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Study of Temperature Control System of a Solar-Heated Anaerobic Digester in Cotonou, Benin Republic, using Hardware in the Loop simulation

***[1]HOUNGUE, CFC; [2]HOUNGUE, RN**

[1]Departement of Electrical Engineering, Université Polytechnique des Sciences Appliquées, Libreville, Gabon.
[2]Departement of Geography, University of Bonn, Germany
**Corresponding Author Email: cessac.houngue@gmail.com*

ABSTRACT: In this work, we studied the performance of the temperature control system of an anaerobic digester heated by solar energy using the hardware in the Loop (HIL) simulation method. The implemented control type is On/Off. The main objective was to implement the control to maintain the temperature between 36°C and 38°C. We also aim to determine the minimum load of the digester which allows minimum stress on the control system in order to increase its service life but also to avoid being too dependent on temperature variations in the study environment. It appears at the end of this work that the temperature is well maintained between 36°C and 38°C, for all the quantities of organic matter studied. For small volumes (less than 1,000 Kg), the bias of the heating system actuator is significant. At best, (that is, for 1,000 Kg) we have on average 5 per day. This causes the heating system to be more dependent on the availability of solar radiation. On the other hand, from 3,000 Kg of organic matter, the temperature of the digester stabilizes better in the desired temperature range. The bias of the heating system is lower, ranging from two (2) per day for 3,000 Kg to one (1) per day for 10,000 Kg of organic matter.

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Anaerobic digestion has many advantages: environmental sanitation, clean renewable energy production, access to energy for developing countries, and the protection of health in rural areas because the use of firewood produces a lot of smoke. (Khoiyangbam, 2011; Ivan *et al*., 2016; Brahma *et al*., 2016) Temperature is one of the factors whose control accelerates the production of biogas thus allowing to transform more waste and to produce more biogas in a record time (X. Chen, Romano, and Zhang, 2010; Axaopoulos *et al*., 2001; Singh, Jain, and Singh, 2014; Y. Chen *et al*., 2020; Mailleret, Bernard, and Steyer, 2003). Heating the digester is therefore a very active research area. In countries with adequate climatic conditions, the use of solar heating is preferred because it avoids using again part of the biogas produced or the use of electrical energy from another source (Hounguè, Houngan, and Adjovi, 2015; Axaopoulos et al., 2001; Sunil, Patil, and Saini, 2011; Singh, Jain, and Singh, 2014; Ali and Al-Sa'ed, 2018). Solar energy is an intermittent source and is unavailable during the night. When these digesters are heated only by solar rays, they gradually lose the energy stored during the day. For digesters with small volumes, stored heat is lost even faster while for larger volumes, the thermal energy stored can be kept a little longer. This study therefore attempts to determine a minimum volume of digester from which it is possible to use solar heating on an insulated household digester by a greenhouse to maintain optimal temperature conditions for anaerobic digestion in Cotonou, Republic of Benin. It also seeks to optimize the service life of the heating system by adapting the size of the digester to the frequency at which the heating system is activated and deactivated in order to maintain the appropriate temperature inside the digester.

MATERIALS AND METHODS

We use HIL simulation because it has several advantages including:

- Conducting in record time studies that involve poorly controlled inputs such as wind in the case of a wind turbine (Munteanu *et al*., 2010; Munteanu, 2008) or solar energy in the case of photovoltaic systems(Crăciun *et al*., 2010),
- Simulating expensive components of the system separately, in order to avoid the risk of destroying them mistakenly etc.… (Isermann, Schaffnit, and Sinsel, 1999; Lee and Lee, 2006; Lu *et al*., 2007). In our case, the heat source used to heat the digester is an

**Corresponding Author Email: cessac.houngue@gmail.com*

intermittent source (solar rays). It depends on weather conditions. Therefore, direct field experiments take a long time and are uncertain. Also, anaerobic digestion is a process that lasts several weeks. Using the HIL simulation greatly shortens the conception time of the regulator which requires testing at several different temperatures. We actually needed to test several heating temperature options during the implementation of the control, to determine the best temperature range that will be adequate for heating the digester.

Delimitation of the set to be studied: The set to be studied consists of: 1. The batch anaerobic digester; 2. The heating system; 3. The heating control system; Fig 1 shows this set. This set will be delimited in two essential parts. The operative part whose behavior will be simulated and the control part which will be kept physical. Fig 2 shows the delimitation of the set to be studied. The simulated part consists of: the Anaerobic Digester Simulation Model, the Heating system simulation model. Simulation models are performed with LabVIEW 2020 simulation software. The physical part is represented by an ATmega168 which hosts the control program of the digester's regulator. An Arduino Uno board is used to interface the control signals of the regulator with the LabVIEW simulation models host in the computer.

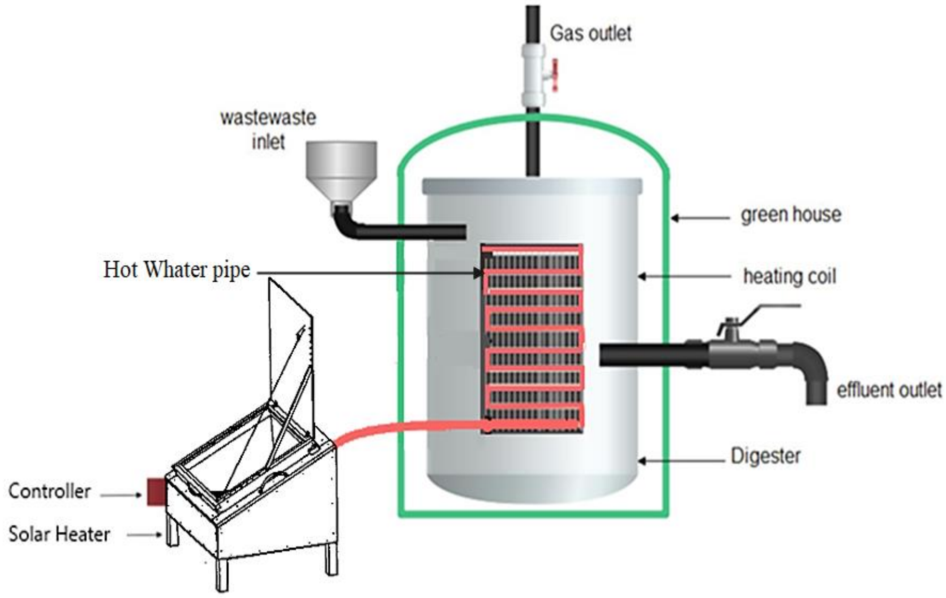

Fig 1: Set to be study using HIL simulation concept

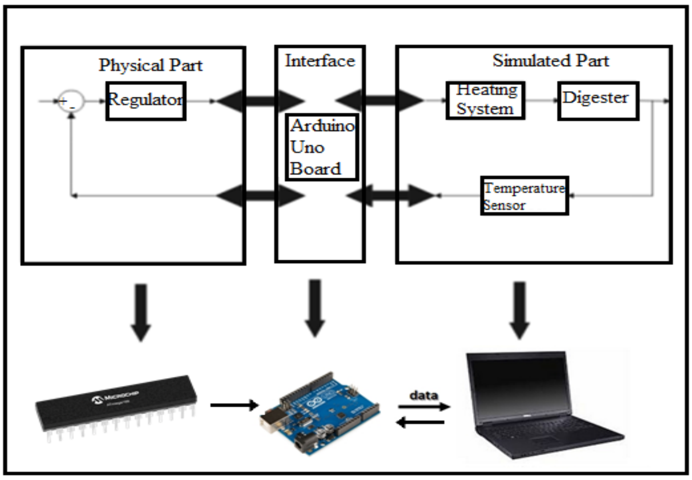

Fig 2: Delimitation of the set under study

Anaerobic Digester Model: As described in (Bernard *et al.*, 2001), the AM2 model for a continuous anaerobic digester consists of the following equations:

$$\frac{dS_1}{dt} = D(S_{1in} - S_1) - K_1\,\mu_1(S_1)X_1 \quad \text{Eq 1}$$

$$\frac{dX_1}{dt} = [\mu_1(S_1) - \alpha D]X_1 \quad \text{Eq 2}$$

$$\frac{dS_1}{dt} = D(S_{2in} - S_2) - K_2\,\mu_1(S_1)X_1 - K_3\,\mu_2(S_2)X_2 \quad \text{Eq 3}$$

$$\frac{dX_2}{dt} = [\mu_2(S_2) - \alpha D]X_2 \quad \text{Eq 4}$$

Where K_1 and K_2 represent pseudo-stoichiometric coefficients, D the dilution rate, $\alpha \in [0, 1]$, the biomass fraction leaving the digester(Benyahia *et al*., 2010).

μ_1 is given by the formula of Monod and μ_2 is given by the formula of Haldane.

$$\mu_1(S_1) = \mu_{1max}\frac{S_1}{S_1 + K_{S1}} \quad \text{Eq 5}$$

K_{S1} being the half saturation constant; μ_{1max} the maximum growth rate of acidogenic bacteria.

$$\mu_2 = \mu_{2max}\frac{S_2}{S_2 + K_{S2} + S_2^2/K_{I2}} \quad \text{Eq 6}$$

With K_{S2} being the half saturation constant; μ_{2max} the maximum growth rate of methanogenic bacteria and K_{I2} the inhibition constant.

But in our case, our study focuses on a batch digester. Then we have:

$$\begin{cases} \alpha = 0 \\ S_{1in} = S_1 \\ S_{2in} = S_2 \end{cases}$$

The equations: Eq 1, Eq 2, Eq 3 and Eq 4 become:

$$\frac{dS_1}{dt} = -K_1\,\mu_1(S_1)X_1 \quad \text{Eq 7}$$

$$\frac{dX_1}{dt} = [\mu_1(S_1)]X_1 \quad \text{Eq 8}$$

$$\frac{dS_1}{dt} = -K_2\,\mu_1(S_1)X_1 - K_3\,\mu_2(S_2)X_2 \quad \text{Eq 9}$$

$$\frac{dX_2}{dt} = [\mu_2(S_2)]X_2 \quad \text{Eq 10}$$

Moreover, since we need temperature as input for the model, we then used Ratkowsky's formula (Ratkowsky *et al*., 1982) into Monod and Haldane relations. That formula is the following:

$$\sqrt{\mu} = b(T - T_{min})[1 - \exp(c(T - T_{max}))] \quad \text{Eq 11}$$

Methane flow is directly dependent on methanogenic bacterial population growth X_2.

The digester model is therefore represented by the following equations:

$$\begin{cases} \frac{dX_1}{dt} = \mu_{1max}\frac{S_1}{S_1 + K_{S1}}\,X_1 \\ \frac{dX_2}{dt} = \mu_{2max}\frac{S_2}{S_2 + K_{S2} + S_2^2/K_{I2}}\,X_2 \\ \frac{dS_1}{dt} = -K_1\,\mu_{1max}\frac{S_1}{S_1 + K_{S1}}\,X_1 \\ \frac{dS_2}{dt} = K_2\,\mu_1\,X_1 - K_3\,\mu_2\,X_2 \\ Q_{ch4} = K_4\,\mu_{2max}\frac{S_2}{S_2 + K_{S2} + \frac{S_2^2}{K_{I2}}}\,X_2 \\ Avec \\ \sqrt{\mu_{1max}} = b_1(T - T_{min})[1 - exp(c(T - T_{max}))] \\ \sqrt{\mu_{2max}} = b_2(T - T_{min})[1 - exp(c(T - T_{max}))] \end{cases} \quad \textbf{12}$$

Thus, we obtain a model for which temperature represents an input. Eleven parameters are involved in that model. They are: b_1; b_2; T_{sub}; T_{min}; K_{S1}; K_{S2}; K_{I2}; K_1; K_2; K_3 et K_4.

To solve the system, we must provide initial conditions which are estimates of the initial values of substrate and bacteria concentrations at the start of the bioreactor. In our simulation, the initial parameters were evaluated by the following values(Hadri *et al*., 2007).

Table 1. Initials Parameters values

Parameters	Value
S_1(0)	10 g/L
S_2(0)	2 g/L
X_1(0)	0,4 g/L
X_2(0)	0.01 g/L
K_{S1}	*35 mg/L*
K_{S2}	*4 mg/L*
K_{I2}	*170 mg/L*
K_1	*50*
K_2	*50*
K_3	*15*
K_4	*75 L^2/mg*

Temperature evolution in the digester: For this modelling of temperature change, it was assumed that:

- The temperatures of the plate, the water used as thermal fluid, and the substrate are uniform.
- Storage heat is neglected except for substrate;
- The substrate is assimilated with water.
- The pipe that connects the heating system to the digester is considered to be a whole with the thermal fluid and the substrate.

We then have: *At the Glass level*

$$hr_{p-v}\,A_0(T_p - T_v) + hc_{p-v}\,A_0(T_p - T_v) = hr_{v-c}\,A_0(T_v - T_c) + hc_{v-a}\,A_0(T_v - T_p) \quad \text{Eq 12}$$

At the plate level

$$\tau_v\,.\,\alpha_p\,.\,G\,.\,A_0 = hr_{p-v}\,.\,A_0.\,(T_p - T_v) + hc_{p-v}\,.\,A_0.\,(T_p - T_v) + h_p\,.\,A_0.\,(T_p - T_{sub}) \quad \text{Eq 13}$$

In the substrate

$$M_{sub}.\,C_p\,.\frac{dT_{sub}}{dt} = h_p\,.\,S_1.\,(T_e - T_{sub}) - h_{loss}\,.\,A_p.\,(T_{sub} - T_a) \quad \text{Eq 14}$$

With $h_{loss} = \frac{K_{is}}{e_{is}} + \frac{K_{is} * S_1}{e_{is} * A_p}$

Control strategy: We have chosen to proceed with an On/Off control for the simplicity of its implementation and because it allows a good control of the temperature. In the control system, the temperature range as set is [36°C - 38°C]. The optimal temperature of anaerobic digestion in the mesophilic domain is around 37°C (Gavala *et al*., 2003; Carotenuto *et al*., 2016). Thus, as soon as heating starts, the temperature of the substrate at which it must be cut is 38°C, and when the substrate temperature reaches 36°C in its cooling phase, heating must be started again. This mode of regulation therefore induces several triggering and cutting of the heating system. We were interested to reduce as much as possible the number of triggering and deactivation of the heating system in order to first of all preserve the actuator of the control system and secondly because, the less we rely on solar rays the more we prevent the risk of not having enough of them.

Table 2. Parameters symbols

Symbols	Parameters
hr_{p-v}	Radiative exchange coefficient between plate and glass
A_0	Absorbent plate surface
T_p	Absorbent plate temperature
T_v	Glass temperature
T_c	Sky temperature
T_e	Water temperature
T_a	Ambient temperature
T_{sub}	substrate temperature
hc_{p-v}	Convective exchange coefficient between plate and glass
hr_{v-c}	Coefficient of radiative exchange between glass and sky
hc_{v-a}	Coefficient of convective exchange between glass and atmosphere
τ_v	Glass transmissivity coefficient
α_p	Plate absorption coefficient
G	Solar illuminance
e	Plate thickness
h_p	Global loss coefficient on the plate
h_{loss}	Global loss coefficient on the substrate
hr_{p-sub}	Radiative exchange coefficient between plate and substrate
hc_{p-sub}	Convective exchange coefficient between plate and substrate
K_{ac}	Plate thermal conductivity coefficient
A_p	The surface area of the digester wall
M_{sub}	Mass of the substrate
S_1	The area of the aluminum pipe that is in contact with the substrate
C_p	Calorific capacity of water
e_{is}	Thickness of digester material
K_{is}	Coefficient of Thermal conductivity of the digester material

RESULTS AND DISCUSSION

This section presents the performance of the heating system. The temperatures and solar radiation used in this study are those of Cotonou, Benin Republic. They were recorded by the weather station at Bernadin Cardinal Gantin International Airport in Cotonou, from February 1st to March 2nd, 2021; 30 days. On the following figures, the 0 on the time axis corresponds to 0 hours (midnight). Each figure displays together:

- substrate temperature (graphs (a) and (d)),
- heating system triggering and deactivation signals (graphs (b) and (e)),

When the control signals shown on the following figures are set to 1, the heating system is on and when the signals are set to 0, the heating system is off. Fig 3, Fig 4, Fig 5 and Fig 6 show these two parameters respectively for 500 kg, 1,000 kg, 1,500kg and 2,000 kg of organic matter.

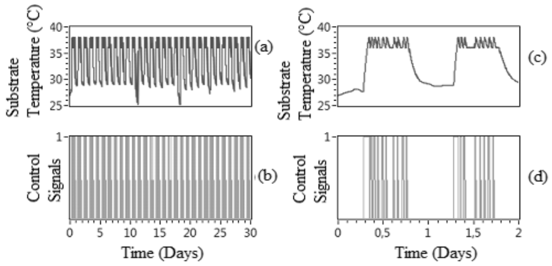

Fig 3 : Substrate temperature and Control signals for 500Kg of organic matter

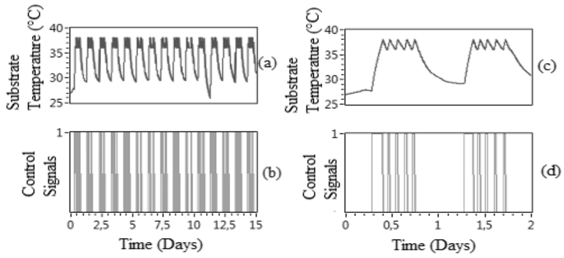

Fig 4 : Substrate temperature and Control signals for 1,000Kg of organic matter

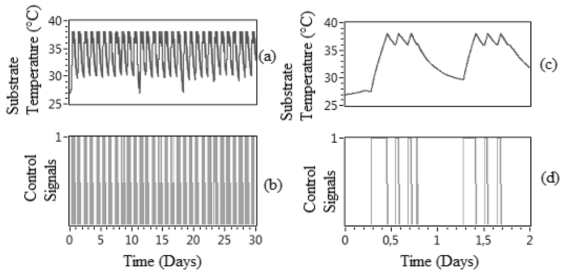

Fig 5 : Substrate temperature and Control signals for 1,500Kg of organic matter

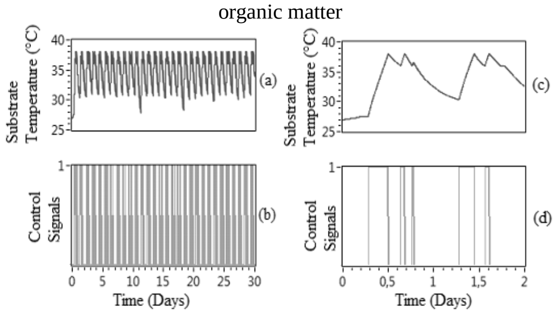

Fig 6 : Substrate temperature and Control signals for 2,000Kg of organic matter

Fig 3 shows that the temperature of the substrate varies greatly. During the night it goes down to the lowest levels, while during the day, it can be maintained between 36°C and 38°C. We noticed over the digestion period that the lowest temperature observed is 27°C, and it occurred only twice; on the night of the

10th to the 11th day and on the night of the 17th to the 18th day of digestion. These moments correspond logically to those where the ambient temperature is lowest. Looking at graphs (b) and (d) on Figure 3, we see that the control signals are quite compacted. This indicates a fairly high frequency of the heating system being switched on and off. This is not at all interesting since it accelerates the aging of the heating system. According to figures Fig 4, Fig 5 and Fig 6, we noticed that the substrate temperature drops less and the number of triggering and deactivation of the heating system decreases. Then the number of heating system activation and deactivation passes from an average value of nine (9) per day for 500kg of organic matter (Fig 3) to three (3) per days for 2,000Kg of organic matter (Fig 5). When we increase the organic matter quantity to 3,000 Kg, we observe that, according to graph (a) of Fig 7, the temperature of the substrate stays between 33°C and 38°C with rare decreases around 30°C. These descents always correspond to the coldest nights of the considered period. Moreover, during the day, the temperature is between 36 and 38°C..

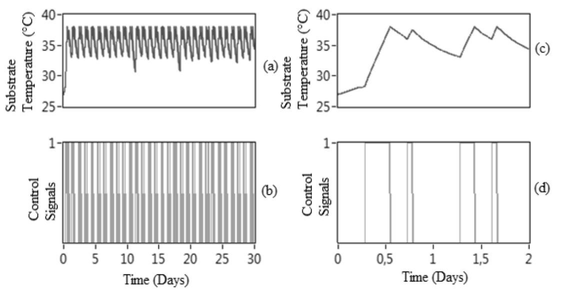

Fig 7 : Substrate temperature and Control signals for 3,000Kg of organic matter

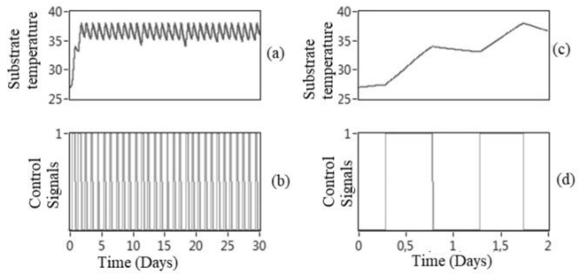

Fig 8 : Substrate temperature and Control signals for 10,000Kg of organic matter

Through graph (c) of Fig 7, we observe that as soon as the heating system is activated on the first day, the substrate will take 403 minutes (a little less than 7 hours) to reach the temperature of 38°C which is allowed as the upper threshold by the heating system. Graph (d) in Fig 7 also shows that the heating system is switched on and off less frequently. A maximum of two switching per day are obtained. The substrate takes much longer to cool compared to 500Kg of organic matter. Since we noticed that the solicitation of the heating system decreases with the increase of organic matter quantity, we passed to 10,000kg of organic matter. The results are on Fig 8. With 10,000 Kg of organic matter, the temperature of the substrate is maintained between 35°C and 38°C with two descents at 34°C. However, the substrate hardly reaches 38°C which constitutes the allowed upper margin. It had to wait for the second day of the experiment to reach 38°C. Once this maximum temperature level is reached, the cooling of the substrate is slow because of the large mass of organic matter. This appears to be an advantage in avoiding sudden temperature variations. On the other hand, we only needed to turn on and off the heating system once **a day. This is also an important advantage**

*Conclusion***:** This work shows that the temperature control system works properly since it allows maintaining the substrate temperature between 36°C and 38°C when solar rays are available. For low quantities of organic matter – under 1,500 kg –, the heat stored during the day is quickly lost whereas for quantities of organic matter higher than 3,000 kg, the heat is well conserved during the night. That prevents thermal shock which is damaging for anaerobic bacteria. Also, with organic matter above 3,000 kg the stress on the heating system is reduced. Thus, we have only one triggering of the system per day for 10,000 kg of organic matter. We deduce that using the solar rays to heat the digester in Cotonou conditions is appropriate for quantities of organic matter higher than 3,000 kg.

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