Optimising simple biogas digesters for use in cold regions of developing countries

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Introduction

Livestock manures represent a valuable resource, which, if used properly, can produce clean renewable energy and replace significant amounts of mineral fertilizers. In most developing countries livestock production is increasing and consequently the amount of animal manure is growing and is a hazard to the environment because of lack of technology for using the manure efficiently as an energy source and a source of mineral fertilizer.

Fermentation of the manure in simple biogas digesters with direct addition of manure and human excreta to the digester is often recommended as a solution to inappropriate manure management. The biogas production will create jobs, and there are environmental and economical benefits. Further, the GHG reduction due to biogas production may be capitalized through CDM (Clean Development Mechanisms), which is a method for selling the reduced GHG emission equivalents at the international marked and channel the money back to the farmers.

After having visited several simple biogas plants at small animal farms in mountain regions with cold winters we are becoming aware, that the plants cannot produce the volumes of gas needed for cooking during the winter season (Hubei Province). This means that when the need of energy is largest the biogas plant can not provide the necessary energy, and there is an urgent need to improve the design of the digesters making them efficient during winter while at the same time being easy to operate. Further, the visits indicated that for the CDM assessment there is a need of a simple model for assessing the GHG reduction capacity of these biogas digesters.

In this presentation we intend to present ideas for new design of the biogas digesters with the purpose of increasing the gas production and also to maintain a high production both summer and winter. Further we will introduce a simple model for a valid assessment of the reduction in methane emission from stored animal manure as well as substitution of carbon dioxide emission from coal (Hayhoe et al. 2002).

Will simple digesters be beneficial a cold climate

Most literature claim that biogas production have several beneficial side effect in addition to production of energy efficiently by using a biomass high in water content. In the following is presented the benefits of biogass production using animal manure as being used in the Biogas Project Division Vietnam (SNV) and in the Hubei Eco-Farming Biogas Project in China.

Less dung/smell living environment (Masse et al. 1997)

Cleaner sanitation, less diseases (Albihn and Vinneås 2007)

Toilets improved

Reduced indoor air pollution in kitchen (Anonym 2004)

BOD5 reduced (Masse et al. 1997)

Less use of chemical fertilizer and pesticides

Green house gas reduction - CO2-neutral energy source (Møller et al. 2004)

These have been the arguments for the financial support to farmers constructing biogas digesters in the Hubei province of China. Many of the farmers installing simple not heated and not stirred biogas digesters live in the mountain regions, where winter temperatures is near 0°C and summer temperature 20-30°C (Table 1). It has been shown that temperature of stored slurry is closely related to air temperature (Hansen et al. 2006). Thus even though the digesters are buried in the ground one may expect the fermentation process rates to be very low during winter time and biogas production correspondingly low. Thus, at a visit in the region farmers were mentioning that there was very little biogas available during winter, where energy is needed. Further, at low temperatures one may a risk that all the benefits presented above disappears.

Therefore, to ensure that the proprietor of the biogas digesters get the benefits from their investment there is a need to improve the techno logy. Further, there is a need for providing documentation for the CO_2 emission reduction due to the biogas production, which can support **a** credible carbon trade process in the clean development mechanism programme of UN, and the technology is only credible if it is working efficiently both summer and winter.

Psychrophilic and mesophilic biogas production

It has been shown that a psychrophilic anaerobic digestion in sequencing batch digesters (SBRs) perform well under standard manure management strategies on small Canadian farms at operating strategies that optimize process performance (Masse et al. 1996). The biogas was produced at rates exceeding 0.48 L of CH_4 per gram of volatile solids fed in the Canadian study at 20°C operating the biogas digestion in batch mode without stirring (Masse et al. 1996). At other temperature intervals biogas production using a sludge of crop residues to feed the digester was 151 ml CH_4 g^{-1}(VS) at 12°C, 310 ml CH_4 g^{-1}(VS) at 25°C and 366 ml CH_4 g^{-1}(VS) at 37°C (Bohn et al. 2007). Thus there is a large effect of temperature, biomass and stirring the biomass in the digester.

Design of the digester

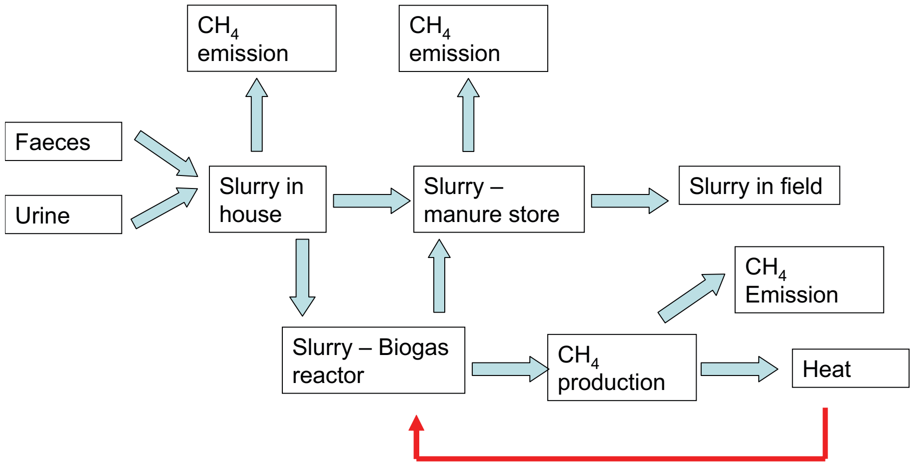
In the following we intend to present strategies for improving the performance of the simple unstirred and unheated biogas digester. These digesters are placed below pig pens on farms producing between 2 and ten fattening pigs per year and the digesters are producing biogas for cooking. The excreted manure is flowing by gravity from the pig pen to the digester.

The biogas production rate and the total production of biogas pr. VS is increased by heating the biomass. There is no electricity available therefore the biomass is heated with circulating water which is heated in a boiler with a fraction of the gas being produced. The heated water will circulate in tubes placed on the periphery of the digester by natural circulation, where warm water with lower density than cold water, displaces he colder water in the upper part of the system. Gasses in the system will escape through an expansion tank placed at the top of the digester, which will also prevent overpressure in case of overheating in the system.

A boiler is placed in a small operator room at the base of the digester. Cooled water from the expansion tank returns to the boiler by gravity. To improve the performance of the digester the slurry may be stirred gently with a propeller driven by a simple windmill. This will also contribute to distributing the heat in the digester. Further, the digester must be insulated using local organic or inorganic materials. In this design we propose straw and dried sphagnum, which is organic material that has a proven high insulation capacity.

It is known that large fluctuations in temperature will greatly affect the performance of the fermentation process. We assume that maintenance and control of the system will not be efficient. Therefore a simple mechanical regulator may be included in the design leading heated water to the domestic part of the farm when there is no need for heating the animal slurry, the surplus energy could heat a mass oven and thereby be stored.

Figure 1. Flowdiagram illustrating manure management methane emission from animal manure and introduction of a biogas digester for producting heat. In the systems without biogas plant there is no outside store of slurry, but when including biogas digesters then an outside store will be needed if the slurry is applied timely to the cro



Calculation biogas production and heat loss from digester

Growth of the biomass in the digester improves if the temperature can be elevated to either the mesophilic (~ 28-42 °C) or the thermophilic regime (~ 45-65 °C). Using pigs manure and humane faeces as feed for the digester, however, cause a relatively high ammonia concentration, which favours the mesophilic regime. Furthermore analysis made by Hashimoto (1984) showed that with very long retention times in the digester the biogas production is approximately equal at 35 °C and at 55°C. The biogas production can be estimated using the adapted Contois model from Chen and Hashimoto (1978). With a mixture of pigs manure, humane faeces and household organic wastes a productivity of 0.48 Nl CH_4 /kg VS fed can be anticipated.

The biogas productivity as a function of temperature can be calculated from:

$$g \equiv \frac{B_0 \cdot S_0}{\Theta}\left(1 - \frac{K}{\Theta \cdot m_m - 1 + K}\right) \quad (1)$$

Where μ_m is expressed as $\mu_m = 0.013 \cdot T - 0.129$ (T is the temperature in °C)

γ is the specific methane production (Nm^3 CH4/kg VS/day), B_0 is the maximal biogas production avalable for a given feed (Nm^3 CH_4/kg VS), S_0 is the feed concentration (kgVS/m^3 feed), S_0 is hydraulic retention time (days), K is a kinetic parameter specific for a given feed and bacterial consortium, μ_m is the maximum specific growth rate (days^{-1}).

A production between 5-10 pigs per year combined with humane faeces results in an accumulated feed flow of ca. 2.5-5 tons manure / year. Given a feed concentration of around 6% TS and a hydraulic retention time of 60 days at a temperature around 30 °C, the methane production according to eq. (1) will be 0.5-1 m^3/day. A reduction in temperature to 15°C will reduce the biogas production with 20%.

The digester will be insulated with 200mm of either well packed straw or dried sphagnum between to single stone walls, where the heating pipes are imbedded in the insulation.

Heat losses from the digester and heating system can be estimated from first order approximation as:

$$Q_\Gamma = k_t \cdot \frac{A}{\Delta x}(T_d - T_a) \quad (2)$$

where

$$k_t = \frac{k_s \cdot k_b}{k_s + k_b} \quad (3)$$

where k_t is the overall heat transfer coefficient (W/grad/m), k_s is the heat transfer coefficient for the insulation and k_b is the heat transfer coefficient of the brick wall. T_d and T_a is the temperature inside the digester and the ambience respectively.

Given a digester temperature of 30°C and a dimensioning ambient temperature in the soil of 0°C, and declared heat transfer coefficient for the building materials: Bricks and compacted straw. The heat loss for the digester can be estimated to be less than 100W for a straw insulation thickness of 200 mm. This heat loss can be compensated with a biogas consumption of about 20% of the biogas production from the digester.

Greenhouse gas reduction

A simple model assessing the volume of biogas produced is developed. Input to the model is animal production, climate variable and insulation of the digester. Output will be assessment of the feasibility to produce acceptable amounts of biogas throughout the year considering the amount of biomass available, climate and the access to insolating material. Output will also be an estimate of the total GHG reduction taking substitution of coal and reduction in CH_4.

The survey of pig production on small pig farms in the Hubei province showed that pigs are housed throughout the year. During housing, excreta are mixed below slatted floors, where the slurry is stored for a period before being transported and applied to arable soil. In accordance with this manure handling system, the model contains a slurry store below the pig pen. Biogas digesters are installed below the pig pens so in this system the slurry is stored in the digester below the pig pens.

The calculations of CH_4 emission are based on excretion of 1 kg *VS* d^{-1}, and storage time is defined by a standard scheme for filling and emptying of the slurry store below the pig pen. In the case of a biogas digester being installed below the pig pen we are using a 3% default value to assess CH_4 emission that leaks from the biogas production, transport and burning (Sommer et al. 2004). The model considers *VS* to be a main driving variable for CH_4, thus, CH_4 emissions are related to the content of degradable *VS*. The algorithms for calculation of CH_4 emissions are also used to determine the reduction in manure *VS* concentration, so if removal of digested manure to a storage tank is included in the design the emission from the end storage can be included in the calculation.

For the purpose of assessing the GHG reduction potential of installing biogas plants in on a pig farm in the Hubei province, there is a need to give a baseline scenario. It is assumed that the farmers constantly are producing four fatteners in the pig house, in total 12 pigs per year. The pigs have the VS production presented in table 1. The manure storage is emptied in April - May. The average monthly temperature of the slurry is set to be similar to the average air temperature of the province is used. Methane emission from the stored slurry is assessed using the following algorithm:

$$F_{month}(VS,T) = VS\ 0{,}1\ \mathrm{e}^{0.1774T} \qquad R^2=0.9892$$

Fmonth(VS,T) is the monthly emission in g CH_4 month^{-1} related to temperature (T,^oC) and the amount of VS (kg month) transferred to the store each month.

In the calculations (Table 2) it is assumed that biogas substitute raw coal and that one kg raw coal have net calorific values of 21 MJ and the emission factor of one MJ is 0.I01 g CO_2. On these farms the biogas digester is below the pig pen so there is no in house storage but an outside store has to be constructed. It is seen that emission GHG is transformed to a net reduction in GHG emission from the manure management system when introducing biogas digesters.

Tabel 1. Temperature and amount of slurry VS stored on a small pig farm with four pig places (12 pigs produced per year i.e. 17 kg VS excreted per month) and the emission of CH_4 from the stored slurry

Month	Temperature	Stored manure	CH_4 emission
#	^oC	Kg VS	Kg CH_4 month^{-1}
1	2.5	153	0.7
2	4.5	170	1.1
3	9	187	2.8
4	15	204	8.8
5	21	17	2.1
6	24	34	7.2
7	28	51	22.0
8	28	68	29.3
9	23	85	15.1
10	17	102	6.2
11	11	119	2.5
12	4.7	136	0.9
Total CH_4			98.8
Total CO2 eqv*			2271

*1 kg CH_4 equals the temperature effect of 23 kg CO_2
" Fermenting will consume 2,6 kg VS per 1 kg CH_4

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Table 2. Emission of GHG from a standard scheme of slurry management on a small farm in a cold mountain climate in the Hubei province and the reduced emission when a biogas digester is included

Source	Standard slurry management	Slurry management with a biogas production
	Kg CO_2 eqv.	Kg CO_2 eqv.
Pig house	2271	0
Biogas digester		171
CO_2 substitution		-1005
Outside store		330
	2271	-504

References

Albihn A., Vinneås, B. 2007. Biosecurity and arable use of manure and biowaste – Treatment alternatives. Livestock Science 112, 232 – 239.

Anonyme 2004. Indoor air pollution – the killer in the kitchen. http://www.who.int/mediacentre/news/statements/2004/statement5/en/, 2pages.

Bohn I., Bjornsson L., and Mattiasson B. 2007. Effect of temperature decrease on the microbial population and process performance of a mesophilic anaerobic bioreactor Environmental Technology, 28, 943-952

Chen YR, Hashimoto AG. Kinetics of methane fermentation. 1978. In: Scott CD, editor. Proceedings of Symposium on Biotechnology in Energy Production and Conservation. New York: Wiley,. p. 269.

Hansen, T.L., Sommer, S.G., Gabriel, S. and Christensen, T. H. 2006. Methane production during storage of anaerobically digested municipal organic waste. J. Environ. Qual., 35, 830-836.

Hashimoto A.G.1984. Methane from swine manure: Effect of temperature and influent substrate concentration on kinetic parameter (K). Agricultural Waste; 9: 299–308.

Hashimoto A. G., Chen Y. R. and Varel V. H. (1981). Theoretical aspects of methane production: state-of-the-art. In Livestock Wastes: A Renewable Resource, ASAE, St. Joseph, MI, pp. 86–91.

Hayhoe K., Kheshgi H. S., Jain A. and Wuebbles D. J. 2002. Substitution og natural gas for coal climatic effects Of utility sector emissions. Climatic Change 54: 107–139,

IPCC (2007)

Masse DI, Droste RL, Kennedy KJ, Patni NK, Munroe JA . 1997. Potential for the psychrophilic anaerobic treatment of swine manure using a sequencing batch reactor. Canadian Agricultural Engineering, 39, 25-33

Møller, H.B., Ahring, B.K. and Sommer,S.G. 2004. Methane productivity of manure, straw and solid fractions of manure. Biomass and Bioenergy. 26, 485-495.

Masse DI, Patni NK, Droste RL, Kennedy KJ 1996. Operation strategies for psychrophilic anaerobic digestion of swine manure slurry in sequencing batch reactors. Canadian Journal of Civil Engineering, 23, 1285-1294

Sommer, S. G., Petersen S. O. and Møller, H.B. 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutrient Cycling in Agroecosystems, 69 (2): 143-154.