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A Model of Solar Energy Utilisation in the Anaerobic Digestion of Cattle Manure

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The anaerobic digestion of cow manure has a higher destruction of pathogens and weed seeds under thermophilic conditions compared to mesophilic conditions. To maintain such conditions, solar energy can be used. In this research, the consequences of the use of solar energy under Egyptian conditions are evaluated. In this study, experiments are combined with modelling. In the experimental part, anaerobic digestion on laboratory scale is studied in two continuously stirred tank reactors at 50 and 60°C. Daily temperature fluctuations in the tank caused a decrease in methane production rate of only 12 and 20% at 50 and 60°C, respectively. The results are used in a model for the thermal energy demand. In the model the net thermal energy production as a function of reactor volumes, thermal insulation and additional pre-heating of the influent is evaluated. The model results show that for continuously stirred tank reactors, additional pre-heater is not advised since it decreases the efficiency. The results also show that a maximum overall heat transfer coefficient of $1\,\mathrm{W\,m^{-2}\,K^{-1}}$ is needed for reaching at least 50% of energy efficiency. Furthermore, adding a solar energy system improves the efficiency for large reactors only slightly, while for small reactors a large improvement is achieved. An energy efficiency of 90% can be reached.

1. Introduction

As the cost of fuel rises, the use of renewable and sustainable energy systems becomes more viable. Agricultural residues represent an important source of bioenergy and valuable products. Technologies for energy production from such resources can be classified as biological (fermentation) or thermal (gasification, pyrolysis, burning). Anaerobic digestion is a biological process by which complex organic materials can be transformed, in the absence of oxygen, into biogas (a mixture of methane; carbon dioxide and traces of other gases). The main objectives of anaerobic digestion are waste stabilisation and energy recovery. Ghosh (1984) mentioned that farm digesters produce a high methane-content gas which, without cleanup, can be used for water or space heating, electricity or steam production to meet other thermal energy demands. It is also technically feasible to utilise methane gas as engine fuel. An important additional benefit is the conservation of the fertiliser value, originally present in the waste (Van Velsen & Lettinga, 1980). The anaerobic digestion process has a key role in environmental pollution control: methane is an important greenhouse gas, but if captured for use, it acts instead as a good renewable energy source (McCarty, 2001). Anaerobic digestion can be achieved under psychrophilic (6 25°C), mesophilic (25 – 40°C) or thermophilic (>45°C) conditions. Digestion under thermophilic conditions has many advantages such as higher metabolic rates (Van Lier, 1995) and a higher destruction of pathogens and weed seeds (Bendixen, 1994; Lund fubm 1995). The latter is very important since the effluent can be used as a soil conditioner. The major drawbacks of thermophilic compared with mesophilic treatment are less stability and higher energy requirements (Buhr & Andrewa, 1977; Wiegant, 1986; Van Lier, 1995).

The completely stirred tank reactor (CSTR) is the most generally applied system for slurry digestion. To keep the reactor temperature constant, external source

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of heating is used. This source may be fossil fuel or produced biogas, but this lowers the energy efficiency. If another renewable energy resource such as thermal solar energy could be integrated in the process then a high gas production can be achieved with high energy efficiency. Egypt has a high solar intensity, the annual global radiation is between 7 and 9 GJ m^{-2}. Utilisation of solar energy in the anaerobic digestion process will lead to the saving of fossil fuel or biogas. Hamdy (1998) mentioned that, in Egypt, about 60% of the cattle wastes are used as fuel by direct burning in low efficiencies burners (less than 10%); another 20% of the animal wastes are used as organic fertiliser, and the remainder is lost in handling. Therefore, in Egyptian rural areas, the produced gas has to be used as a direct fuel source. So using it for cogeneration of heat and power (CHP) is not a good option here; even not when the waste heat was used to maintain the thermophilic conditions in the reactor.

The combination of solar energy and biogas production represents a kind of solar energy storage in the gas. The incorporation of solar energy in the anaerobic digestion process may affect the process stability, which is resulting from the daily fluctuations of the available solar energy. So far this effect is not known and has to be investigated.

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The objectives of the present study are:

1. experimental determination of the effect of both temperature and temperature fluctuation on methane production from thermophilic anaerobic digestion of cow manure;
2. determining in a model the effect of reactor size, outside insulation and separate pre-heating on net energy production; and
3. study the possibility of solar energy utilisation in this process.

2. Materials and methods of the experimental work

Two experimental runs of anaerobic digestion have been carried out. In the first run, two reactors were kept at a constant temperature: one at 50°C and one at 60°C, respectively. After about 50 days 'steady state' was reached characterised by constant methane production rate together with constant volatile fatty acid concentration (El-Mashad fu bm 2001). To test the reproducibility of the result, this 'steady state' maintained during 9 days. Then a second run was performed, in which the reactor temperatures were reduced 10°C for 10 h daily for both reactors. The magnitude of temperature reduction was chosen based on simple model calculations of temperature reduction of a 2 m^3 reactor operated at 50°C, with overall heat transfer coefficient of 5 W m^{-2} K^{-1}, in worst case scenario by applying first-order cooling model. The worst case conditions were considered as a constant ambient temperature of 15°C and the longest sunset hours under Egyptian situation of 16 h and there is no auxiliary heating during sunset hours. The results of these calculations showed that the reactor temperature dropped to about 40°C. From these calculations, a temperature reduction of 10°C was chosen.

2.1. Fyqfsjnfoubm sfbdupst

Two CSTR reactors (cylindrical vertically oriented), each with a working volume of 8 l, were used in this study at a hydraulic retention time (HRT) of 20 days. The diameter of the reactor is 0·18 m and its height is 0·45 m. The reactors were continuously mixed at 6 min^{-1} using a gate type mixer (diameter 0·12 m). The reactors were heated by hot water recirculation through a water jacket surrounding the reactors. The reactors were seeded with 8 l of thermophilic sludge obtained from a 2700 m^3 reactor from the VAGRON, (Groningen, NL) treating municipal waste at a temperature of 52–57°C and a retention time of 18 days. One week after inoculation, the feeding was started. The system feeding was performed once a day. As the feeding process requires only 10 min, no heat recovery from the effluent is possible here. In the second run, the feeding regime was started at about 8 o'clock in the morning, then the temperature of the water in the jacket was reduced for both reactors. The reactors reached the reduced temperature after about 20 min. Around 6 o'clock in the evening the temperature returned back to 50 and 60°C, respectively.

2.2. Gffetupdl

The feeding consisted of diluted cow manure. The manure used in this study was produced from dairy cows weighing about 650 kg.The cows were fed on a ration consisting of 70% grass and 30% maize as well as about 5 kg of concentrated feed per day. The diet contained also 0·1 kg of minerals and vitamins without any antibiotic addition. The manure was stored in a refrigerator at 4°C until used. Before feeding, the manure was diluted with tap water to yield a 5% total solid (TS) feedstock. In Table 1, the influent composition is given. The influent composition has been measured as described by El-Mashad fu bm (2001).

Table 1
The influent composition

Parameter	Value
Total solid (TS), %	5
Volatile solid (VS), % of TS	80
NH_4^+-N, g l^{-1}	0·85
Dissolved chemical oxygen demand, g l^{-1}	9·3
Volatile fatty acids (VFA), g [COD] l^{-1}	3·3
Total nitrogen, g l^{-1}	2
Total chemical oxygen demand (Total COD), g l^{-1}	57·9

2.3. Methane measurement

Produced methane was collected in gas bags after removing CO_2 by passing the biogas through a glass column containing 150 ml of 3% NaOH solution. The solution was changed twice a day. The amount of NaOH required was calculated as follows (Anaerobic Lab Work, 1992):

$$V_{NaOH} = \frac{2V_{CH_4}}{0{\cdot}7C_{NaOH}} \qquad (1)$$

where: V_{NaOH} is the tolerated volume of NaOH in ml; V_{CH_4} is the volume of methane, when it is time to replace the NaOH solution, in ml and C_{NaOH} the concentration of NaOH in g ml^{-1}.

The daily methane production was measured using a wet gas meter. The methane production has been recalculated for standard temperature and pressure.

3. Modelling

For calculating the energy consumption for heating the substrate and maintaining the desired reactor temperature, a model has been made. To achieve this, two systems have been modelled: a CSTR without pre-heater and one preceeded by a pre-heater as schematically shown in Fig. 2. This system has been proposed for the sake of using the available solar energy to heat the feedstock during daylight. The heat required for the pre-heating process and the constant temperature of the reactors can also be achieved by using a conventional heater. Since the experimental results showed that the reactor operated at 50°C has higher methane production compared with the reactor operated at 60°C, all calculations have been performed at a digestion temperature of 50°C.

3.1. Pre-heater heat model

The pre-heater is assumed to be a batch process. In the pre-heating process, the influent temperature is increased from ambient temperature, to the digestion temperature (50°C). The assumption that manure increased from ambient temperature was based on the fact that the system of animal breeding varies from roofed stable to open roof stables, which consequently affects the manure temperature. It is assumed that the pre-heating is accomplished within 10 h. The pre-heater temperature is represented by the following equation:

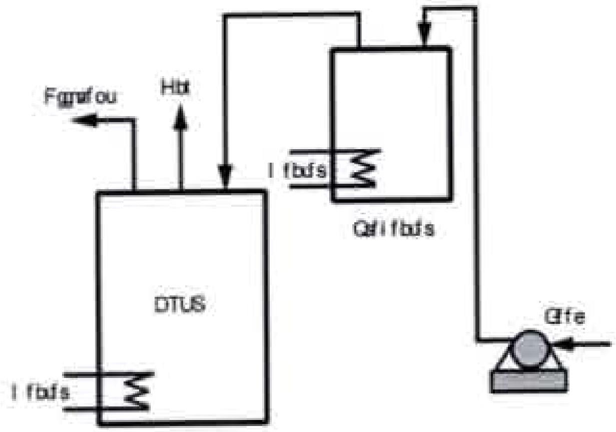


Fig. 2. Continuous stirred tank reactor (CSTR) with pre-heater.

$$\rho V_{pre} C_p \frac{dT_{pre}}{dt} = E_{pre} - U_{pre} A_{pre} (T_{pre} - T_a) \qquad (2)$$

where: T_{pre} is the pre-heater temperature in K; V_{pre} is the pre-heater volume in m^3; ρ is the manure density in kg m^{-3}; C_p is the specific heat of manure in J kg^{-1} K^{-1}; t is the time in s; E_{pre} is the power needed for pre-heater in W; U_{pre} is the overall heat transfer coefficient of the pre-heater in W m^{-2} K^{-1}; A_{pre} is the pre-heater surface area in m^2; T_a is the ambient temperature in K.

It should be mentioned that Eqn (2) does not include the heat capacity of the pre-heater material since this is negligible compared to the heat capacity of the loaded manure. Density and specific heat of the manure are calculated from its solid content (Achkari-Begdouri & Goodrich, 1992).

For calculating the product $U_{pre}A_{pre}$, it is assumed that the pre-heater has a cylindrical shape, its height equals 60% of its diameter (i.e. aspect ratio is 0·6). The overall heat transfer coefficient U has been calculated for different insulation types and different thickness, assuming the heat transfer coefficient to the ambient air (h_o) equals 10 W m^{-2} K^{-1} (Beek & Muttzall, 1975).

$$\frac{1}{U_{pre}} = \frac{1}{h_o} + \sum_{i=1}^{n} \frac{d_i}{k_i} \qquad (3)$$

where: d_i is the thickness of material i in m; k_i is the thermal conductivity of material i in W m^{-1} K^{-1}.

Table 2
The calculated overall heat transfer coefficient V for different insulation materials thickness with thermal conductivity of 0·04; 0·3 and 0·8 $W m^{-1} K^{-1}$ for rock wool; straw loam and bricks, respectively (Gaskell, 1992)

Nbufsjbm boe uijdloftt	Dbmdvmbufe V- $X n^{-2} L^{-1}$
10 cm bricks + 11 cm rock wool	0·33
40 cm straw loam	0·67
30 cm straw loam	1
40 cm bricks or concrete	1·7
9 cm straw loam	2·5
8 cm bricks or concrete	5

The calculated values for different types of insulation are shown in Table 2 and will be used in further calculations. These calculations will be also used for the reactor.

3.2. Dpoujovpvt tujssfe ubol sfbdups ifbu npefm

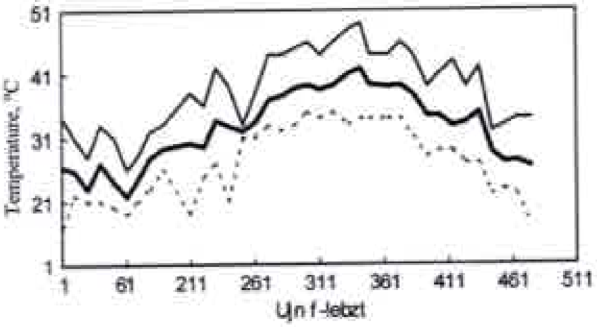
The CSTR operation mode is characterised by constant flow rates of both the influent and the effluent, leading to a constant reactor volume in time. The reactor temperature can be described by the following equation:

$$sWD_q\frac{dU_S}{du} = g_W sD_q(U_{jo} - U_S) + F_s - VB_s(U_S - U_b) \quad (4)$$

where: W is the reactor volume in m^3; U_{in} is the influent temperature in °C; U_R is the reactor temperature in °C; g_W is the flow rate $m^3 s^{-1}$; V is the overall heat transfer coefficient of the reactor in $W m^{-2} K^{-1}$; B_r is the reactor surface area in m^2; F_r is the heater power in the reactor in W.

As convective heat losses by gas are small compared to that of the manure, it is assumed that only the flow rate and heat capacity of the manure has to be considered in the convective term $(g_W sD_q(U_{jo} - U_S))/$ Equation (4) does not contain the direct solar gain due to absorption throught the reactor walls, because the absorbtion part depends significantly on many factors like the location of the reactor instalation (indoor or outdoor), shading conditions and colour. So, the model presented here is the most simple case. It should also be mentioned that the reactor has a cylindrical shape with an aspect ratio of 0·6. The aspect ration was chosen based on the calculations of Beuger (2001).

The product of the overall heat transfer coefficient and surface area of the reactor can be calculated also from the data given in Table 2.



Gjh/ 3/ Njojnvn - bwfsbhf boe nbyjnvn bncjfou bjs ufnqfsbuvsf Upwfs b xipmf zfbs voefs Fhzqujbo dpoejujpot; . . . . - U_{min}, ——— - U_{av} <——U_{max}

3.3. Bncjfou bjs ufnqfsbuvsf

Minimum, maximum and average daily air temperatures for some days every month were available at 10 days interval for Egyptian conditions. The measured data was obtained from Wunderground weather report during years 1999 and 2000 (Wunderground, 2000). To obtain typical data for the daily minimum, maximum and average temperatures over the whole year, the available data were interpolated. Gjhvsf 3 shows the daily minimum U_{min}, average U_{av} and maximum U_{max} air temperatures. As can be seen from this figure, the temperature starts to increase by the beginning of March (day 60) and starts decreasing by mid August (day 250).

The characteristic time (WsD_q/VB) for the reactor is in the order of days, but hourly data are needed in this model because: (1) every day fresh manure needs to be heated from ambient temperature to reactor temperature; and (2) available solar energy highly fluctuates during the day.

The hourly ambient temperature has been obtained by approximation of the available daily temperatures (minimum, maximum and average) by a sine function. For this function the minimum temperature was assumed to be at 3 o'clock in the morning, and the maximum temperature at 3 o'clock in the afternoon.

4. Results and discussion

4.1. Nfuibof qspevdujpo

Firstly, the effect of temperature level is investigated. Table 3 shows the average methane production rate (N QS), expressed as m[CH_4] m^{-3}[reactor] day^{-1}, during steady state conditions together with the standard deviations between the observations. For the first run, 'steady state' conditions were reached after 50 days and

Table 3
Mean methane production rate (MPR) during constant and fluctuating (FL) temperatures and its standard deviation (SD) during 'steady state'

Sfbdups	Ufn qfsbuvsf- 9D	N fbo N QS- mDI ‚^n^{-4}\ sfbdups^ ebz^{-1}	TE pg N QS- mDI ‚^n^{-4}\ sfbdups^ ebz^{-1}	Ovn cfs pg pctf svbujpot- ebzt
S_{50}	50	394	20	9
S_{60}	60	347	8	9
S_{50FL}	50 + 40	348	17	15
S_{60FL}	60 + 50	279	14	15

maintained during another 9 days to obtain some replications of the measurements. From Table 3 it can be seen that methane production rate at a reactor temperature of 50°C, denoted by S_{50}, is higher than that at a reactor temperature of 60°C, denoted by S_{60}. This may be attributed to the effect of free ammonia concentration under the higher temperature (El-Mashad fubm 2001). It should be mentioned that the magnitude of free ammonia concentration (NH_3-N) depends on many factors like, ammonium nitrogen (NH_4^+-N) concentration; pH and temperature (Angelidaki & Ahring, 1993).

Secondly, the effect of fluctuating temperatures is investigated. The daily temperature fluctuation, due to adding once per day fresh manure at ambient temperature, is small. The hydraulic retention time of 20 days results in a fresh manure supply of 5% of the reactor volume per day. The accompanying temperature drop is always less than 2°C. If solar energy is used as a heating source, without auxillary heating or heat storage, temperature drops during the night. Here, an extreme daily temperature drop of 10°C during 10 h is considered (see Section 2). The temperature regime of 14 h at 50°C and 10 h at 40°C denoted as S_{50FL}; and the regime of 14 h at 60°C and 10 h at 50°C denoted by S_{60FL}. A small, but significant decrease of methane production rate can be observed at fluctuating temperature conditions. It should be mentioned that 'steady state' conditions, for the second run, were reached after 55 days, from the end of the first run, and maintained during 15 days. Average values and standard deviations of methane production rate during 'steady state' conditions are shown in Table 3.

From the influent composition (Table 1), it can be calculated that 2·9 kg [COD] per m^3 [reactor] is added daily, where the chemical oxygen demand is abbreviated as COD. Now the methane yields during steady state are determined at about 136, 120, 120 and 96 rf[CH_4] kg^{-1}[COD added] for S_{50}, S_{60}, S_{50FL} and S_{60FL}, respectively. It can be seen that temperature fluctuations have a minor effect: S_{50F} is 12% lower than S_{50} and S_{60FL} is 20% lower than S_{60}. In this case, the influence of temperature fluctuations on the methane production is higher at higher temperatures. From these results it can be concluded that it is possible to use the available solar energy to heat the reactor without severe effect on the methane production or process stability at 50°C because, in practice the reactor temperature is not reduced to the severe conditions studied here.

4.2. N pef mgps ofu u l f sn bml of shz qspevdujpo

There are many parameters, which affect the net energy produced from the anaerobic digestion process, such as the feed composition. Here, it should be mentioned that the undiluted fresh manure has 8·6% volatile solids (VS) and the dilution used in these experiments was to mitigate the high ammonia concentration effect. In many countries, less protein rich feed is used, resulting in a lower NH_4^+-N content of the manure. In the experiments, daily 5% of the reactor volume is replaced with diluted manure (4% VS). When operated with non-diluted manure, a reactor volume of 1 m^3 per cow is needed. Since the volatile solids concentrations do not affect the process stability (j/f. inhibition) while the ammonia concentrations do (Zeeman, 1991), based on the experimental results, the methane yield per kg VS added was calculated to be 197 rf[CH_4] kg^{-1} [VS added] at 50°C. By using manure with 8·6% VS, the loading rate (at 20 days HRT) would be 4·3 kg [VS] m^{-3} [reactor] day^{-1}. Multiplying 197 rf[CH_4] kg^{-1} [VS added] by 4·3 kg [VS] m^{-3} [reactor] day^{-1} produces 845 rf[CH_4] m^{-3}[reactor] day^{-1}. The daily net thermal energy production (NTEP) at 50°C, has been calculated using a methane calorific value of 37 MJ m^{-3} (Hill & Bolte, 2000).

Specific net thermal energy production (SNTEP) is defined as net energy production per cubic metre of the reactor: it is the caloric value of the produced methane minus the energy needed for heating the feed, and the heat losses to the environment. Table 4 shows the calculated SNTEP of different reactor volumes preceeded by pre-heaters expressed as a percentage of the energy potential production. The larger the reactor

Table 4
The annual specific net thermal energy production as a function of different reactor volumes and different insulation (details, see Table 2) expressed as a percentage of the energy potential of methane produced (11·4 GJ m^{-3}[reactor] yr^{-1}) including a pre-heater

Sfbdups wpmn f- n^{J}	Sfbdups ejbn fufs- n	Qspqpsujpo pg f of shz qspevdf e- &					
		Jotvmbuf e csjdl t	51 dn mpbn	41 dn mpbn	51 dn csjdl t	: dn mpbn	9 dn csjdl t
2·0	1·62	70·2	58·1	46·1	22·1	—	—
4·0	2·04	72·7	63·1	53·6	34·5	10·6	—
10	2·77	75·2	68·1	61·1	47·0	29·5	—
20	3·49	76·7	71·1	65·5	54·3	40·3	—
40	4·39	77·8	73·4	68·9	60·0	49·0	15·7
100	5·96	79·0	75·7	72·5	65·9	57·7	33·2
150	6·83	79·5	76·6	73·7	68·0	60·8	39·4
200	7·52	79·7	77·0	74·5	69·3	62·8	43·3

Table 5
The annual specific net thermal energy production as a function of reactor volumes and different insulation (details, see Table 2) expressed as a percentage of the energy potential of methane produced (11·4 GJ m^{-3}[reactor] yr^{-1}) without a pre-heater

Sfbdups wpmn f- n^{J}	Sfbdups ejbn fufs- n	Qspqpsujpo pg f of shz qspevdf e- &					
		Jotvmbuf e csjdl t	51 dn mpbn	41 dn mpbn	51 dn csjdl t	: dn mpbn	9 dn csjdl t
2·0	1·62	73·8	61·9	50·2	26·6	—	—
4·0	2·04	76·2	66·8	57·5	38·7	15·3	—
10	2·77	78·6	71·7	64·8	51·0	33·8	—
20	3·49	80·0	74·6	69·1	58·2	44·5	3·4
40	4·39	81·2	76·9	72·5	63·8	52·9	20·4
100	5·96	82·4	79·1	75·9	69·5	61·5	37·5
150	6·83	82·8	78·0	77·2	71·6	64·6	43·6
200	7·52	83·0	80·5	77·9	72·8	66·5	47·4

volume, the higher is the SNTEP. This may be attributed to the fact that the surface area to the volume ratio decreases with increasing reactor volume. For insulation material with a heat transfer coefficient of 5 W m^{-2} K^{-1}, it is not possible to obtain a system SNTEP of 50% even with a reactor size of 200 m^3. For large reactors (larger than 100 m^3, needed for 100 cows) it is possible to use 30 cm of straw loam as insulation (V = 1 W m^{-2} K^{-1}) to obtain at least 70% of the energy potential. It should be mentioned that straw loam, commonly used as a building material, is a mixture of straw and loam (Mink, 2000).

It can be concluded that, applying insulation materials with V 5 1 W m^{-2}K^{-1}, the reactor volume larger than 100 m^3 does not affect the SNTEP too much. From this table, it can also be concluded that for small farms (2 cows) it is possible to achieve 70% system SNTEP, but this requires at least 10 cm bricks together with 11 cm of rook wool (l = 0·04 W m^{-1} K^{-1}) to insulate the system (V = 0·33 W m^{-2} K^{-1}).

Table 5 shows the effect of insulation type on the annual SNTEP of different CSTRs without pre-heaters. Conclusions similar to those related to Table 4 can be drawn: SNTEP increases with increasing reactor volume, so smaller reactors need better thermal insulation to achieve equal SNTEP as large reactors. But comparing these data with the data presented in Table 4, it can be concluded that the external pre-heater reduces the net thermal energy production by roughly 3% compared with the system without pre-heater. On the other hand, adding the fresh manure will reduce the reactor temperature by about 2°C, which may reduce the biogas production. Furthermore, the addition of the pre-heater will increase the cost and needs more space without adding any benefits to the system, it can be concluded that the adding of a pre-heater is not necessary. For the solar application, the time of adding the new manure to the system should be specified according to the interaction between the available solar energy and the system configurations.

4.3. N pef mps of u u f sn bmf of shz qspevdujpo jodmejoh tpmbs f of shz

To avoid combustion of the produced methane for maintaining the required temperature inside the CSTR, the required energy for heating can be produced by a

Table 6
The annual specific net thermal energy production as a function of different reactor volumes, without pre-heater (s), and different insulation includes the solar system mounted on the reactor roof

Sfbdups wpmvn f- n³	Sfbdups ejbn fufs- n	Qspqpsujpo pg fofshz qspevdfe- &					
		Jotvmbufe csjdl t	51dn gpbn	41dn gpbn	51dn csjdl t	:dn gpbn	9dn csjdl t
2·0	1·62	99·0	87·2	75·4	51·8	22·3	—
4·0	2·04	96·3	86·9	77·5	58·8	35·4	—
10	2·77	93·4	86·5	79·6	65·8	48·6	—
20	3·49	91·8	86·3	80·9	69·9	56·2	15·1
40	4·39	90·5	86·2	81·8	73·1	62·3	29·7
100	5·96	89·2	86·0	82·8	76·4	68·4	44·4
150	6·83	88·7	86·0	83·2	77·6	70·6	49·6
200	7·52	88·5	85·9	83·4	78·3	72·0	52·9

thermal solar collector system. Table 6 shows the system SNTEP after incorporation of the input energy, which can be covered by a solar collector system, mounted on the reactor roof. This is performed for different reactor sizes and different insulation materials under Egyptian conditions. Beam and diffuse solar radiation are calculated based on the equations presented by Sukhatme (1997). The solar energy calculations were based on a flat plate solar collector with a tilt angle equal to the latitude of Cairo (30°) and overall heat loss coefficient from the collector of 5 W m^{-2} K^{-1}.

To calculate the system SNTEP after applying the solar energy F_T, the following equation can be used:

$$F_U = \frac{\sum_{j=1}^{365} F_j - (1 - Q_j)J_j}{\sum_{j=1}^{365} F_j}$$

where : Q_j is the percentage of daily heat requirements which can be covered by solar energy for day j; J_j is the daily heat requirements to heat the reactor at the desired reactor temperature level; and F_j is the potential energy production based on daily methane production in the CSTR .

Comparing the data in Tables 5 and 6, it can be seen that the solar energy incorporation has a pronounced effect on the SNTEP of the small reactors. The magnitude of the increase of SNTEP, when including solar input depends on the reactor volume. Furthermore, the higher V values of the reactor the lower is SNTEP. As can be seen it is possible to obtain a system SNTEP higher than 90% but this is relevant for the small reactors and low V value insulation. On the other hand, the incorporation of solar collectors mounted on the reactor roof increase the system SNTEP of about 6% with a reactor volume of 200 m³

Concluding, the available specific surface area of the reactor (m² [roof] m^{-3} [reactor]) decreases with the increase of the reactor height and hence with the reactor volume. Since land occupation is one of the drawbacks of using solar energy, mounting the solar system on the reactor roof is the best option. When extra land has to be used for solar energy installation, this will in turn increase the fixed cost of the system.

5. Conclusions

The specific net thermal energy production (SNTEP) from the anaerobic digestion of cattle manure has been studied in a model. The model results are based on experimental determination of methane production rate from continuous stirred tank reactors. The model studied the effect of pre-heater addition; different insulation materials and solar energy heating system on the SNTEP from different reactors volumes without considering the heat recovery from the effluent. Based on the results obtained from this study the following conclusions can be drawn.

1. The experiments showed that the methane production rate during anaerobic conditions of cow manure at 50°C is higher than that at 60°C. This may be due to the higher free ammonia concentration at 60°C compared to that at 50°C.
2. A daily temperature fluctuation of 10°C is decreasing the methane production with only 12% at digestion temperature of 50°C.
3. It is possible to use solar energy for applying thermophilic anaerobic digestion of cow manure at 50°C under Egyptian conditions with a minor effect on gas production rate.
4. The larger the reactor size, the larger is the net specific thermal energy production.
5. From the energy efficiency viewpoint, it is not recommended to use a pre-heating step before the continuous stirred tank reactor since this leads to increase system costs without adding any benefits to the system.

6. The smaller the reactor, the better insulation is required to obtain high specific net thermal energy production (SNTEP), therefore the investment costs for small reactors are relatively high.
7. A thermal insulation value for the reactor of about $1\,\mathrm{W\,m^{-2}\,K^{-1}}$ (i.e. 30 cm straw loam) seems to be sufficient to provide a SNTEP of at least 50%. If the reactor volume is at least $10\,\mathrm{m^3}$; the SNTEP increases to at least 65%.
8. Incorporation of solar energy can increase the system SNTEP over 90%, but this is only possible for small, well-insulated systems.
9. Using solar energy, the maximum SNTEP is found for small reactors with good thermal insulation (V6 $1\,\mathrm{W\,m^{-2}\,K^{-1}}$), while for bad thermal insulation ($V > 1\,\mathrm{W\,m^{-2}\,K^{-1}}$) the maximum SNTEP is found for large reactors.
10. For large reactor volumes ($100\,\mathrm{m^3}$ or more), it is not recommended to use solar energy by roof solar collectors since the extra efficiency is low.
11. With solar energy system mounted on the reactor roofs, it is possible to obtain at least 75% of the energy potential for moderate insulation ($V = 1\,\mathrm{W\,m^{-2}\,K^{-1}}$).

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