected to the produced biogas. In this case 4 vol% of air was used for the desulphurisation. An average gas production of 6030 $m^3.d^{-1}$, led to an air supply of about 240 $m^3.d^{-1}$, with a load of 50,4 $m^3.d^{-1}$ of oxygen or 2117 mol O_2 (17 °C). This results in a heat energy release from desulphurisation (Q_D) of 1118 $MJ.d^{-1}$.

$$2\,H_2S + O_2 \rightarrow 2\,H_2O + S_2 \qquad \Delta H_R^\circ = -528\ kJ/Mol \qquad (10)$$

Oxygen input via solid substrates input into the digester. Due to the technical input equipment for solid substrates, a certain input of air together with the solids can be estimated. The oxygen in the air leads to an oxidation of organic compounds in the digester like it is shown in equation (11) for glucose degradation. Since the air which is entering is not quantifiable, the enthalpy data were generated via oxygen exclusions experiments (cf Material and methods).

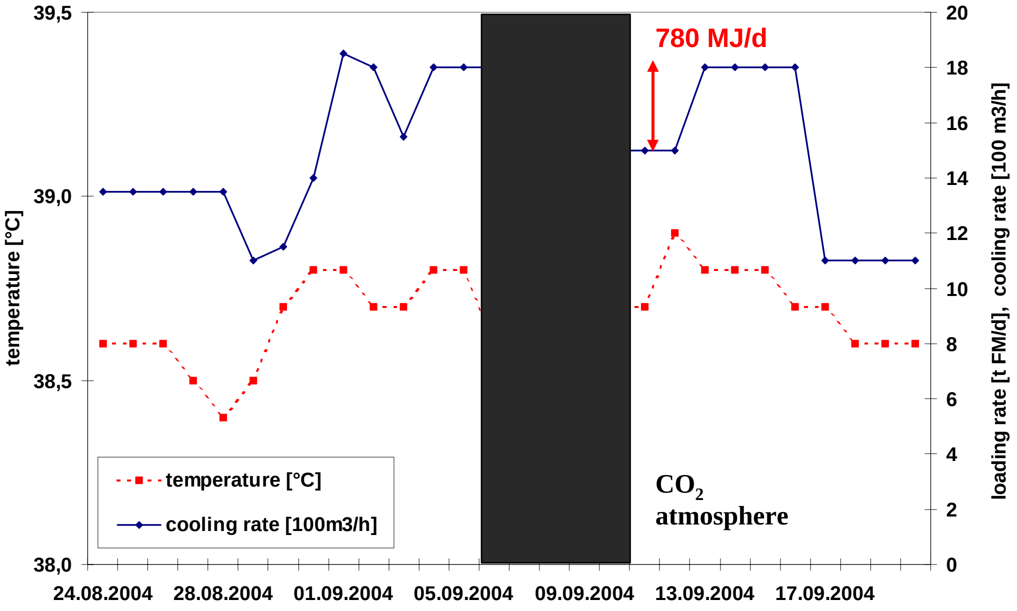

Figure 2: Oxygen exclusion experiment. Heat energy release was calculated on the amount and the temperature increase of the cooling water.

In figure 2 the period in which CO_2 atmosphere was installed is marked in grey. The mean value of the heat energy release due to oxygen input (Q_O) basing on two experiments was 810 MJ.d^{-1}.

$$1\ C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O \qquad \Delta H_R^0 = -1767\ kJ.mol^{-1} \qquad (11)$$

Heat release from neutralisation. Inside the digester there is a pH value of about 7.8. The silages that are used as solid substrates show a pH value of about 4.25. After Meier-Schneiders et al. (1996), the acidic substrate which is brought in will be neutralised in an exothermic way (12). But since there are just 10^{-4} mol.l^{-1} of H^+ ions in the input substrates the heat energy release caused by neutralisation is just 235.6 kJ.d^{-1}, which is very low and has no influence on the thermodynamics of the investigated digester.

$$OH^- + H^+ \rightarrow H_2O \qquad \Delta H_R = -55.9\ kJ.mol^{-1} \qquad (12)$$

Heat enthalpy (microbial heat). Gallert & Winter (2005) indicate a heat energy release of 4.6 % of the calorimetric energy content of the substrate glucose. In this case that would result in an heat release of 6530 MJ.d^{-1} if the substrate would consist just of glucose. Since the agricultural substrates consist of more substances, the heat release in this example was calculated basing on the reaction enthalpies of the stoichiometric degradation of reference substances for carbohydrates (glucose), fats (palmitic acid) and proteins (alanin). ΔH_R^0 values were calculated on ΔH_B^0 values of the educts and products which were taken from D'Ans & Lax (1983). To control the results, the theoretical biogas yield was calculated using the specific biogas yields for fats, carbohydrates and proteins according to Baserga (2004) and compared with the real biogas yield.

As it can be seen in the equations (13) – (15), the total heat enthalpy in the degradation of organic materials is strongly related to the composition of the biomass. In the anaerobic degradation of fats and proteins, $\Delta H_R^0 > 0$, which means that their anaerobic degradation is endothermic, at least in some cases. Due to the simultaneous exothermic degradation of the carbohydrates included in the substrates, the microbial heat production (Q_M) resulted in 2603 MJ.d^{-1}.

Since the control calculation of the biogas yield just differs 5.6 % from the real biogas yield (6389 m^3 theoretical, 6030 m^3 real), the calculated heat enthalpy value appears to be in a right dimension.

$$1\ C_6H_{12}O_6 \rightarrow 3\ CO_2 + 3\ CH_4 \qquad \Delta H_R^\circ = -138{,}5\ kJ/Mol \qquad (13)$$
$$2\ C_3H_7NO_2 + 2\ H_2O \rightarrow 3\ CO_2 + 3\ CH_4 + 2\ NH_3 \qquad \Delta H_R^\circ = +198{,}5\ kJ/Mol \qquad (14)$$
$$2\ C_{16}H_{12}O_6 + 14\ H2O \rightarrow 9\ CO_2 + 22\ CH_4 \qquad \Delta H_R^\circ = +544{,}5\ kJ/Mol \qquad (15)$$

Table 1: Composition and heat enthalpies of the input substrates.

	carbohydrates	**fats**	**proteins**
Input mass [t.d^{-1}]	6.83	0.24	0.96
Input mol [mol.d^{-1}]	37917	931	10787
Fraction [%]	85.1	2.9	11.9
ΔH_R [MJ.d^{-1}]	**- 5251**	**+ 507**	**+ 2141**

Summary heat energy balance

All the heat energy releases (Q_C) in the investigated period can be summarised in the form $Q_C = Q_T+Q_A+Q_{Gas}+Q_R+ Q_{SH}$. This results in a daily heat energy consumption of 12540 MJ.d^{-1}. The energy supply (Q_S) can be summarised in the form $Q_S = Q_{ST}+Q_D+Q_O+Q_N+Q_M$ in the regular digester processing. This results in a daily heat energy supply of 4750 MJ.d^{-1}. Compared to the calculated heat losses, there is still a heat deficit of about 7790 MJ.d^{-1}. In figure 2, an overview of the heat fluxes in the investigated digester is shown.

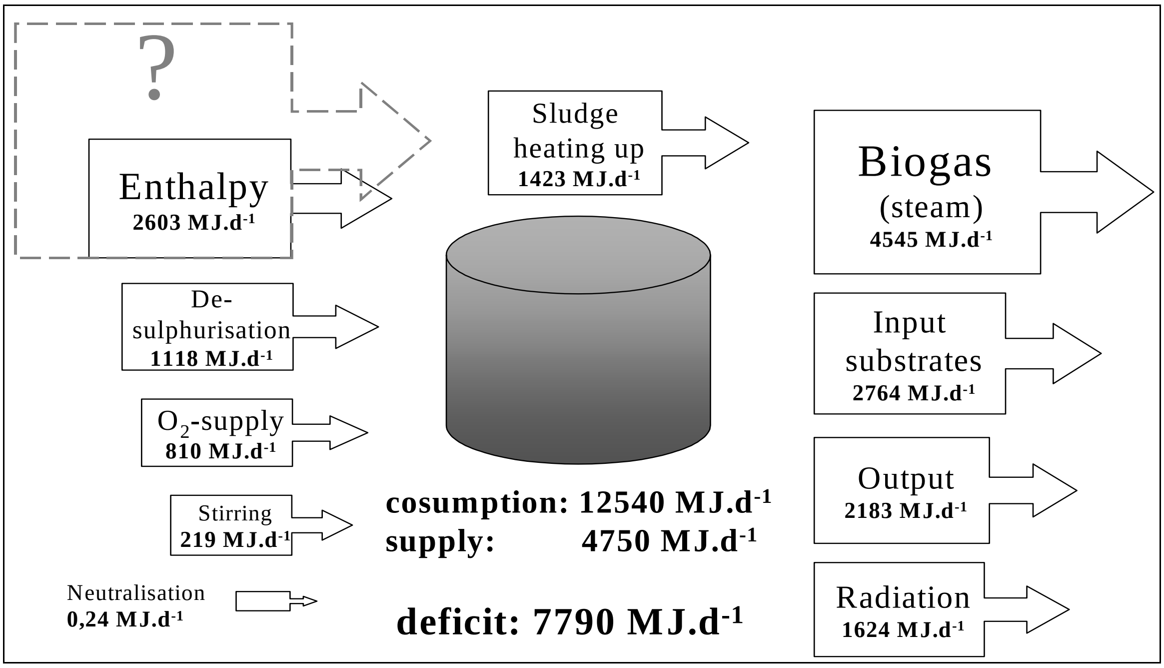

Figure 3: Thermodynamics of the main digester, biogas plant in Reidling (Austria), representative period march 2004.

Influence of substrates

As already mentioned, some experiments were carried out to isolate possible causes for the detected heat energy deficit. The analysis of the process data accompanying the realised substrate changes showed a strong effect of some substrates on the digester temperature. As it can be seen from the example in figure 3, the course of digester temperature and the cooling rate follow the input of corn/maize (silage of whole plant and grains). In this case the corn was substituted by silage from lucerne. The input of total solids was the same.

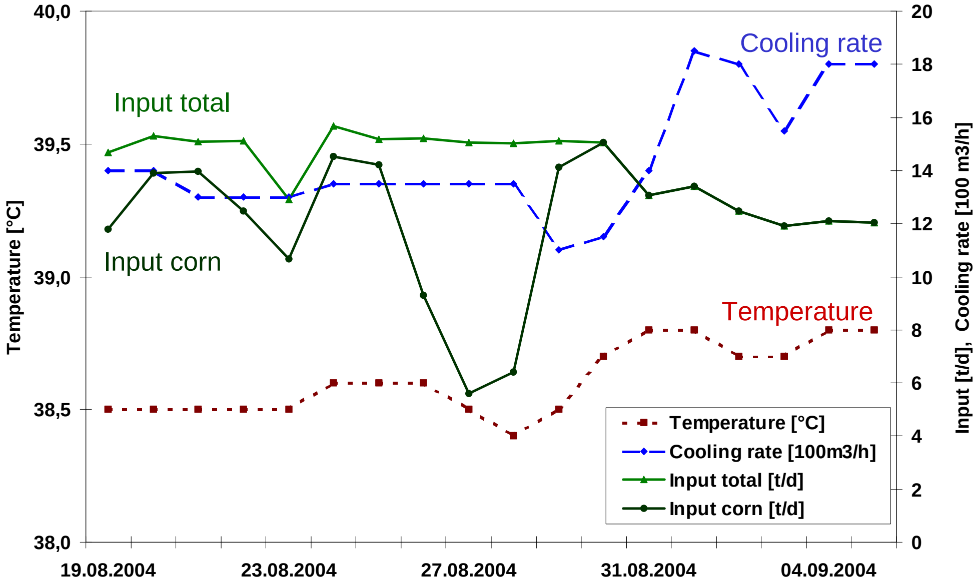

Figure 4: Impact of substrate change on digester temperature and cooling rate.

This increase in temperature connected with a substrate change was observed in other digesters as well, especially after the application of corn-cob-mix or grains from wheat and maize. The increase of the loading rate in general results in the raise of the digester temperature as well, as you can see in figure 4. After the increase of the input of total solids into the digester to 2 $t.d^{-1}$, the temperature and the cooling rate raised enormously.To compare the results of the experiments, 37 operators of agricultural digesters in Austria were interviewed. Fourteen of them, mostly running digesters with a volume bigger than 1000 m^3, and all of them using maize or other ceraels as one of the main substrates, observed the self-heating in their plant. 17 operators usually with smaller digester volumes didn´t observe self-heating (five didn´t give information about this). But like there are exceptions in all directions the causes can not be focussed on one or two parameters.

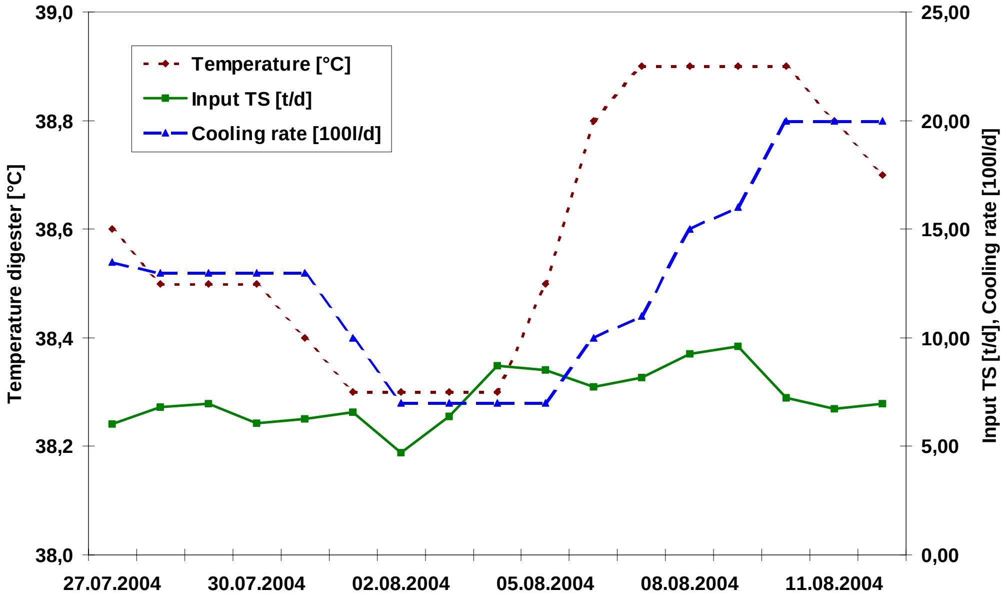

Figure 5: Impact of the increase of the loading rate (total solids) on digester temperature and cooling rate.

Discussion

Within the concerned parties (operators of biogas plants, constructing companies and involved scientists), there exist different theories concerning the self-heating of digesters. The majority believes that the input of oxygen via solid substrate input is the main cause. But calculating the additional amount of air that is needed to generate the necessary heat energy through aerobic degradation of glucose (11), you would end at about 2200 Nm^3 of fresh air which had to be added every day, which is obviously impossible. Furthermore, one digester is using a liquid input system in which solid substrates are first mixed with recyclate and then pumped into the digester. This digester shows the same thermodynamic behaviour as those feeding solid substrates directly.

Another theory is the influence of solar radiation, but considering the facts that the self-heating appears all the year in some plants and that this balance was carried out in the beginning of march with an average surrounding temperature of 4 °C, this theory can be excluded as well. As previously found out, the percentage of carbohydrates in the substrate plays a key role in the thermodynamics of an anaerobic digester. Mainly substrates with a high starch content as potatos, maize and other cereals, show great influence on the self-heating of digesters. Still, the maximum theoretical heat enthalpy based on literature data for anaerobic degradation of glucose is not enough to explain the self-heating. Additionally there is still no explanation for the fact that some digesters show this phenomenon, while others do not.

All these facts lead to the conclusion that the real cause for the self-heating of digesters is associated with the bacterial metabolism. That would implicate that the anaerobic metabolism could be much more exothermic than supposed so far in the main microbiological literature. However, a few studies did already obtain similar results. Gallert & Winter (2005) mention a potential self-heating capacity in anaerobic digesters of waste water treatment plants. Von Stockar & Liu (1999) presented data of so called enthalpy versus entropy driven growth of methanogenes, which partly show very high heat enthalpies. Finally Meier-Schneiders & Schäfer (1996) demonstrated that experimental enthalpy data could vary enormously from calculated enthalpy data.

As long as this phenomenon is not explained, the operators of anaerobic digesters are forced to either cool down their digesters further on or to let them heat up and thus risk a maybe significant temporary reduction of the biogas yield caused by thermal inhibition of the microbial community. At least two biogas plants realised that step and operate now in a temperature range between 38 °C and 45 °C without heating or cooling, controlled by the substrate input and the surrounding temperature. If the digester construction and chemical parameters inside the digesters allow it, the change to thermophilic processing at 55 °C could be an interesting alternative. Especially new digesters could start up directly with a temperature level higher than 40 °C, to avoid a change from a mesophilic to a thermophilic microbial community. Research on the specific biogas yield with the way of processing mentioned above and a controlled change to a thermophilic microbial community, with a minimum collapse of the biogas yield, are conducted.

Conclusions

The phenomenon of self-heating in anaerobic digesters using energy crops can not yet be entirely explained. In the present work, a detailed analysis of the heat energy fluxes in an agricultural digester was carried out. In combination with first results of the realised experiments concerning oxygen input and substrate effects, it can be assumed that the self-heating has to be traced back to microbial activity, which is in contrast to the current thermodynamic knowledge. But, data and experiences of other digesters in Austria give indifferent results. An interaction between carbohydrate rich substrates, especially with high starch contents, to the self-heating could be shown, but still there are exceptions. Biogas plants with small digester volumes will never have this phenomenon, since heat losses are higher than their self heating potential. To elucidate the phenomenon, more research has to be focussed on dynamics in the microbial community of anaerobic systems.

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References

Baserga, U. and Egger, K. (2004). Vergärung von Energiegras zur Biogasgewinnung. Report Biogas Forum. http://www.biogas.ch/projekte.htm

D'Ans,J. and Lax,E. (1983). Organische Verbindungen, Springer-Verlag, Berlin, Heidelberg, New York, Tokyo.

Gallert,C. and Winter,J. (2005). Bacterial Metabolism in Wastewater Treatment Systems. In: Jördening,H.J. and Winter,J. (eds), pp. 1-48, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

Hartmann,H. and Lewandowski,I. (1999). Produktion und Bereitstellung biogener Festbrennstoffe. In: Leitfaden Bioenergie, pp. 49-82, Fachagentur Nachwachsende Rohstoffe e.V..

Langhans,G. (2000). Der Wärmehaushalt der Vergärung (Teil1). *Entsorgungs-Praxis* (EP) 7-8**,** 20-23.

Leschber,R. and Loll,U. (1996). Klärschlamm, ATV Handbuch, Ernst & Sohn, Berlin.

Meier-Schneiders,M. and Schafer,F. (1996). Quantification of small enthalpic differences in anaerobic microbial metabolism--a calorimetry-supported approach. *Thermochimica Acta* 275 (1), 1-16.

Oechsner, H. and Helffrich, D. (2005). Technische Anforderungen an Biogasanlagen bei der Vergärung nachwachsender Rohstoffe. 3. VDI Fachtagung Energietechnik, Biogas Energieträger der Zukunft, Osnabrueck, 2005, Conference Proceeding.

Von Stockar,U. and Liu,J.-S. (1999) Does microbial life always feed on negative entropy? Thermodynamic analysis of microbial growth. *Biochimica et Biophysica Acta (BBA) - Bioenergetics* 1412 (3), 191-211.