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Dynamic modelling of an anaerobic digester for wastes at the territory level

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Abstract: The operation of an anaerobic digestion located on a farm and primarily fed by cattle slurry and manure, has been simulated using the Anaerobic Digestion Model 1. The effect of seasonally varying temperature on the biological reactions has been taken into account, as well as the non-availability of cattle slurry in summer. This can be compensated by co-digesting other substrates easily found in the vicinity of the farm such as glycerol (waste from biodiesel production) or roadside green weed silage.

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Keywords: Anaerobic digestion, agro-waste, methane production.

1. INTRODUCTION

Biogas obtained by anaerobic digestion of various carbonaceous substrates has been proposed to alleviate the greenhouse gas (GHG) emissions induced by fossil fuels combustion. Heat and electricity can be produced by fuelling the biogas to a cogenerator. Their production is function of the size of the digester, of the availability of substrates and of the size of territory on which they can be collected. Indeed the transport distance between substrate collection sites and the digester should be taken into account in a life cycle assessment of the biogas production, as they increase the GHG emissions.

Small units can be implemented on animal (i.e. cattle, pigs, and poultry) farms to treat the manure and/or slurry. However, depending upon the type of herd management (indoor or outdoor) the availability of substrate can fluctuate in time. In France, roughly 50% of cattle faeces can be collected when the animals are sharing their time between barn (winter) and pasture (summer).

In the periods of low availability of the main substrates the farmer should either decrease the biogas production (and the income related to it) or find other substrates. Their quality is an important factor, in terms of digestibility but also in terms of potential chemical and biological contaminants as the digestate is later spread as a fertilizer on fields.

Finally change in cattle management practice on a farm can also induce change in substrate availability: the use of a robot for cow milking facilitates the collection of manure and slurry, when, with a more traditional milking machine (milking twice a day) cows are allowed to pasture during the day, reducing the potential substrate collection.

The anaerobic digester of the Bouzule farm (our case study) was initially planned when a robot milking was used. Change in that practice induced a severe change in the availability of substrate and forced to adapt the feeding strategy of the digester. In the design phase, manure was supposed to be lacking in summer and slurry to be available all year around

(Pons et al., 2010): the inverse situation is observed now and the farmer has to find a solution.

The goal of this contribution is to analyse, based on the Anaerobic Digestion Model 1 (ADM1) the actual operation of a farm digester and to evaluate how biogas production can be stabilized on a year-long basis, by the use of co-substrates available in the vicinity of the farm, i.e. at the territory level.

2. CASE STUDY

2.1 La Bouzule experimental station

The Bouzule digester has a total volume of 452 m³ and a workable volume of 300 m³. It is run without pH control. The temperature setpoint is 39°C. The gas is stored in a gasholder, before being used in a combined heat and power (CHP) 39 kW plant. Both the digester and the gasholder, used to store both the biogas and the digestate, have deformable membrane covers. The heat is used to control the digester temperature and the electricity is delivered to the grid.

On the experimental station there are two cattle herds: a cow herd, for milk production, and an ox herd. Both herds are kept in the barn in winter and on pasture in summer. For these reasons the available amounts of slurry (mixture of faeces and urine) and manure (mixture of straw and slurry), which are both temporarily stored before being digested, are varying with respect to time. In summer slurry is not always available. Slurry (or any other liquid substrate) is supposed to be fed continuously and manure is added twice a day.

In summer, when the slurry is not available, two options are available to the farmer: the digestate can be recycled from the gasometer to the digester or other substrates (glycerol, used oil, goat whey from the farm dairy, ensiled maize, grass or green weed from nearby roadsides, etc.) can be used depending upon their availability and digestibility.

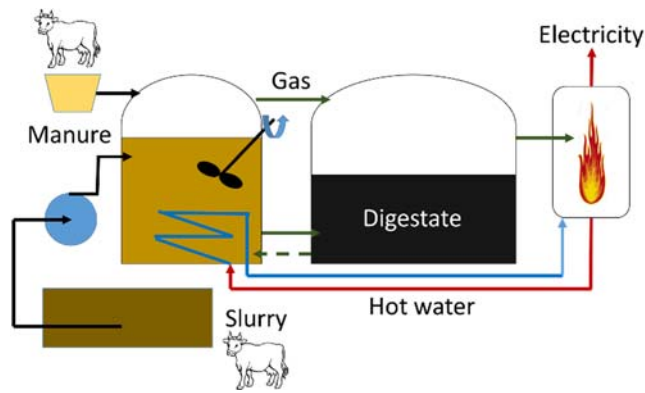


Fig. 1. Plant setup.

2.2 Substrates composition

Manure and slurry compositions are very much related to the feeding recipe of the cattle. The average composition selected for the simulation results from the combination of literature data (Van Kessel and Reeves, 2000; Hartmann and Ahring, 2005; Moral et al, 2005; Lübken et al, 2007; Capel et al, 2008; Marino et al, 2008; Alvarez and Lidén, 2009; Dareioti et al, 2009; Gali et al, 2009; Schievano et al, 2009). Data for oil and glycerol have been taken from Canler (2001) and Siles López et al (2009), respectively. Information related to grass silage has been taken from Thamsiriroj and Murphy (2011). Table 1 summarizes the slurry and manure composition.

Table 1. Slurry and manure composition (see the nomenclature section for definitions)

Parameter	Unit	Slurry	Manure
CODp	gCOD m ⁻³	94200	188400
CODs-VFA	gCOD m ⁻³	10083	10083
VFA	gCOD m ⁻³	4584	4584
TOC	gCOD.m ⁻³	37360	74720
Norg	gN m ⁻³	2392	3588
TAN	gN m ⁻³	1136	1136
TP-orthoP	gP m ⁻³	748	748
ortho-P	gP m ⁻³	128	128
TIC	mol HCO ₃ ⁻ m ⁻³	241.6	241.6
Scat	eq m ⁻³	240	240
FS	gm ⁻³	21588	43176

3. MODELLING

3.1 Digester modelling

ADM1 is based on sewage sludge anaerobic digestion and give a unified representation of disintegration, hydrolysis, acidogenesis, acetogenesis and methanogenesis (Batstone et al., 2002). A set of 26 state variables are used to describe the fate of the various species in the basic DAE implementation. When applied to agro-wastes, the first steps of disintegration and hydrolysis are critical and they are supposed to vary in function of the substrate. The burden can be put either on the disintegration step (Gali et al., 2009; Thamsiriroj and Murphy, 2011), on the hydrolysis step (Zaher et al., 2009b; Koch et al., 2010) or on both (Biernacki et al., 2013; García-Gen et al.,

2015), with modifications of the proteins, lipids, carbohydrates and inerts content stoichiometric factors in function of the substrate. The GISCOD model has been incorporated to the ADM1 implementation (Zaher et al, 2007; Zaher et al, 2009a; Zaher et al, 2009b) to transform the Table 1 practical variables into ADM1 variables. Tables 2 and 3 summarize the main influent ADM1 state variables (X_{ch} = carbohydrates, X_{pr} = proteins and X_{li} = lipids) and their hydrolysis kinetic constants respectively, for some substrates.

The digester temperature is not constant as shown in Fig. 2. It is higher than 39°C in summer and lower in winter. A heat balance has shown that the digester heat exchanger was undersized and that solar and atmospheric radiation fluxes could increase the temperature through the membrane covers in summer.

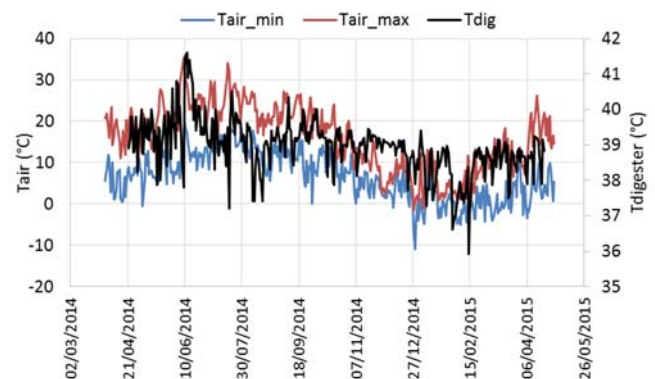


Fig. 2. Variations of the minimal and maximal air temperature in Nancy (data from www.meteociel.fr) and of the digester temperature (T_{dig}) over one year.

To take into account the effect of the temperature variations on the kinetics, the equation proposed by Markowski et al. (2014) has been used. For any reaction, the maximal reaction rate μ_{max} is given by:

$$\mu_{max} = \begin{cases} \mu_{opt} & \text{if } T_{dig} \leq T_{opt} \\ \mu_{opt} \left(\frac{b+T_{max}-T_{opt}}{T_{max}-T_{opt}} \right) \cdot \left(\frac{T_{max}-T_{dig}}{b+T_{max}-T_{dig}} \right) & \text{if } T_{opt} < T_{dig} < T_{max} \\ 0 & \text{if } T_{dig} \geq T_{max} \end{cases}$$

where T_{opt} is the optimal temperature for mesophilic anaerobic digestion (= 308 K), T_{max} the maximal temperature (= 318 K), μ_{opt} is the maximal reaction rate at T_{opt} and b (= 6.275 K) (Sangsurasak et al., 1998) is the sensitivity of growth kinetics to an increase in temperature. The relation is valid between 35°C and 45°C (i.e. between 308 K and 318 K).

The implementation has been done in FORTRAN. A basic Runge-Kutta 4th order algorithm with a constant integration step was used ($1 \cdot 10^{-4}$ day) for the differential equations integration. Hydrogen in the liquid phase and pH are treated algebraically (Pons et al, 1983; Rosen et al, 2006). A simulation case is run as follows: stabilization with a constant feedrate ($15 \text{ m}^3 \cdot \text{d}^{-1}$) over 100 days using the digested activated sludge data from BSM2 (Rosen et al, 2006) followed by two years of operation with varying feed conditions.

Table 2. ADM1 influent state variables (in kgCOD.m⁻³). AS = activated sludge

Variable	AS	Slurry	Manure	Glycerol	Used oil	Ensiled grass
X_c	0	0	0	0	0	371
X_{ch}	3.72	49.1	126.5	967.	0	0
X_{pr}	15.9	8.12	8.05	0	0	0
X_{li}	8.05	3.94	3.05	0	2208.	0

Table 3. Hydrolysis rate constants (in d⁻¹)

Substrate	k_{dis}	k_{hyd_ch}	k_{hyd_pr}	k_{hyd_li}
AS	0.5	10	10	10
Slurry	0.5	0.019	0.025	0.022
Manure	0.5	0.0019	0.025	0.022
Glycerol	1.3236	1.2516	0.0018	0.0086
Grass silage	1.7433	0.7366	0.0104	0.0149
Maize silage	0.7705	0.6865	0.2446	0.1216
Green weed silage	0.8168	0.6659	0.0014	0.0513

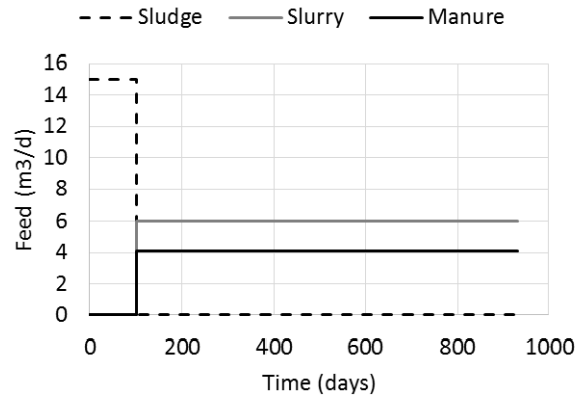
4. RESULTS

4.1. Open-loop simulations

Figure 3 summarizes the basic case with a constant feeding of manure (4.1 m³.d⁻¹) and slurry (6 m³ d⁻¹), which correspond to the mean annual values for these two substrates. The slight variations seen on the biogas flowrate and the percentage of methane in the biogas are due to temperature. It is not possible to compare the simulated biogas flowrate to the real one, as there is no flowmeter yet on the digester. The simulated percentage of methane in the biogas is 50%, slightly lower than the average real value (55%). The average simulated pH is 7.66 when the average real pH over one year is 7.55.

In reality, it is not easy to feed the manure and the slurry to the digester: a hopper is used for manure and a pump for slurry. But the rheological properties of cow slurry are complex, even more when straw fragments are present (Hreiz et al., 2015) and the pump design is not optimal. The actual feedrates are very noisy. In spite of those variations the digester is stable, with an average methane production of 72.4 kg CH₄.d⁻¹ (Figure 4).

a)



b)

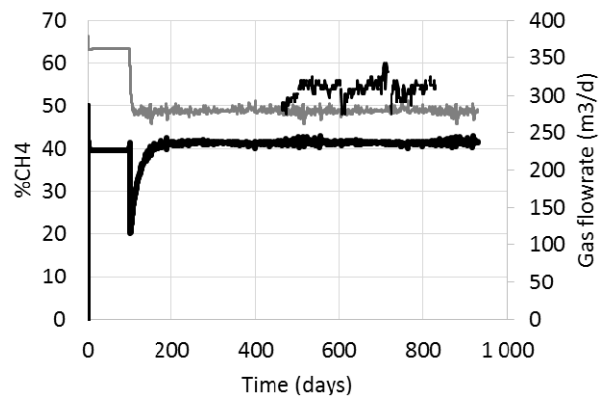


Fig. 3. Gas flowrate (thick black line) and %CH₄ in biogas (grey line for simulation and thin black line for real data) (b) for constant slurry and manure feedrates (a).

The lack of slurry in summer (from beginning of July to end of September) causes a large decrease in methane production (Figure 5). The partial recycle of digestate from the gasometer to the digester does not solve the problem (data not shown). The use of one or several co-substrates easy to find in the farm vicinity is required to maintain the methane and electricity production.

4.2. Closed loop simulations

In order to maintain a constant methane production in spite of variations in the slurry and manure feedrates, the possibility of using external wastes has been tested. A simple PI controller has been used and the set point has been fixed at 75 kg CH₄.d⁻¹, which is slightly higher than what is obtained in the previous open loop case. The switch to closed loop was done at t = 120 days. The PI parameters were not optimized.

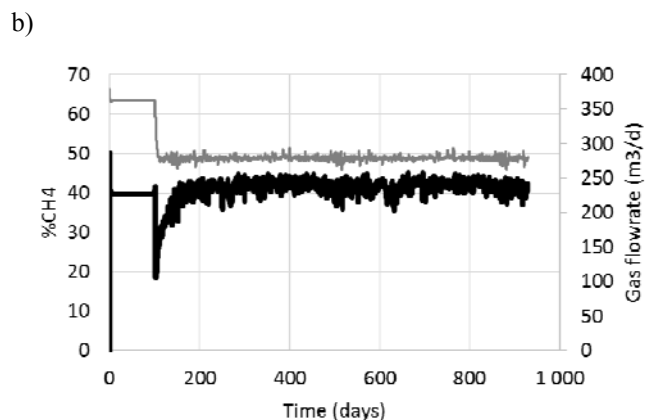
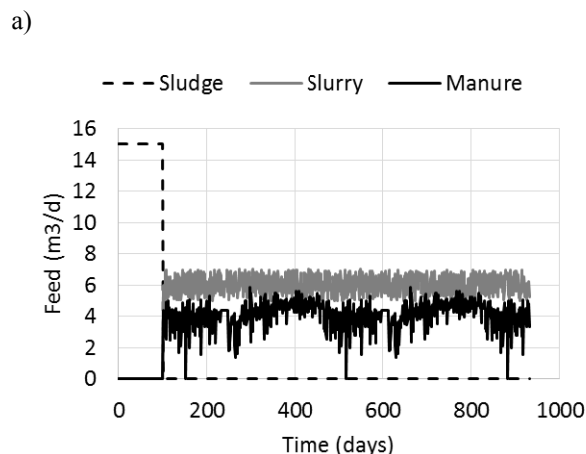


Fig. 4. Gas flowrate (thick black line) and %CH₄ in biogas (grey line) (b) for noisy slurry and manure feedrates (a).

Glycerol is a waste from the production of biodiesel from rapeseed (Coniglio et al., 2014). Lorraine, where the farm is located, is one of the main regions of production of rapeseed in France, so glycerol is largely available as a complementary substrate. It is possible to maintain the methane production in summer using glycerol, as shown in Figure 6. Another option is to use some old maize or grass silage available on the farm and improper for cattle feeding or roadside green weed which is cut in spring and can be easily ensiled (Voinov et al., 2015). As for glycerol it is possible to maintain the methane production using this co-substrate (Figure 7).

6. CONCLUSIONS

A realistic simulation of the behaviour of an anaerobic digester for farm residues subject to variable seasonal composition of the feed has been performed. The simulation allows to test various situations and to provide guidelines for the farmers. Controlled addition of external substrates such as biodiesel waste or silage is possible to maintain the methane production as a desired level.

The temperature variations in the digester have been taken into account but data on the effects of slight temperature variations on anaerobic digestion kinetics are limited: further research is advisable in the direction.

Disintegration and hydrolysis are key steps in the case of complex substrates. Various solutions are proposed in literature and it is difficult to consolidate the data between different authors due to this diversity (Weinrich and Nelles, 2015). The source of the difficulty might be in the structure of ADM1, which makes the identification of the disintegration and hydrolysis kinetic parameters not straightforward.

Future work is focused on the integration of the energy balance to the modelling of the digester to test fault scenarios related to the temperature control. The addition of new sensors to the plant should allow a fine comparison between the full-scale digester and its model.

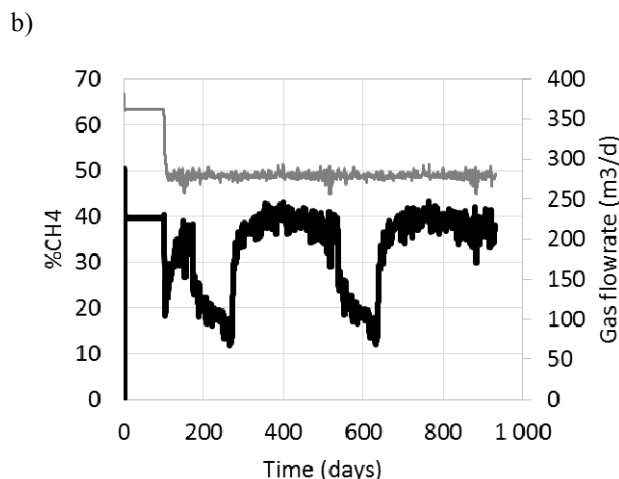
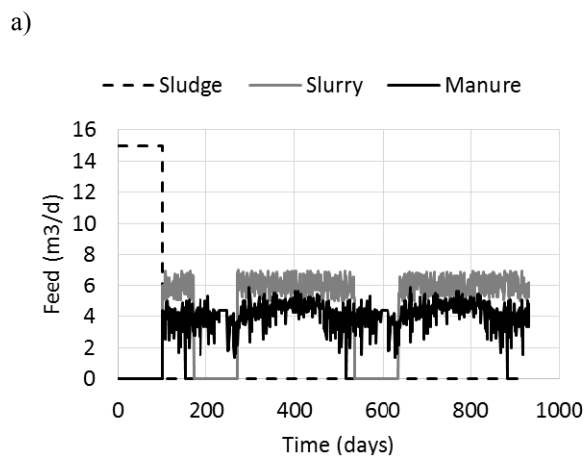


Fig. 5. Gas flowrate (thick black line) and %CH₄ in biogas (grey line) (b) for real slurry and manure feedrates (a).

7. ACKNOWLEDGMENTS

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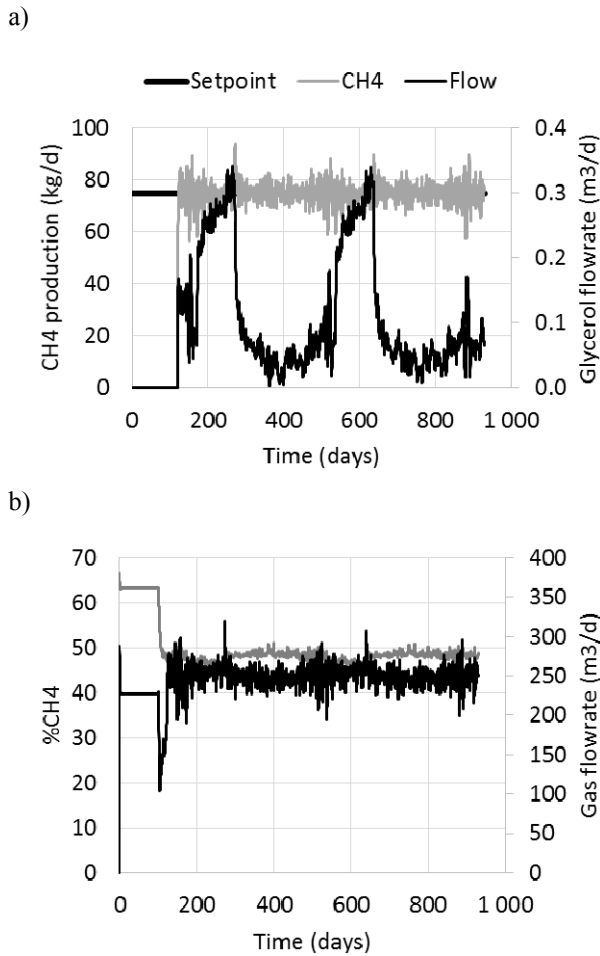


Fig. 6. Gas flowrate (thick black line) and %CH4 in biogas (grey line) (b) with control of methane production with glycerol (a).

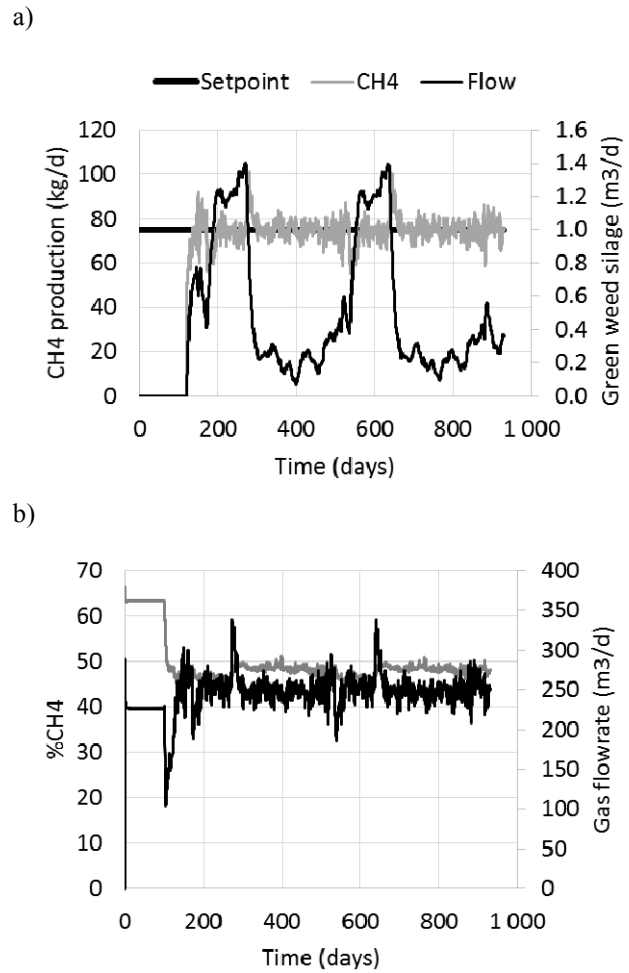


Fig. 7. Gas flowrate (thick black line) and %CH4 in biogas (grey line) (b) with control of methane production with ensiled green weed.

NOMENCLATURE

COD	Chemical Oxygen Demand
CODp	Particulate COD
CODs-VFA	Soluble COD without VFA COD
FS	Fixed solids
Norg	Total Organic Nitrogen
orthoP	Ortho Phosphate
Scat	Total alkalinity
TAN	Total Ammonia Nitrogen
TIC	Total Inorganic Carbon
TOC	Total Organic Carbon
TP	Total Phosphorous
TP-orthoP	Organic Phosphorous
VFA	Volatile Fatty Acids

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