J. Agric. Sci. Mansoura Univ., 33 (9): 6527 - 6542, 2008

A SIMULATION MODEL OF A SMALL ANAEROBIC DIGESTER

El-Mashad, H.M.
Agric. Eng. Dep., Fac. of Agric., Mansoura University

ABSTRACT

A mathematical model was developed for the methane production and the heat balance of a family size anaerobic continuous stirred tank digester treating liquid cattle manure. The developed mathematical model was used for simulating the performance of a 5 m^3 digester for two consecutive years under the Egyptian weather conditions. Simulations were performed for the digester when operated under constant temperatures (i.e., a heat exchanger was installed) and when operated under ambient conditions without adding any heat energy (i.e. no heat exchanger was installed). The developed model was used to calculate the net thermal energy produced from the digester. Heating the digester feed was proposed as a strategy to increase the digester temperature during cold weather. This strategy would simplify the digester design eliminate the blackout times needed to maintain the heat exchanger and temperature controller from fouling and other operational problems. The obtained results showed that, operating the digester under mesophilic conditions produced little net thermal energy during the winter time as compared with that produced during the summer time. Under a constant digester temperature of 35°C, the maximum net thermal energy of 9.53 GJ/m^3.year could be obtained when operating the digester at a hydraulic retention time (HRT) of 15 days. When the digester operated under ambient conditions, without adding any heat energy, a net thermal energy of 3.93, 4.68 and 5.66 GJ/m^3.year, could be obtained, respectively, at HRTs of 25, 20 and 15 day. Heating the digester feed by 20 °C above the original temperature, when it is lower than 25°C, was found to be an effective way to achieve the highest net thermal energy as compared with heating the feed by 5, 10, 15 and 25 °C. A stabilization period is needed to reduce the global warming that could be resulted from disposal of non-stabilized digestate especially under lower temperatures and HRTs.

INTRODUCTION

Anaerobic digestion is a sustainable technology for treating wastes and wastewaters. Renewable energy production, in the form of biogas, is an important objective of this process (Zeeman, 1991; El-Hadidi and Seufort, 1997). Anaerobic digestion can be achieved under psychrophilic (< 25°C), mesophilic (25-40°C) and thermophilic (>45°C) conditions (Van Lier, 1995).The digestion rate increases with increasing temperature up to an optimum (Hawkes, 1980). Different digester configurations and designs are being applied in different scales, varying from family size to centralized digesters (Lettinga, 2001). Predicting the net energy produced from the digestion of a certain waste under certain operational conditions is a first step in constructing and operating anaerobic digester. To do so, an energy balance and prediction of the amount of methane production should be conducted for the intended digester.

Many studies have been conducted to calculate the net thermal energy production from different digestion systems that treat different wastes under different conditions. Chen (1983) presented a model for calculating the net thermal energy production from anaerobic Continuous Stirred Tank Reactor (CSTR) treating swine manure under both mesophilic and thermophilic conditions. Results showed that a higher digestion temperature resulted in greater net thermal energy production only at short retention times. El-Mashad (2003) developed a model for calculating the net thermal energy production from thermophilic CSTR systems treating liquid cattle manure and operating with and without solar heating system under the Egyptian climatic conditions. Results showed that the net thermal energy was a function of digester size and the type of reactor insulation. Higher net thermal energy per unit digester volume could be achieved for larger digester volumes. Zupančič and Ros (2003) presented a mathematical model for predicting heat requirements for a continuous thermophilic digester treating wastewater and operated under Slovenia weather conditions. Heat requirements were consist of the heat losses of the digester and inflow sludge heating. Heating of inflow sludge was the main part of heat requirements .The heat losses represented 2 to 8% of the heat requirements. Abd El-Latif and El-Mashad (2005) presented a simulation model for evaluating the net thermal energy production from themophilic batch digesters operated under Egyptian climatic conditions. Results showed that the net energy was a function of digester volume, length of digestion time, substrate concentration and the weather conditions around the digester.

Though keeping a constant temperature inside a digester is important to obtain a stable and sustainable production of biogas, there are many digestion systems and covered lagoons that are successfully operated under ambient conditions especially in China, India and the USA. Such systems are simple in designs and no heat is added to the digester. This leads to reduction of biogas production during cold conditions because the temperature inside the digester is seriously affected by the ambient temperature (Philip and Itodo, 2007). On the other hand, keeping a constant temperature inside a digester requires installation of a proper temperature controller and a heat exchanger. Nevertheless, the effectiveness of a heat exchanger is reduced over operating time due to the fouling on its inner and outer surfaces. To keep successful operation, proper maintenance should be applied for both of heat exchanger and temperature controller. These would entail that the digester should be stopped periodically.

To increase the temperature of a digester, operated without installing a heat exchanger and a temperature controller, during the cold weather, a strategy was suggested to heat the feed to certain temperatures before adding it to a digester. The proper increase of the feed temperature should be determined and the digester temperature should be known before applying such a strategy in practice. The objectives of this study were:

1) To develop a mathematical model for predicting the temperature and the net thermal energy production from a mesophilic CSTR operating under different conditions of temperatures and Hydraulic Retention Time (HRT) operated under the Egyptian weather conditions.
2) To predict the performance of a digester that is working without installing both of a heat exchanger and a temperature controller.

3) To evaluate the effect of preheating the influent to different temperatures on the digester performance and on the net energy production.

MATHEMATICAL MODEL

A mathematical model has been developed based on energy and mass balances. The developed model has two submodels: the first is a biochemical submodel and the second is an energy balance one. The first submodel enables the prediction of methane production rate from a digester so that net thermal energy could be determined.

2.1. Methane production submodel

Methane production rate from the digester was predicted using the models of Chen and Hashimoto (1978), Hashimoto (1983) and Hashimoto et al. (1980). For the simulation of biogas production at temperatures lower than 20°C, it was assumed that biogas production is nil. This is because the equation of Hashimoto et al. (1980), for calculating the maximum specific growth rate, is valid in the temperature range of 20-60°C. However, Zeeman (1991) studied the performance of anaerobic digesters operated under psychrophilic temperatures (<20 °C). Yet, her data could not be used to derive an equation for calculating the maximum specific growth rates at these low temperatures.

2.2. Digester heat balance submodel

A schematic diagram of different heat flow terms around an anaerobic digester is shown in Fig. (1).

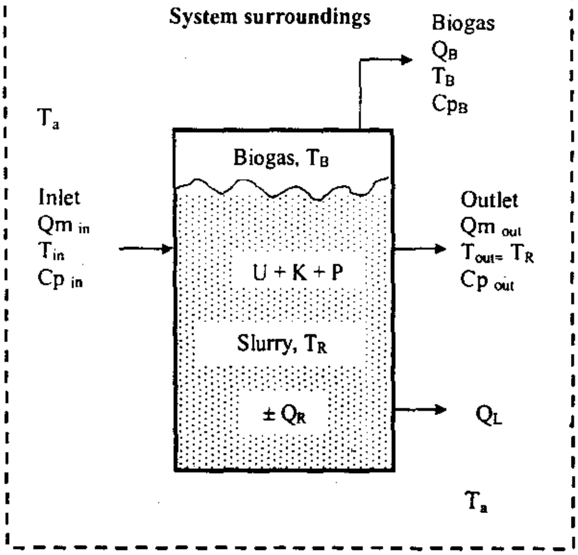

Fig.(1): A schematic diagram of energy balance around an anaerobic digester

The total energy balance for a digester can be presented as a modification of the models presented by Stephanopoulos (1984) and El-Mashad (2003):

$$\frac{d(U+K+P)}{dt} = \phi m_{in}\ h_{in} - \phi m_{out}\ h_{out} - Q_B \pm Q_R \pm Q_L$$

Where:

U, K, P = internal, kinetic, and potential energies of the system, respectively (J);

ϕm_{in} = mass flow rate of the influent (kg/s);

ϕm_{out} = mass flow rate of the effluent (kg/s);

h_{in} = specific enthalpy of the influent (J/kg);

h_{out} = specific enthalpy of the of the effluent (J/kg);

Q_B= rate of heat lost with the biogas produced (W);

Q_R = rate of heat of reaction (W);

Q_L = rate of heat exchanged between the system surface and its surroundings (W);

t = time (s).

Since the digester does not move, the rate of change of total energy of the digester contents can be formulated as follows:

$$\frac{d(U+K+P)}{dt} \approx \frac{dU}{dt}$$

For liquid systems, the internal energy (U) is the total enthalpy (H) of the system contents (Stephanopoulos, 1984):

$$\frac{dU}{dt} \approx \frac{dH}{dt}$$

The total enthalpy can be determined as follows:

$$H = \rho_R\ V C_{p_R}\left(T_R - T_{ref}\right) = M_R c_{p_R}\left(T_R - T_{ref}\right)$$

Where:

ρ_R = density of the digester content (kg/m^3);

V= digester volume (m^3);

C_{p_R} = specific heat of the influent (J/kg°C);

T_R= digester temperature (°C);

T_{ref} = reference temperature where the specific enthalpy of the influent is assumed to be zero (°C).

Density and specific heat of the influent and the effluent were calculated based on the equations of Achkari-Begdouri and Goodrich (1992). The specific enthalpies of the influent and the effluent can be calculated as follows:

$$h_{in} = Cp_{in}\left(T_{in} - T_{ref}\right) = Cp_{in} T_{in}$$

$$h_{out} = Cp_{out}\left(T_{out} - T_{ref}\right) = Cp_{out} T_{out}$$

The rate of heat losses with the biogas can be determined as follows:

$$Q_B = \phi_B T_R\ Cp_B$$

Where:

ϕ_B = mass flow rate of the biogas(kg/s);

Cp_B = specific heat of the biogas (J/kg.°C).

Energy exchange between digester surface and the surroundings is the summation of heat exchanges between the surroundings and digester top, bottom and sides.This can be calculated as follows:

$$Q_L = (T_R - T_a)\sum_i U_i A_i$$

Where:

U_i = overall heat transfer coefficient from the i^{th} surface of the digester ($W/m^2.°C$)

A_i = Area of the i^{th} surface of the digester (m^2)

T_a = Ambient temperature (°C)

Assuming constant mass of substrate in the digester, a total energy balance equation can be formulated as follows:

$$\frac{d\left(\rho_R \ V C_{p_R} T_R\right)}{dt} = \phi m_{in} Cp_{in} T_{in} - \phi m_{out} Cp_{out} T_{out} - \phi_B T_R \ Cp_B \pm$$
$$\pm \ Q_R \pm (T_R - T_a)\sum_i U_i A_i$$

Since the digester volume is constant and assuming that the specific heat and density of the digester content do not change with time, this differential equation can be written in the following form:

$$\left(\rho_R \ V C_{p_R}\right)\frac{d T_R}{dt} = \phi m_{in} Cp_{in} T_{in} - \phi m_{out} Cp_{out} T_{out} - \phi_B T_R \ Cp_B \pm$$
$$\pm \ Q_R \pm (T_R - T_a)\sum_i U_i A_i$$

Assuming that the heat of reaction is negligible (Hobson *et al.*, 1981) and mass flow rate and specific heat of the influent equal that of the effluent, then the temperature of the digester content can be calculated as follows:

$$\left(\rho_R \ V C_{p_R}\right)\frac{d T_R}{dt} = \phi m \ Cp_{in}(T_{in} - T_R) - \phi_B T_R \ Cp_B \pm (T_R - T_a)\sum_i U_i A_i$$

2.3. Ambient air temperatures

Hourly temperatures of ambient air are important to conduct the simulation of digester temperature and to determine the net thermal energy production. Unfortunately, the available measured data, for Cairo, Egypt, were for the monthly average minimum and maximum temperatures (Weather-UK, 2007). These data were used to calculate the daily maximum and minimum temperatures via the linear interpolation using Matlab Softwear (7.0). Then, hourly ambient air temperature was calculated using the cosine function that was proposed by De Wit (1998) and used by Debele et al. (2007). A slight modification to this equation was manipulated assuming that the maximum temperature of the day occurs at 1: PM as follows:

$$T_a = \left(\frac{T_{max} - T_{min}}{2}\right). \cos\left(\frac{\pi(t-13)}{12}\right) + T_{av}$$

Where:

T_a = air temperature (°C) at time t (hr) starting from the midnight;

T_{av}, T_{max}, T_{min} = average, maximum and minimum daily temperatures (°C), respectively.

The calculated hourly temperatures of ambient air of the first day of some months are shown in Fig. (2). As can be seen that, during January, the minimum and maximum temperatures were 10.5 and 19.5 °C, respectively. While, during July, the minimum and maximum temperatures were 22.1 and 34.5 °C, respectively.

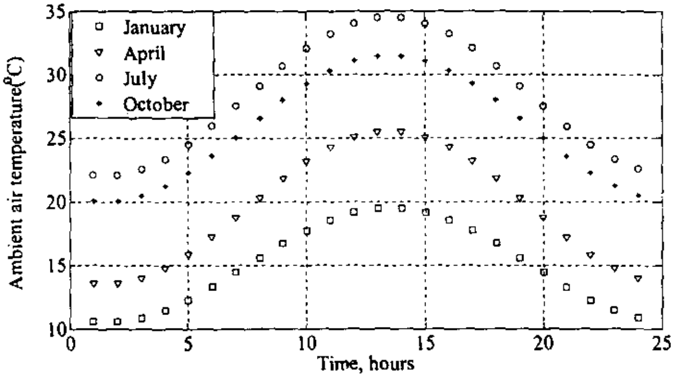

Fig. (2): Calculated hourly ambient air temperatures in Cairo

2.4. Net energy calculations

The energy output was calculated as the product of the total amount of methane production and the calorific value of methane. A calorific value of 37 MJ per m^3 of methane was used in these calculations (Hill and Bolte, 2000). The net thermal energy was calculated as the difference between the energy output and the energy needed to heat up the influent and to compensate the energy losses to the environment as described by El-Mashad (2003) and Abd El-Latif and El-Mashad (2005).

SIMULATIONS

The developed model was used to simulate two anaerobic digesters operated under the Egyptian weather conditions. The first digester was assumed to be operated under steady state conditions. The temperature of this digester was kept constant at mesophilic conditions (35, 37 and 40°C) over a whole year by using a heat exchanger to provide the energy required to heat up the influent and to compensate the heat losses to the environment. The second system was assumed to be operated without adding any external heating. Therefore, the system is operated under transitional conditions. This means that the digester temperature is dynamically changed as the ambient temperature changes. Therefore the biogas production is affected because the temperature is a crucial factor affecting the growth rate of anaerobic microorganisms. For the second system, the effect of preheating of the influent on the digester temperatures was also simulated. This is the strategy that was proposed to increase the digester temperatures without the need for installing a heat exchanger and a temperature controller. In this strategy, it was proposed that if the temperature of the influent is below 25°C, the influent will be heated at 5, 10, 15, 20 and 25 °C above its original temperature.

SIMULINK tool, in MATLAB ® software (7.0), was used to code and solve the model equations. Two MATLAB programs were coded for calculating the energy input and output from the first studied system and to simulate the temperature of the second digester. In the second program, the ordinary differential equation solver (ode45), which is based on Runge-Kutta scheme, was used with a variable time step. A block oriented structure of the model is shown in Fig. (3). The simulations were run assuming that the initial conditions of the state variable equals to 30°C. Table (1) shows the input parameters applied in the simulations.

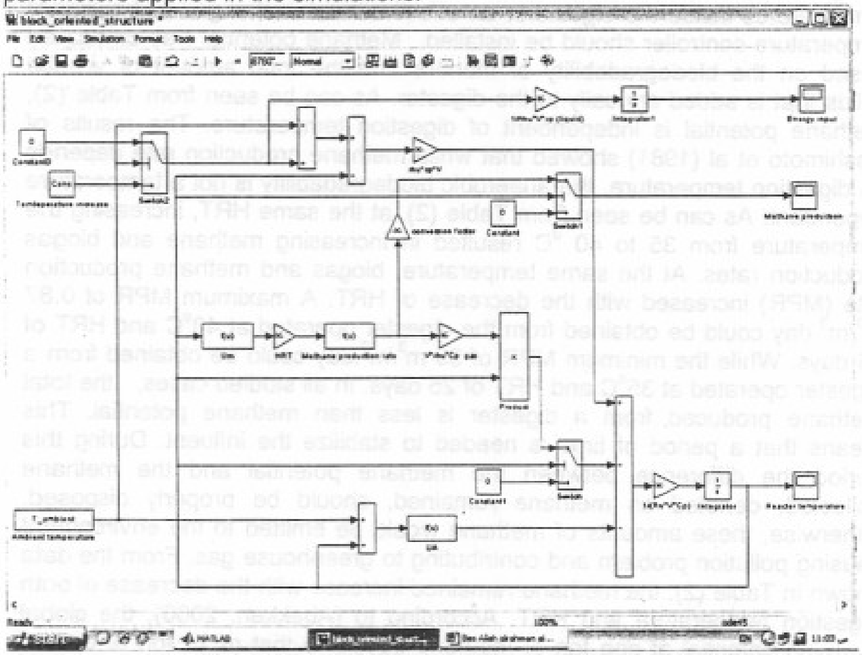

Fig.(3): Block oriented structure of the studied model

Table (1): Input parameters applied in the simulations

Parameter	Value
Digester volume (m^3)	5
Aspect ratio (height/diameter)	0.60
Head space volume (% of effective volume)	10
Overall heat transfer coefficient from the digester ($W/m^2.^oC$)	0.33
Biogas density (kg/m^3)	1.3
Methane density (kg/m^3)	0.66
Biogas specific heat ($J/kg.^oC$)	1600
Total solids (TS) of manure (%)	8
Volatile solids (VS)/ TS (%)	80
Ultimate methane yield ($m^3/kg[VS]$)	0.24
Methane content of biogas (%)	60

RESULTS AND DISCUSSION

4.1. Simulation of the performance of a digester operates under constant temperature

4.1.1 Biogas production

The simulation results of a 5 m^3 anaerobic digester are shown in Table (2). The simulations were conducted for a digester operated at different constant temperatures (35, 37 and 40°C) and HRTs (15, 20 and 25 days) using the parameters shown in Table (1). To keep these constant temperatures inside the digesters, an effective heat exchanger and a proper temperature controller should be installed. Methane potential was calculated based on the biodegradability of manure and the total amount of volatile solids that is added annually to the digester. As can be seen from Table (2), methane potential is independent of digestion temperature. The results of Hashimoto et al (1981) showed that while methane production rate depends on digestion temperature, the anaerobic biodegradability is not a temperature dependant. As can be seen from Table (2), at the same HRT, increasing the temperature from 35 to 40 °C resulted in increasing methane and biogas production rates. At the same temperature, biogas and methane production rate (MPR) increased with the decrease of HRT. A maximum MPR of 0.87 m^3/m^3.day could be obtained from the digester operated at 40°C and HRT of 15 days. While the minimum MPR of 55 m^3/m^3.day could be obtained from a digester operated at 35°C and HRT of 25 days. In all studied cases, the total methane produced from a digester is less than methane potential. This means that a period of time is needed to stabilize the influent. During this period the difference between the methane potential and the methane collected, denoted as methane remained, should be properly disposed. Otherwise, these amounts of methane would be emitted to the environment causing pollution problem and contributing to greenhouse gas. From the data shown in Table (2), the methane remained increase with the decrease of both digestion temperature and HRT. According to (Abakken, 2006), the global warming potential of one ton of methane equals to that of 21 ton of carbon dioxide. Therefore, to obtain the maximum methane yield (i.e., 1584.1 m^3/year) from a 5 m^3 digester, about 3.95 ton of CO_2 could be emitted annually from the non-captured methane (i.e., 285 m^3/year).

4.1.2. Energy balance

The data in Table (2) show the annual energy output and the net thermal energy produced from a 5 m^3 digester operated at different temperatures and HRTs. As can be seen from the data in that Table, the net thermal energy increased with the decrease of digestion temperature and HRT. This is due to the fact that with increasing the digestion temperature, heat losses to the surrounding and heat needed for heating the feed increase. Moreover, with decreasing the HRT, higher rates of methane are produced. A maximum specific net thermal energy of 9.53 GJ/m^3.year could be obtained when the digester operated at a temperature and an HRT of 35 °C and 15 days, respectively. This amount of net thermal energy represents about 84% of the total energy production from the digester. At these operational conditions about 4.77 ton of CO_2 could be emitted from the non-stabilized effluent.

Specific energy needed and net thermal energy production for a digester operated at an HRT of 15 days and a temperature of 35°C over a whole year is shown in Fig. (4). The simulated data shown in this Figure started on the first of January and stopped at the end of December. As can be seen less energy was needed during the summer and consequently more net thermal energy could be calculated. This is due to the increase of the ambient temperature in summer (Fig.2) and therefore less energy losses to the environment are evident and less energy is needed to heat up the influent.

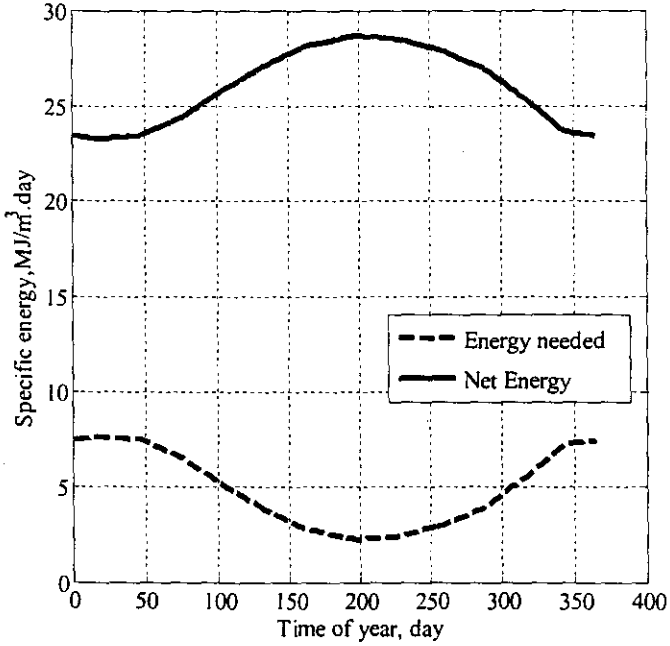

Fig. (4): Calculated specific net thermal and thermal energy needed for a 5 m^3 anaerobic digester operated at 35°C and 15 days HRT

4.2. Simulation of the performance of a digester operates without installing a heat exchanger and a temperature controller

The effect of the influent heating on the digester temperature and net thermal energy production was simulated at different HRTs without installing a heat exchanger inside the digester. The simulations were carried out for two consecutive years started on the first of July. The average digestion temperature and MPR are shown in Table (3). The energy output, input energy and net thermal energy are also shown in the same Table.

Table (2): Energy production from a 5 m^3 digester operated under different temperature and HRTs

Temperature (°C)	hydraulic retention time (days)	Organic loading rate (kg[VS]/m^3.day)	Methane production rate (m^3/m^3.day)	Methane potential (m^3]/year)	Methane production (m^3]/year)	Biogas production (m^3/year)	Methane remained (m^3 /year)	Emitted Carbon dioxide (ton /year)	Energy output (GJ/m^3.year)	Energy output (GJ/year)	Net thermal energy (GJ/m^3.year)	Net thermal energy (GJ/year)	Net thermal energy (% of output)
40	**25**	2.6	0.56	1121.3	1019.7	1568.7	101.61	1.41	7.54	37.73	5.82	29.1	77.1
	20	3.2	0.68	1401.6	1242.3	1911.3	159.29	2.21	9.19	46.00	7.19	36.0	78.3
	15	4.2	0.87	1868.8	1584.1	2437.0	284.72	3.96	11.72	58.60	9.28	46.4	79.2
37	**25**	2.6	0.55	1121.3	1008.2	1551.2	113.03	1.57	7.46	37.10	6.02	30.11	80.7
	20	3.2	0.67	1401.6	1224.3	1883.6	177.25	2.46	9.06	45.30	7.40	37.00	81.7
	15	4.2	0.85	1868.8	1551.8	2387.3	317.04	4.41	11.48	57.42	9.45	47.30	82.3
35	**25**	2.6	0.55	1121.3	999.1	1537.1	122.2	1.70	7.39	36.97	6.14	30.70	83.2
	20	3.2	0.66	1401.6	1209.9	1861.4	191.67	2.67	8.95	44.77	7.52	37.58	84.0
	15	4.2	0.84	1868.8	1525.8	2347.4	343.0	4.77	11.29	56.50	9.53	47.70	84.4

Table (3): Operation conditions and performance of a 5 m3 digester that fed with heated liquid manure at different temperatures

Parameter	HRT* (days)	OLR** (kg[VS]/m^3.day)	Temperature increase of the influent (°C) 0	5	10	15	20	25
Mean temperature (°C)	25	2.6	21.49 (±4.87)	24.67 (±3.50)	27.85 (±2.16)	31.05 (±0.94)	34.26 (±1.02)	37.47 (±2.28)
	20	3.2	21.58 (±4.96)	24.77 (±3.56)	27.97 (±2.22)	31.19 (±0.99)	34.41 (±1.05)	37.64 (±2.29)
	15	4.2	21.68 (±5.0)	24.90 (±3.62)	28.11 (±2.27)	31.35 (±1.05)	34.59 (±1.08)	37.82 (±2.31)
MPR*** (m^3/m^3.day)	25	2.6	0.29(± 0.25)	0.43(± 0.18)	0.52(± 0.0.1)	0.54(± 0.00)	0.55(± 0.25)	0.55(± 0.01)
	20	3.2	0.36(± 0.29)	0.50(± 0.21)	0.61(± 0.02)	0.64(± 0.01)	0.66(± 0.01)	0.67(± 0.01)
	15	4.2	0.42(± 0.35)	0.60 (±0.26)	0.76 (±0.04)	0.80(±0.01)	0.83 (±0.01)	0.85 (±0.02)
Energy output (GJ/m^3.year)	25	2.6	3.93	5.79	7.00	7.22	7.36	7.47
	20	3.2	4.68	6.80	8.35	8.69	8.92	9.08
	15	4.2	5.66	8.13	10.23	10.84	11.24	11.54
Energy added (GJ/m^3.year)	25	2.6	0	0.20	0.40	0.59	0.79	0.99
	20	3.2	0	0.25	0.50	0.74	0.99	1.24
	15	4.2	0	0.33	0.66	0.99	1.32	1.65
Net thermal Energy (GJ/m^3.year)	25	2.6	3.93	5.59	6.61	6.63	6.57	6.48
	20	3.2	4.68	6.56	7.86	7.95	7.93	7.85
	15	4.2	5.66	7.80	9.57	9.85	9.92	9.89

* Hydraulic retention time

** Organic loading rate

*** Methane production rate

4.2.1. Simulation of the performance of digesters operate without heating the feed

As can be seen from Table (3) that there is no pronounced effect of the HRT on the digester temperature. The average annual digestion temperatures were about 21.5 °C for the digester operated at any studied HRT. Under these conditions the calculated average methane production rates were 29, 36 and 42 m^3/m^3.day at HRTs of 25, 20 and 15 days, respectively and the calculated specific net thermal energy were 3.93, 4.68 and 5.66 GJ/m^3.year, respectively. The temperature profile over a two years period and the biogas production rates from the digester operated at an HRT of 15 days without heating the influent are shown in Figs. (5) and (6). As can be noticed, the temperature of the digester decreased from its initial temperature (30°C) till reaching 15 °C during the winter time. Then the temperature increased reaching a maximum of about 27°C during the next summer (i.e., after 10000 hours of operation). Following the temperature profile, biogas decreased from the beginning reaching zero after about 2800 hours then biogas production commenced after about 7000 hours reaching a maximum after about 10000 hours of operation. A maximum biogas production rate of 1.17 m^3/m^3.day could be calculated after 10000 hours. The average annual biogas production could be calculated to be 0.65 m^3/m^3.year. This amount could be entirely converted into net thermal energy because there was no energy added to the digester. Yet, the increase of the influent temperature was proposed to increase the digester temperature during the cold weather. This would increases the energy output and the net thermal energy production during winter time.

4.2.2. Simulation of the performance of digesters operate with heating the feed

The effect of increasing the feed temperature by 5, 15, 15, 20 and 25 °C above its original temperature was simulated at different HRTs. As expected, the average highest digester temperatures were obtained when increasing the influent temperatures by 25 °C. At these conditions, the average MPR were 0.55, 0.67 and 0.85 m^3/m^3.day for the digesters operated at HRTs of 25, 20 and 15 days, respectively. The calculated annual specific energy outputs were 7.47, 9.08 and 11.54 GJ/m^3.year, respectively. On the other hand, the highest annual net thermal energy was obtained when increasing the feed temperature by 20°C. At these conditions, the average temperature for all simulated digesters was about 35°C with a standard deviation of about 1 °C. The net thermal energy outputs were 6.57, 7.93 and 9.92 GJ/m^3.year, respectively at HRTs of 25, 20 and 15 days. These results are in line with the results obtained from the digester operated under a controlled temperature of 35 °C. The data in Figs. (5) and (6) show that as the temperature of the heated feed increased little variations, between winter and summer, in the digester temperature and biogas production rates could be observed.

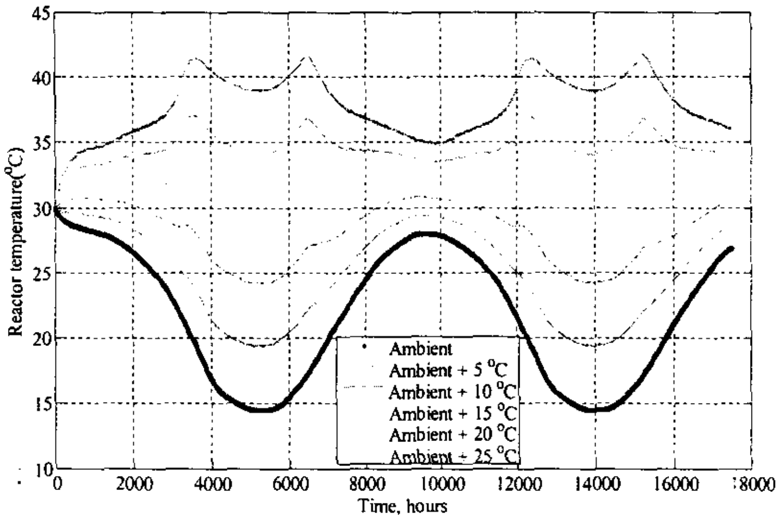

Fig. (5): Temperature profile of a digester operated at 15 days HRT

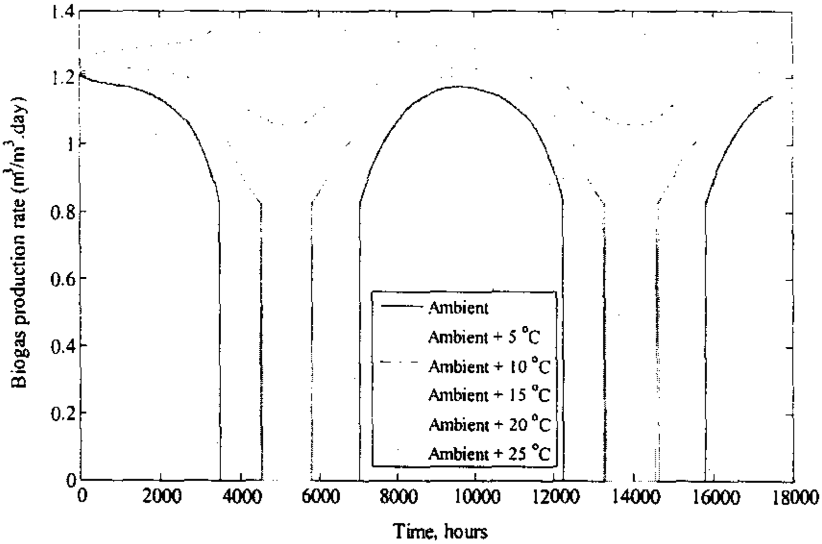

Fig. (6): Biogas production rate of a digester operated at 15 days HRT

The results obtained in this study demonstrate that it is possible to operate an anaerobic digester without the need for installing a heat exchanger and a temperature controller. Therefore, there will be no concern about either heat exchanger fouling or the malfunctioning of a temperature controller. Moreover this strategy would simplify the digester design that suits the operators of family size digesters. However, a small preheating unit should be used to heat the feed before adding it to the digester. Sizing of the preheating unit needs to be determined. For a batch preheating unit, the maximum volume of the preheating unit ($VPre_{max}$) could be calculated as follows:

$$V\,Pre_{max} = \frac{Reactor\ volume}{HRT}$$

As can be determined for a 5 m^3 digester operated at an HRT of 15 days, a preheating unit with a maximum volume of 0.33 m^3 is needed. When installing this unit, it would be much easier to clean up its heat exchanger periodically and to fix any problem of the temperature controller without the need for stopping the digester operation. For a continuous preheating unit, much smaller preheating unit could be installed. Research is needed to design both batch and continuous preheating units.

Although the simulations showed promising results, experiments are needed to calibrate and validate the heat balance model. Moreover, experiments are also needed to examine the effect of the addition of hot influent on the stability of the digester performance in terms of pH, accumulation of volatile fatty acids and soluble chemical oxygen demand and on the biogas production rates under different HRTs. Again the amount of carbon dioxide that could be emitted from the non-stabilized digestate should be considered when designing an integrated system for treating liquid cattle manure under the studied conditions. Finally, the available amount of manure in the neighborhood of the digester should be matched with the studied loading rates.

CONCLUSIONS

Based on the results obtained in this study the following conclusions can be drawn:

1- A maximum methane production rate of 0.87 m^3/m^3.day could be obtained from a digester operated at a constant temperature of 40°C and hydraulic retention time (HRT) of 15 days.

2- A maximum specific net thermal energy of 9.53 GJ/m^3.year could be obtained when operating the digester at a temperature and HRT of 35 °C and 15 days, respectively.

3- The amount of methane remained in the effluent increases with the decreases of both HRT and digestion temperature. Therefore a stabilization period is needed to prevent the global warming arisen from the emissions of these remains.

4- When operating a digester under ambient conditions, the calculated specific net thermal energy was 3.93, 4.68 and 5.66 GJ/m^3.year at HRTs of 25, 20 and 15 days, respectively.

5- Heating the influent was proved to be a good strategy to design anaerobic digester without installing a heat exchanger and a temperature controller. The highest annual net thermal energy was obtained when increasing the feed temperature by 20°C above its original temperature.

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نموذج محاكاة لمخمر لاهوائى صغير

حامد الموافى المشد
قسم الهندسة الزراعية- جامعة المنصورة

فى هذا البحث تم تطوير نموذج رياضى لانتاج الميثان و توازن الطاقة لمخمر لاهوائى مستمر ذو حجم يناسب الأسرة و يعمل على معالجة المخلفات الحيوانية السائلة. تم تطبيق هذا النموذج لمحاكاة أداء مخمر حجمه ٥ م^{٣} و ذلك فى حالة وجود وعدم وجود مبادل حرارى بالمخمر و ذلك لمدة عامين متتاليين تحت الظروف المصرية . وفى هذا البحث تم أيضا اقتراح و محاكاة طريقة لرفع درجة حرارة المخمر أثناء وقت الشتاء. و تتلخص هذه الطريقة فى رفع درجة حرارة المخلف الى درجات حرارة مختلفة قبل تغذيته الى المخمر. و قد تتم عملية التسخين فى وحدة تسخين صغيرة منفصلة عن المخمر أو عن طريق تخفيف مادة تغذية المخمر باستعمال الماء الساخن. و عند تطبيق هذه الطريقة فانه يمكن تبسيط تصميم المخمر بحيث يمكن أن يعمل بدون تركيب مبادل حرارى أو أى نظام للتحكم فى درجة الحرارة. و فى هذه الحالة فانه يمكن التخلص من مشاكل التشغيل التى قد تظهر فى كلا من المبادل الحرارى و نظام التحكم فى درجة الحرارة. و قد أوضحت النتائج أن صافى ناتج الطاقة من مخمر يعمل تحت درجات الحرارة ثابتة مع اضافة حرارة للمخمر (٣٥ –٤٠ ° م) يكون أقل فى الشتاء عنه أثناء الصيف. و كان أقصى صافى ناتج الطاقة الحرارية السنوى ٩,٥٣ جيجا جول / م^{٣}.سنة و ذلك من مخمر يعمل عند ٣٥ ° م و زمن بقاء هيدروليكى مقداره ١٥ يوم . و عند تشغيل المخمر بدون اضافة حرارة يكون صافى ناتج الطاقة الحرارية السنوى ٣,٩٣ و ٤,٦٨ و ٥,٦٦ جيجا جول / م^{٣}.سنة و ذلك عند أزمنة بقاء هيدروليكى ٢٥ و ٢٠ و ١٥ يوم على الترتيب. و قد وجد أيضا أن تسخين المخلف لدرجة حرارة ٢٠ ° م أعلى من درجته الأساسية (اذا كانت أقل من ٢٥ ° م) تحقق أعلى صافى ناتج للطاقة الحرارية مقارنة برفع درجة حرارة المخلف ٥ و ١٠ و ١٥ و ٢٥ ° م. و أوضحت النتائج أيضا أنه لابد من التحكم فى مخرجات المخمر حيث أنها يمكن أن تسبب انبعاثات لبقايا الميثان التى لم يمكن تجميعه من المخمر خصوصا عند درجات الحرارة المنخفضة و عند أزمنة البقاء الهيدروليكى القصيرة.