J. Int. Environnemental Application & Science, Vol. 3 (3): 195-200 (2008)

A Contribution to the Optimisation of Biogas Digesters with the Design of Experiments Method

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Received June 9, 2008; Accepted July17, 2008

Abstract: The big challenge of modern life is the search for technologies that will allow for more efficient and cost-effective waste treatment. One technology that can successfully treat the organic fraction of wastes is anaerobic digestion. It is a biochemical process in which bacteria digest biomass in an oxygen-free environment, resulting in the production of "biogas". Thus, we turn a waste problem to a profit centre. This makes it attractive for many developing countries and constitutes an ideal sustainable growth option. Among factors that affect the production of biogas which are the temperature, the Volatile Solids (VS), and the Hydraulic retention time (HRT). A mathematical model allows us to determine the biogas produced as a function of these three parameters. Using the design of experiments method, we found that the effects of the parameters that influence the methane production are, in a decreasing order: the volatile solids, the temperature followed by the retention time. The interaction of these parameters is also analysed. This allows us to optimize the design of anaerobic digester.

***Key words**: Waste, Anaerobic, Biogas, Digesters, Optimisation.*

Introduction

The big challenge of modern life is the search for technologies that will allow for more efficient and cost-effective waste treatment. One technology that can successfully treat the organic fraction of wastes is anaerobic digestion (AD) (Chynoweth, 1987; Mattocks, 1984). Biogas is produced in a biochemical process in which organic matter is degraded in the absence of oxygen. This anaerobic decomposition process occurs naturally in wetlands, lake bottoms, and deep in soils. Biogas contains about 60% methane, 40% carbon dioxide, and trace amounts of nitrogen, hydrogen, and hydrogen sulphide (Rivard, 1995). Anaerobic digestion not only provides pollution prevention, but also allows for sustainable energy, compost and nutrient recovery. Thus, AD can convert a disposal problem into a profit centre .This makes it attractive for many developing countries and constitutes an ideal sustainable growth option (Marchaim, 1992 ; Barnett, A. et all , 1978).

A digester is the device in which the digestion process occurs (Buswell, 1936; Meynell ,1976). The organic feedstock, which is called the substrate, may consist of manure, crop or kitchen residues, or similar materials. The substrate is usually diluted with water. It is then fed into the digester where it undergoes degradation in a sealed oxygen-free chamber. The biogas is collected for direct usage. There are two general design characteristics of digesters: batch-feed and continuous feed. The batch digester is filled, sealed, and after a period of gas collection, emptied. The continuous feed digester receives substrate on a continuous or daily basis with a roughly equivalent amount of effluent removed. There are many possible design variations for continuous feed digesters. The primary goal of this project is to optimize the design of anaerobic digester through the use of the design of experiment method (Fischer, 1925; Benoist et all, 1994).

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Materials and Method

Factors that may affect the performance of the digester are numerous (Hill, 1983; Powers, 1997). The primary and controllable ones that affect the size of a biogas digester are the temperature, the Volatile Solids (VS), which is a measure of the amount of organic matter in a material and the Hydraulic retention time (HRT): a measure of the amount of time the digester liquid remains in the digester. Numerous models have been developed to provide a theoretical understanding of anaerobic digestion. The following equations based on the *Contois Model* have been used to describe the kinetics of anaerobic digestion of swine waste at steady state (Chen 1983).

$$B = B_o\left(1 - \frac{K}{\mu_m\theta - 1 + K}\right) \tag{1}$$

$$\lambda\nu = B_o L\left(1 - \frac{K}{\mu_m\theta - 1 + K}\right) \tag{2}$$

Where:

B= methane yield, m^3/kg VS
B_o= ultimate methane yield at infinite retention time, m^3/kg VS
K= kinetic parameter (inversely related to digester performance; values<0.6 indicate stability)
μ_m= maximum specific growth rate, d^{-1}
γ_v= volumetric methane production rate, m^3 CH_4/m^3 digester volume per day
L= volumetric loading rate, kg VS/m^3 digester volume per day.

Hashimoto (1984) evaluated the effect of temperature and influent substrate concentration on a kinetic constant (K) which is an indicator of digester stability. A comprehensive work has been done by P. Harris from the University of Adelaide-Australia, who developed an Excell methane production calculator program. This model is based on the work of Chen and considers the effect of input volatile solid, operating temperature and retention time on the digestion of different waste types in a continuous stirred tank digester. The methane production is expressed by:

$$\mathrm{CH_4} = \left(\frac{0.45 \times \mathrm{VS/HRT} \times (1 - (0.6 + 0.0006 \times \mathrm{EXP}(0.1185 \times \mathrm{VS}))}{(0.013 \times \mathrm{TEMP} - 0.129) \times \mathrm{HRT} - 1 + (0.6 + 0.0006 \times \mathrm{EXP}(0.1185 \times \mathrm{VS}))}\right) \tag{3}$$

Using this model, he investigated the production of methane versus each of these factors. The obtained results constitute a valuable data for designers. However, they are somehow truncated as the considered factors are taken individually, thus neglecting the eventual interactions which may play an important role. In our work we use this program to simulate methane production of pig manure by varying the three parameters (versatile solids, temperature and retention time) to each one of them we affect three values or levels and run all the possible combinations (3^3=9). We then construct the matrix of the events and through the use of design of experiments method we determine the importance of these parameters along with that of their interactions.

Results and Discussion

The results of the different runs are presented in Table 1. Applying the design of experiments method we determine the coefficients of the three parameters taken into account and their interactions. They are presented in Table 2. The methane production can therefore be approximated by the polynomial form:

$$Y=12.57+2.78\ VS+1.86Temp+1.40\ RT+0.6\ VS\times Temp+0.42\ VS\times RT-0.7Temp\times RT \qquad (4)$$

Table 1. Results of the different runs.

Vltile Slds (kgl^{-1})	**Temp.** (^oC)	**Ret. Time** (days)	**Gwth Rte** ($days^{-1}$)	**K**	**Methane** m^3/m^3 day	**Methane** m^3/m^3 day
30	15	30	0.056	0.621	0.214	6.4
30	15	45	0.056	0.621	0.193	8.7
30	15	60	0.056	0.621	0.161	9.7
30	20	30	0.093	0.621	0.301	9.0
30	20	45	0.093	0.621	0.226	10.2
30	20	60	0.093	0.621	0.179	10.7
30	25	30	0.150	0.621	0.345	10.3
30	25	45	0.150	0.621	0.244	11.0
30	25	60	0.150	0.621	0.188	11.3
40	15	30	0.056	0.669	0.275	8.3
40	15	45	0.056	0.669	0.251	11.3
40	15	60	0.056	0.669	0.211	12.7
40	20	30	0.093	0.669	0.394	11.8
40	20	45	0.093	0.669	0.298	13.4
40	20	60	0.093	0.669	0.236	14.2
40	25	30	0.150	0.669	0.455	13.6
40	25	45	0.150	0.669	0.323	14.5
40	25	60	0.150	0.669	0.250	15.0
50	15	30	0.056	0.825	0.308	9.3
50	15	45	0.056	0.825	0.294	13.2
50	15	60	0.056	0.825	0.251	15.1
50	20	30	0.093	0.825	0.463	13.9
50	20	45	0.093	0.825	0.358	16.1
50	20	60	0.093	0.825	0.287	17.2
50	25	30	0.150	0.825	0.548	16.4
50	25	45	0.150	0.825	0.395	17.8
50	25	60	0.150	0.825	0.307	18.4

Table 2. coefficients of the parameters and their interactions

Methane	**Coeff. SC**	**Std. Err.**	**P**	**Conf. Int (±)**
Constant	12.5741	0.095432	7.17653 e-031	0.199069
V.S.	2.78333	0.116880	7.76807 e-016	0.243808
Temp.	1.86667	0.116880	7. 5301 e-031	0.243808
RT	1.40556	0.116880	1. 0933 e-031	0.298603
*V.S*Temp*	0.6	0.143148	0.00045 e-031	0.298603
*V.S*RT*	0.425001	0.143148	0.17653 e-031	0.298603
*Temp*RT*	-0.758333	0.143148	3.17653 e-031	0.298603

Where VS represents the volatile solids, RT the retention time and Temp the temperature; the products represent the corresponding interactions. The most influent parameter is the volatile solids, followed by the temperature and the retention time. The most important interaction is that of the temperature and the retention time; the second interaction is that of the volatile solids and temperature. These effects are well represented in Figure 1. Figure 2-a,b,c represent the methane production versus the three parameters. As expected, the maximum methane production corresponds to the highest values of each parameter. However it is worthwhile noticing that for the three parameters the pattern is the same: the increase from level

1 to level 2 is more then that from level 2 to level 3. This will play an important role in the optimization attempt. Figure 3-a shows the effect of the retention time- temperature effect on the methane production. The narrowing of the distance between the graphs indicates a strong reaction. We can see that the effect of retention time is important for low levels of temperature and almost neglect able for high values of temperature. Figure 3-b shows the effect of the volatile solids-temperature reaction. The effect of temperature is clearly less for low levels of volatile solids. In Figure 3-c we can see that the volatile solids- retention time exhibits the same pattern.

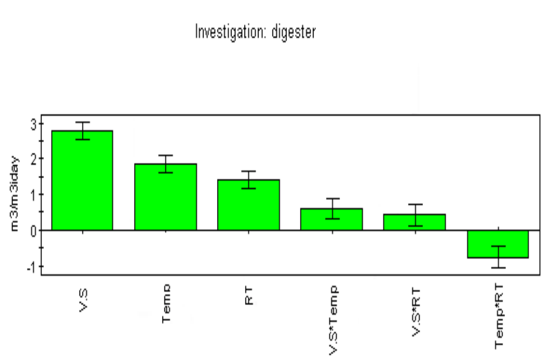

Figure 1. Coefficients diagram of the parameters and their interactions

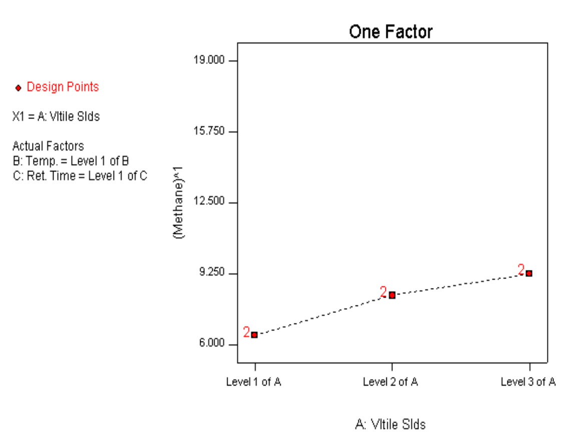

Figure 2-a. Methane production versus volatile solids (with respect to the three levels)

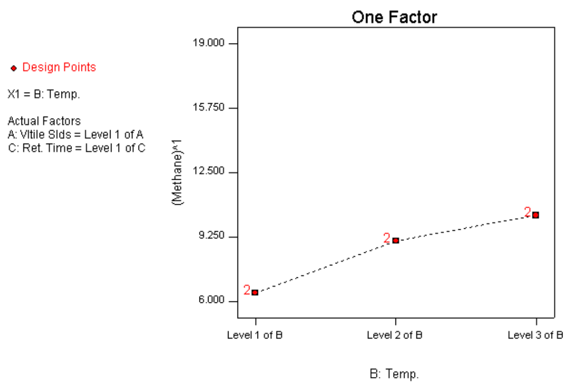

Figure 2-b. Methane production versus temperature (with respect to the three levels)

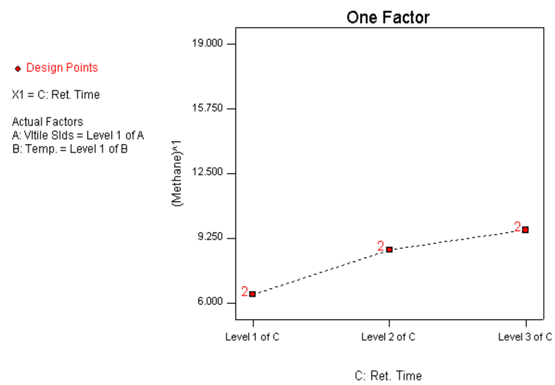

Figure 2-c. Methane production versus retention time (with respect to the three levels)

It is obvious that the maximum methane production is obtained with the highest levels of the three parameters. However this could not constitute the optimum solution as it does not take into consideration side effects. In deed any optimization tentative should consider the constraints that are always present in any design project. In this particular case, the retention time should be reduced as much as we can. On the other hand if the effect of temperature can only be beneficial, one should keep in mind that raising the operating temperature increases the cost of methane production. Searching the best compromise is made possible by using the design of experiments methods. Depending on the particular conditions under which we are working, we can use the full factor response given in Figure 4. We can obtain a satisfactory methane production with either a low temperature and a high retention time or a high temperature and low retention time. The best design would be with intermediate values of temperature and retention time and high volatile solids concentration.

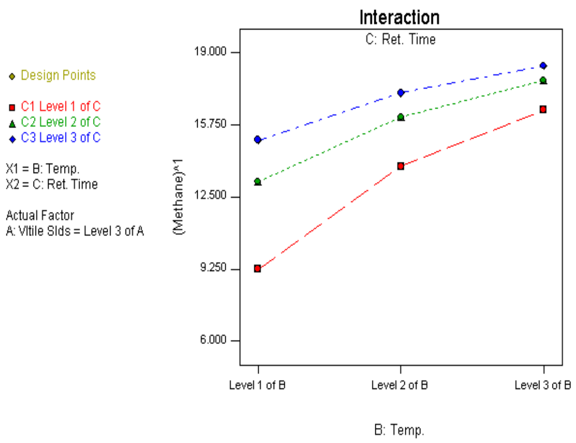

Figure 3-a. Effect of the interaction temperature-retention time on the methane production

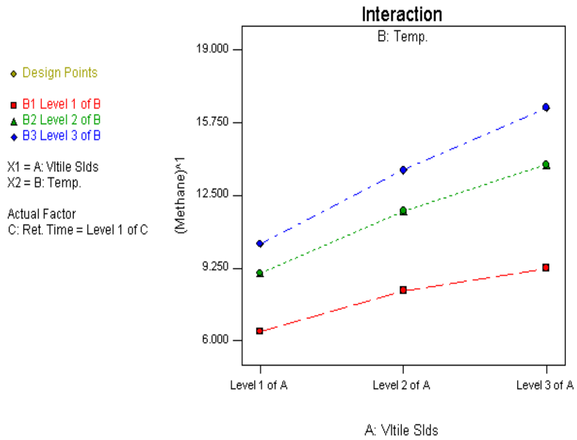

Figure 3-b. Effect of the interaction volatile solids-temperature on the methane production

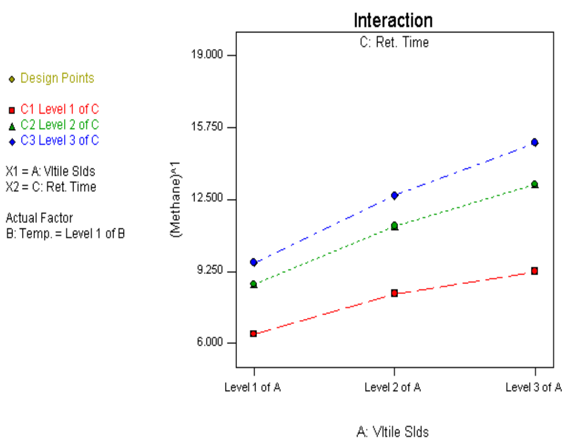

Figure 3-c. Effect of the interaction volatile solids -retention time on the methane production:

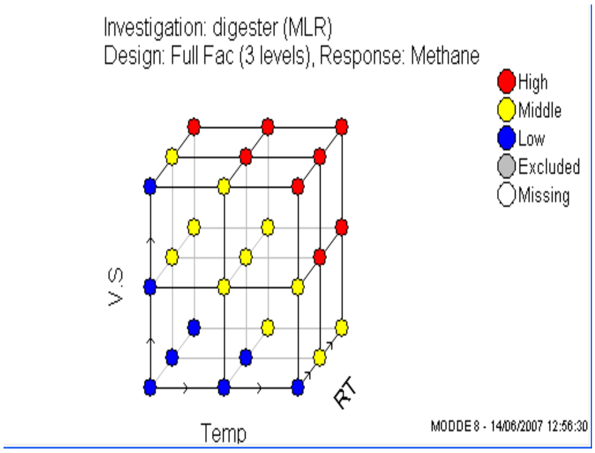

Figure 4. Full factors response.

Conclusion

The aim of this work was a tentative to optimize bio-digesters designs. It is vital to ensure that the most efficient way to enhance methane production. The use of the design of experiments method allowed us to analyse the effect of the parameters taken into account as well as their interactions. We were able to pinpoint the most influent factor (the volatile solids). According to the particular conditions in which a designer would be, this method will permit the obtaining of the best compromise.

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