0273-2289/89/2021—0541$03.80

Continuous Production of Biogas from Dairy Manure Using an Innovative No-Mix Reactor

A. E. GHALY* AND R. M. BEN-HASSAN

Agricultural Engineering Department, Technical University of Nova Scotia, PO Box 1000, Halifax, Nova Scotia, Canada, B3J 2X4

ABSTRACT

A 25 L no-mix anaerobic digester was designed and fabricated. The digester was designed to act as liquid–solid separator. The sludges obtained from the bottom of the digester had high nitrogen and ash concentrations while the effluent had no offensive odor. The performance of the no-mix digester was compared to that of a continuous stirred tank reactor at two temperatures and five hydraulic retention times. The no-mix digester had higher biogas production rate and pollution potential reduction.

Index Entries: Dairy manure; anaerobic digestion; biogas; digester; hydraulic retention time; temperature.

INTRODUCTION

Traditionally, animal manure has been applied onto agricultural lands. The land application of such a large quantity of manure may cause pollution of the natural environment (*1*). Anaerobic digestion with energy recovery through methane production is an effective means of solving the pollution problem, yet producing gas that could be used for space and water heating of farm houses and animal shelters, grain drying, and as a fuel for heating greenhouses during the cold weather (2).

Anaerobic digestion is a biological process in which biodegradable organic materials are decomposed in the absence of oxygen to produce methane, carbon dioxide, and some other trace gases, such as, hydrogen sulfide, water vapor, and nitrogen (2–6). The process is carried out in

*Author to whom all correspondence and reprint requests should be addressed.

three stages. These are: (a) a liquefaction stage, in which extracellular enzymes are produced by microorganisms present in the system to breakdown the organic compounds into simple, soluble compounds; (b) an acid producing stage, in which acid-forming bacteria convert simple organic compounds such as cellobiose, sugars, and glucose to volatile acids such as acetic acid and propionic acid; and (c) an anaerobic decomposition process called the methanoganic, or gasification stage, in which methane-producing bacteria produce intracellular enzymes that are required to convert organic acids to gaseous endproducts, containing mostly methane and carbon dioxide.

However, most farmers are reluctant to adopt the biogas technology, since complex equipment are required for pH and temperature control, thereby necessitating a high initial investment. High energy input is also required to keep the digester temperature at the optimum level for microbial activity, and the pollution potential of the digester effluent (as measured by the concentrations of the total solids and chemical oxygen demand) is very high, necessitating further disposal (2).

OBJECTIVES

The objectives of this research were to develop an anaerobic digester that will maximize the biogas output and reduce both the energy input to the system and the pollution potential of the digester effluent, and to compare the performance of the new system with that of a continuous stirred tank reactor at various temperatures and hydraulic retention times.

EXPERIMENTAL APPARATUS

The experimental apparatus used in this research consisted of 2 no-mix reactors, 2 continuous stirred tank reactors, and the associated feeding and control equipment. The following are descriptions of the systems components.

Digester Vessel

Four digesters were designed and constructed from polyvinyl chloride (PVC) and acrylic glass materials; two were continuous stirred tank reactors (Fig. 1) and two were no-mix reactors (Fig. 2). Each digester was constructed from a 10 mm thick PVC cylinder of 300 mm inside diameter. The bottom of the cylinder was constructed from 12 mm thick PVC circular plate while the lid was fabricated from a plexiglas material of the same thickness.

Two considerations were taken into account when choosing the capacity of the digesters: (a) since the manure required for the entire experiment was to be collected, mixed thoroughly, and stored in a freezer until

1. electric motor
2. shaft-casing collar
3. digester lid
4. plexiglas disc
5. impeller shaft casing
6. outlet
7. mixing shaft
8. inlet tube
9. baffle
10. mixing impeller
11. digester wall
12. digester bottom

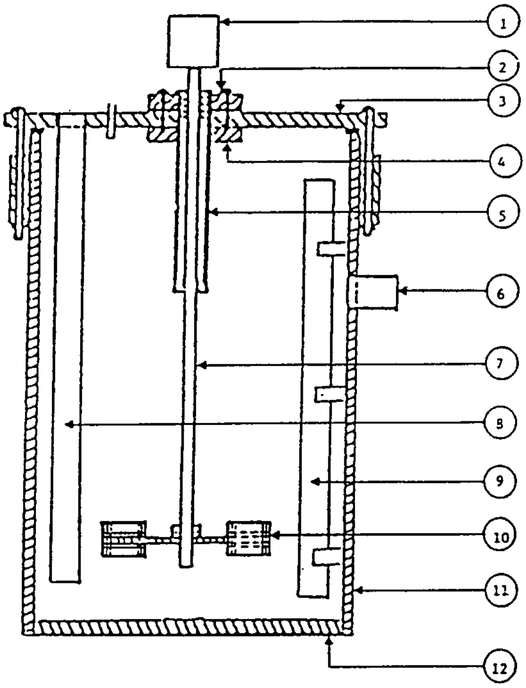

Fig. 1. Details of the continuous stirred tank reactor.

1. gas outlet
2. digester lid
3. PVC lugs
4. digester outlet
5. inlet tube
6. digester wall
7. vertical wall
8. slide valve
9. conical bottom
10. digester bottom

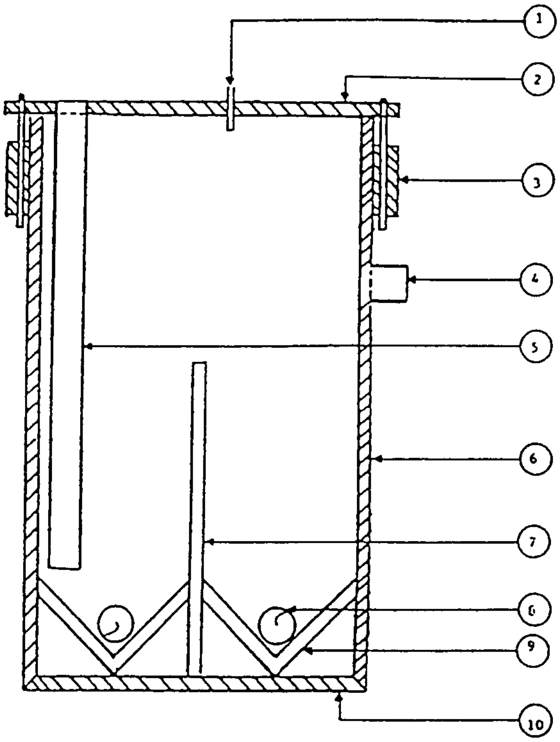

Fig. 2. Details of the no-mix, innovative digester.

needed, there was a logical reason for designing a small capacity digester, and (b) it was considered essential that the capacity of the digester be large enough to allow extrapolation of the results for scaleup purpose. Lyons (7) recommended minimum tank dimensions of 300 mm diameter and 200 mm depth for bench scale type if the results are to be used for scaleup. These recommendations were met in the designs.

An electric motor-driven, flat-bladed turbine impeller was used to mix the contents of the continuous stirred tank reactor. The impeller had six blades and operated at 125 rpm. The nonmix reactor was made of two equal compartments separated by a 300 mm high and 10 mm thick PVC, vertical wall. The lower portion of each compartment consisted of a V-shaped trough of 45° angle, at the base of which was an auger system with a slide valve for the removal of sludge. The influent manure is received in the inlet side compartment, whereas the effluent material was removed from the outlet side compartment. More information on the design, construction, and operation of the two types of digester can be found in Ben-Hassan et al (2).

Manure Feeding System

The feeding system was fully automated, reliable, and easy to operate. The system included manure feeding tank, manure feeding pump, five timers, and four solenoid valves. Figure 3 shows a schematic diagram for the manure feeding system.

The timing device is used to insure feeding of the digesters in sequence at preselected feeding rates and to stir the contents of the feed tank prior to and during the feeding operations. For example, during a typical feeding process, timer T_0 sets the feeding tank stirrer working 5 min before the opening of the solenoid value SV_1, which occurs simultaneously with the starting of the manure feeding pump to deliver manure at a predetermined rate to Digester 1. Other valves are opened in sequence while the feeding pump is on until the feeding operations is completed. Each digester is fed six times a day, the duration of each feeding operation being dependent on the hydraulic retention time and the feeding pump capacity, which is 0.3 L/min.

Gas Collection, Cleaning, Measuring, and Storage System

Figure 4 shows a schematic representation of the gas collection, cleaning, measuring, and storage system. The daily gas production (in liters) was measured for each of the four digesters. The biogas was collected through a "Y" shaped plastic tube that was fixed onto the lid of each digester. One branch of the "Y" shaped plastic tube was fitted with a rubber septum so that gas samples could be taken with a syringe from the head space of the digester for analysis. The other branch of the "Y" shaped plastic tube was connected to a water column. The gas was bubbled through

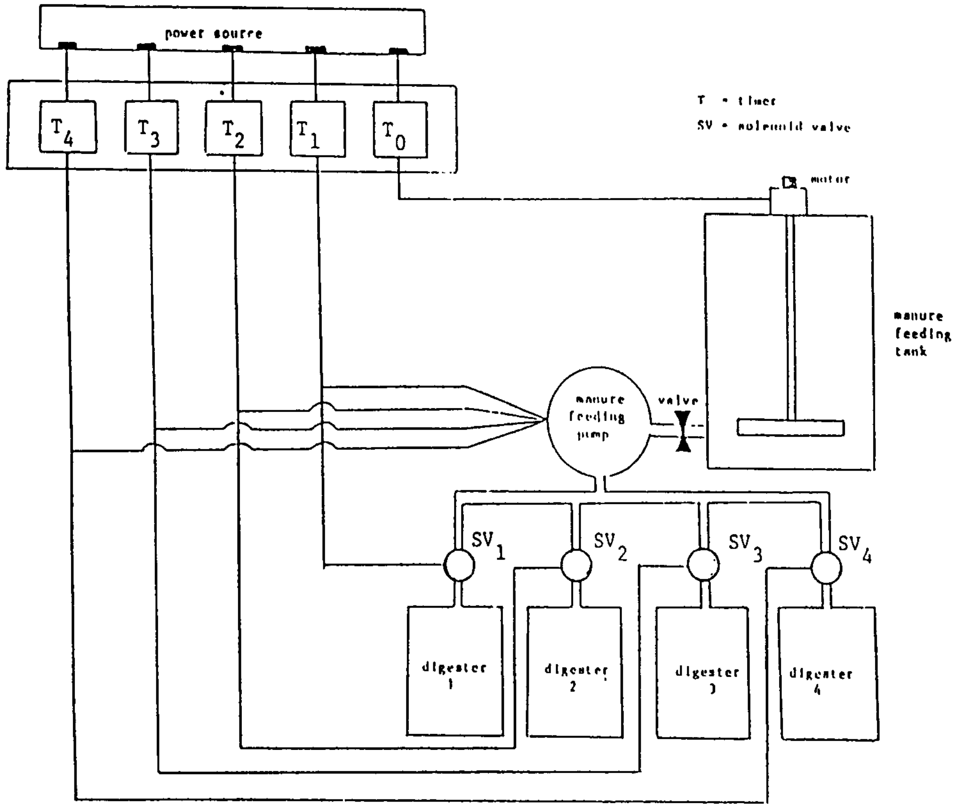

Fig. 3. A schematic representation of the manure feeding system.

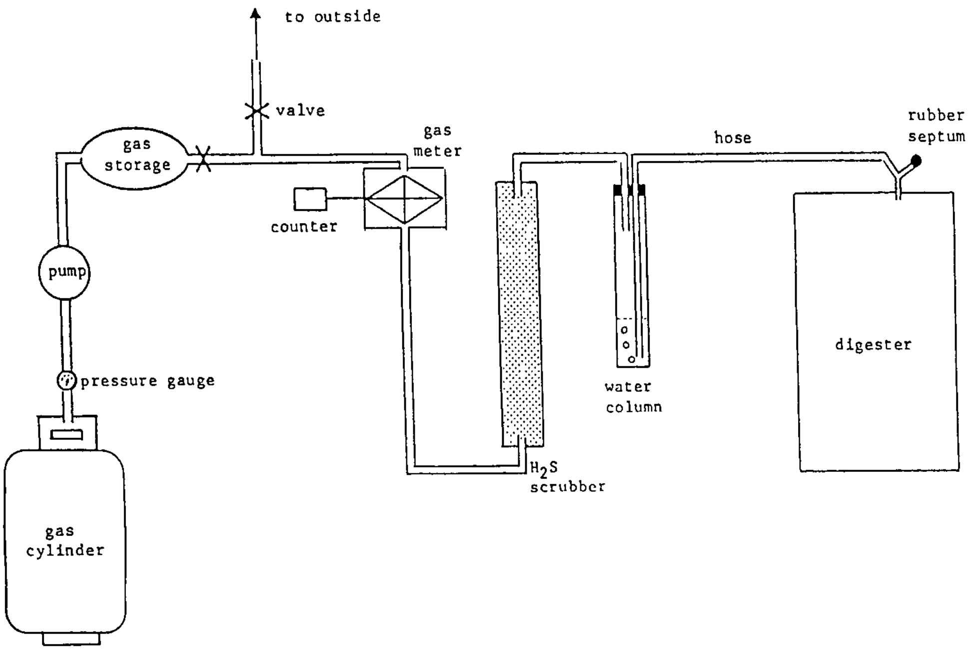

Fig. 4. A schematic representation of the gas collection, cleaning, measuring and storage system.

a 20 mm head of water, which was sufficient to provide adequate back pressure to the head space of the digester in order to keep the working volume of the digester at 25 L.

The gas was subsequently fed into a gas-scrubber for the removal of the hydrogen sulfide. Each scrubber was constructed of a plexiglas tube. The biogas is fed to the bottom of the scrubber and collected through the top. The scrubbing was effected by passing the gas through a mixture of wood shaving and steel wool. The iron oxide reacted with the hydrogen sulfide to form iron sulfide, thereby stripping off the hydrogen sulfide from the biogas.

A cumulative volume gas meter was designed for small gas flow and used to measure the gas production. The meter was based on the tipping balance concept. Four meters were used and were calibrated to tip after 50 ± 0.2 mL of the gas had been collected in the chamber. An electric counter was used to keep a record of the number of the gas meter tips, thus enabling the determinations of the amount of gas produced over a given period of time. The released gas was collected in a temporary storage bag and then pumped into a gas cylinder.

Effluent Removal from the Digester

This effluent was collected in plexiglas cylinders. Effluent removal was accomplished by a plastic tube connected to the digester outlet below the liquid surface. The other end of the tube was kept above the level of the digester. This kept a constant back pressure in the head space of the digester that, in turn, maintained a constant liquid depth in the digester and kept the effluent tube filled with liquid, thereby sealing the digester from the outside air.

Temperature-Controlled Water Bath

A thermostatically controlled water bath was used to maintain the temperature in the digesters at the desired levels. The water bath was built of plywood and it was divided into two water-tight compartments so that two experiments could be run simultaneously at different temperatures.

A float valve assembly was used in each compartment to automatically maintain a constant water level. The required temperatures in both compartments were maintained by two thermostatically controlled electric heating elements. Two submersible pumps, of 20 L/min capacity each, were used to continuously circulate the water to maintain a uniform temperature within each compartment. Peanut shaped polystyrene packing materials were placed on the surface of the water to minimize the amount of evaporation and the heat losses from the surface.

Table 1
Some Characteristics of the Diluted Manure Used in the Study

Item	Measurement value
Total solids (TS)	65 870 mg/L
Volatile solids (VS)	53 960 mg/L
VS as percent of TS	81.92%
Ash	11 910 mg/L
Ash as percent of TS	18.08%
Total chemical oxygen demand	74 880 mg/L
Soluble chemical oxygen demand	24 100 mg/L
Total Kjeldahl nitrogen	4 460 mg/L
Ammonium nitrogen	560 mg/L
pH	7

EXPERIMENTAL PROCEDURE

The performance of the two types of digester were evaluated at two temperatures (25 and 35°C), and five hydraulic retention times (25, 20, 15, 10, and 5 d). The equivalent flowrates were 1.00, 1.25, 1.67, 2.50, and 5.00 L/d, respectively.

Manure Collection, Storage, and Preparation

Dairy cattle manure was obtained from a free stall dairy barn on Winding River Farms located in Stewiacke East, approximately 80 km from Halifax, Nova Scotia. The manure was scrapped in a semisolid form and was then screened to remove coarse materials such as straws and other large fibrous materials. The screened manure was collected in a 200 L tank, diluted with water (2 manure: 1 water) and then mixed thoroughly. The diluted manure was placed in plastic bags that were then sealed and stored at −25°C until needed.

Prior to putting the manure in the feeding tank, it was removed from the freezer and allowed to thaw for 48 h at room temperature. The manure was again diluted with water to obtain the desired solid concentration (approx 6%). Some characteristics of the diluted manure are presented in Table 1.

Methods of Sampling and Analysis

Daily samples were taken from the effluent of both the continuous stirred tank reactors and no-mix reactors. Samples were also taken from the sludges removed from the no-mix reactors at the end of each experimental run. Sampling was not commenced until the reactors had been operated successfully for five retention times in order to ensure that steady state had been reached. Sampling was then continued on a daily basis until 20 samples were collected during the steady state condition. Based on previous experiences, it was judged that 5 retention times would be sufficient for the system to reach the steady state operating condition. This was later confirmed by consistent biogas production rate and constant COD and solids concentrations in the effluent.

The solids and chemical oxygen demand analyses were performed on the samples taken from the influent, effluent, and sludges, whereas the nitrogen analyses were only performed on the samples taken from the influent and sludges. These analyses were performed according to the procedures described in the Standard Method (*8*).

The gas production (in liters) was measured for each of the four digesters. Samples of gases were taken daily, after the steady state condition has been reached, and analysed using a gas chromatography.

RESULTS AND DISCUSSION

Biogas Production, Productivity, and Composition

The daily rate of biogas production by each of the four digesters operating at steady state for different hydraulic retention times and temperatures is shown in Table 2. The data are the average of 20 measurements each. The standard deviation and coefficient of variation for each observation are also shown in Table 2. The data show that there was no fluctuation in the performance of all the digesters, since the coefficient of variation was relatively small ranging from 1.44 to 5.08%, and the four digesters were operating at the steady state for all temperatures and hydraulic retention times.

It is evident from the results that both the hydraulic retention time and the temperature had significant effects on the biogas production of both types of digester. Generally, increasing the temperature or decreasing the hydraulic retention time (i.e., increasing the loading rate) increased the biogas production of both types of digester. However, the no-mix reactor (NMR) appeared to be superior in terms of biogas production when compared with the continuous stirred tank reactor (CSTR) at all temperatures and hydraulic retention times. It produced 13.85–36.26 L/digester/d compared to that of 8.95–23.88 L/digester/d for the CSTR. It also produced as much biogas at 25°C as that produced by the CSTR at 35°C. This may be attributed to the high microbial cell build up in the NMR as evidenced by the higher microbial population found in the sludge from this digester. Although, mixing is know to bring microbial cells in contact with food substrate, thereby increasing the conversion efficiency of the food sub-

Table 2
The Biogas Production (L/digester/d)
at Various Temperatures and Hydraulic Retention Times[a]

Digester type	Hydraulic, retention time, d	Water bath temperature, °C 25 Mean	STD	CV	35 Mean	STD	CV
CSTR	25	8.95	0.35	3.89	12.01	0.45	3.78
	20	10.56	0.54	5.08	14.72	0.64	4.36
	15	13.42	0.53	3.95	18.01	0.57	3.19
	10	17.56	0.51	2.93	20.30	0.56	2.76
	5	19.96	0.36	1.81	23.88	0.34	1.44
EER	25	13.85	0.47	3.43	19.89	0.64	3.21
	20	17.00	0.84	4.95	22.91	0.84	3.67
	15	19.35	0.50	2.60	26.06	0.45	1.73
	10	21.31	0.56	2.62	30.57	0.79	2.58
	5	22.03	0.48	2.20	36.26	0.54	1.49

[a]Values are the average of 20 determinations.
CSTR = continuous stirred tank reactor.
NMR = no-mix reactor.
STD = standard deviation.
CV = coefficient of variation (in percent).

strate, the higher microbial mass in the NMR has resulted in substantial increase in biogas production that overweighed that caused by mixing. Because of the higher conversion rate in this type of system, the biogas production rate of the NMR was also higher than those values reported in the literature for various types of digester operating at same hydraulic retention times and temperatures on dairy manure having similar solid concentration (*9–12*).

The biogas productivity, defined as biogas produced per kg VS added, was determined for the four digesters at all temperatures and hydraulic retention times. This is shown in Fig. 5. Generally, increasing the temperature and/or the hydraulic retention time increased the biogas productivity for both types of digester. However, the biogas productivity of the NMR was higher than that of the CSTR at all temperatures and hydraulic retention times; the biogas productivity of the NMR ranged from 0.082 to 0.368 m^3 biogas/kg VS added compared to that of 0.074 to 0.228 m^3 biogas/kg VS added for the CSTR.

The biogas produced from each digester was analyzed using a gas chromotograph to determine the percentage of CH_4 and CO_2 in the gas mixture. The analysis showed that the four digesters produced gas mixtures having almost the same proportions of methane and carbon dioxide. The methane percentage ranged from 58.06 to 59.55, whereas the carbon dioxide percentage ranged from 28.04 to 29.65. The percentage of other

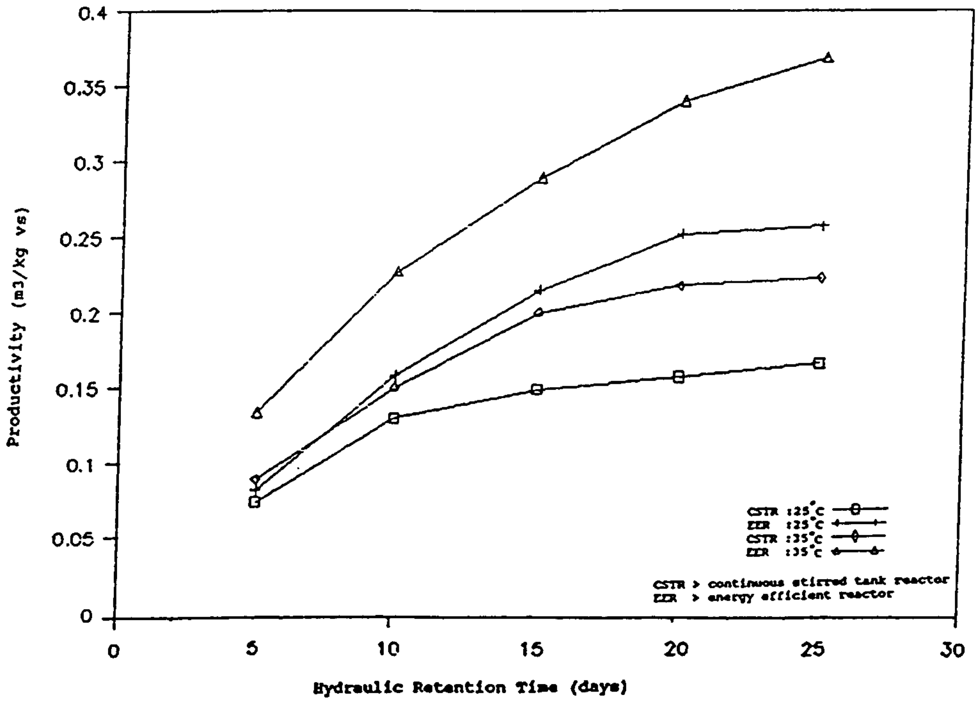

Fig. 5. Biogas productivity at various temperatures and hydraulic retention times.

gases in the mixture (nitrogen, water vapor, hydrogen, and hydrogen sulfide) ranged from 12.27 to 12.66. The percentage of methane in the biogas produced in this study is within the range of 57.25% to 59.6% reported by several authors (*9,10,12,13*).

Chemical Oxygen Demand

Both the total chemical oxygen demand (TCDD) and soluble chemical oxygen demand (SCOD) analyses were performed on the samples taken daily from the effluent of the four digesters during steady state operation. For each experimental run, the mean, standard deviation, and coefficient of variation of both the total and soluble chemical oxygen demand of the effluent were calculated. These are shown in Table 3. The COD data also confirmed that the four digesters were operating at the steady state condition at all temperatures and hydraulic retention times.

The total and soluble COD reductions of the effluent obtained from the four digesters are illustrated in Fig. 6. These increased as the hydraulic retention time and/or the temperature increased for both types of digester. The results also indicated that the NMR appeared to be superior in terms of total and soluble COD reductions when compared with the CSTR at all temperatures and hydraulic retention times. The effluent total COD of the NMR was reduced by 37.5–70.6%, compared to that of 4.8–33.3%

Table 3
The Effluent Chemical Oxygen Demand (mg/L) at Various Temperatures and Hydraulic Retention Times[a]

Digester type	Hydraulic retention time, d	Total COD						Soluble COD					
		25°C			35°C			25°C			35°C		
		Mean	STD	CV	Mean	STD	CV	Mean	STD	CV	Mean	STD	CV
CSTR	25	51420	1354	2.6	49910	994	2.0	13930	794	6.0	12660	693	5.4
	20	54410	1045	1.9	51990	1031	2.0	14930	1007	6.7	13610	867	6.4
	15	63630	937	1.3	59530	673	1.1	18320	359	2.0	17270	550	3.2
	10	67210	758	1.1	62740	554	0.9	21920	1205	5.5	19430	451	2.8
	5	71310	798	1.1	64530	512	0.8	22860	245	1.1	20820	175	0.8
EER	25	23780	754	3.2	22040	652	2.9	9060	478	5.3	8340	403	4.8
	20	35350	957	2.7	33020	880	2.5	10130	585	5.7	9500	589	6.2
	15	43000	716	1.7	40430	567	1.4	13440	279	2.1	12540	433	3.5
	10	45870	486	1.1	42620	445	1.1	14010	90	0.6	12970	240	1.8
	5	46800	320	0.7	43540	522	1.2	14830	300	2.0	13830	179	1.8

[a] Values are the average of 20 determinations.
Influent total chemical oxygen demand = 74880 mg/L.
Influent soluble chemical oxygen demand = 24100 mg/L.
CSTR = continuous stirred tank reactor.
NMR = no-mix reactor.
STD = standard deviation.
CV = coefficient of variation (in percent).

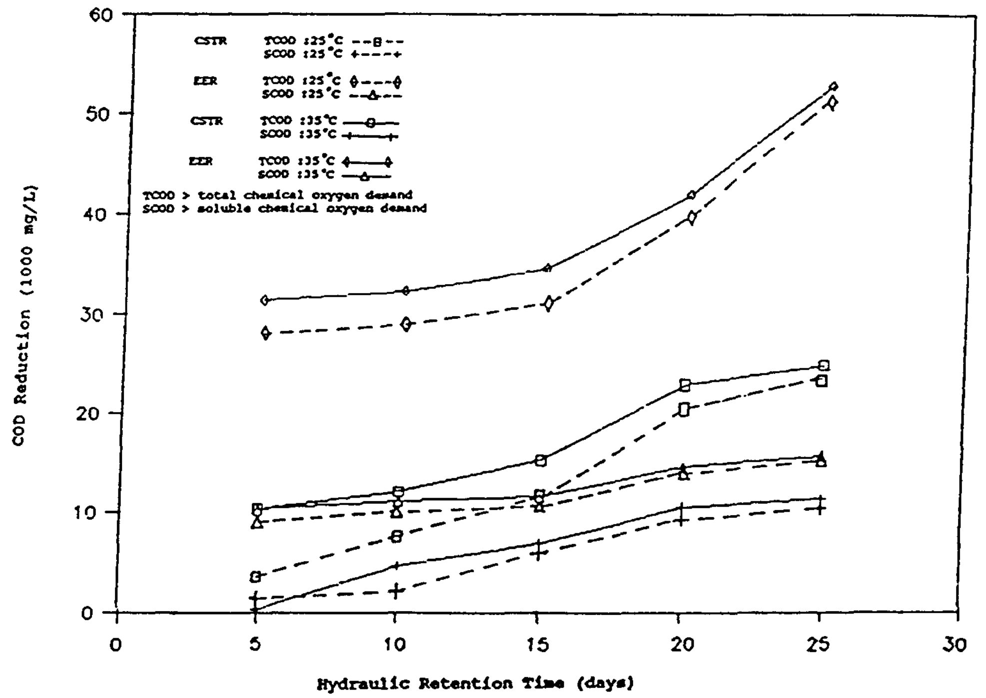

Fig. 6. The COD reductions at various temperatures and hydraulic retention times.

of the CSTR, whereas effluent soluble COD of the NMR was reduced by 38.5–65.4%, compared to that of 5.2–47.5% for the CSTR.

No mixing resulted in settling of some of the suspended solids that formed sludge at the bottom of the digester. As these solids came in contact with the dense microbial population in the sludge, a higher conversion rate was achieved resulting in higher COD reduction.

Solids

The solids (total and fixed) analyses were performed on the daily samples taken from the effluent of the four digesters during the steady state operation. The mean, standard deviation, and coefficient of variation of the total and fixed solids for each experimental run are shown in Table 4. The volatile solids concentration is also shown in Table 5. These analyses also confirmed that the four digesters operated at the steady state condition.

Generally, decreasing the temperature and/or the hydraulic retention time increased the effluent total solids for both types of digester. Neither the temperature nor the hydraulic retention time had any significant effect on the fixed solids (ash) of the effluent from the CSTR, although the average value of the fixed solids was slightly lower than that of the influent. Although the CSTR was continuously mixed, the lower value of the

Table 4
The Effluent Solids (mg/L) at Various Temperatures and Hydraulic Retention Times[a]

Digester type	Hydraulic retention time, d	Total solids						Ash					
		25°C			35°C			25°C			35°C		
		Mean	STD	CV	Mean	STD	CV	Mean	STD	CV	Mean	STD	CV
CSTR	25	43130	743	1.7	41140	772	1.9	9670	337	3.5	9490	567	6.0
	20	46680	984	2.1	43860	762	1.7	10520	390	3.7	10140	715	7.1
	15	50900	811	1.6	48100	789	1.6	10420	519	5.0	9600	536	5.6
	10	54090	604	1.1	52200	591	1.1	10300	279	2.7	10850	576	5.3
	5	57830	378	0.6	54840	319	0.6	10350	340	3.3	10010	129	1.3
EER	25	23920	599	2.5	22090	489	2.2	6110	254	4.2	5960	181	8.2
	20	30020	773	2.6	27770	965	3.6	7170	568	7.9	6310	490	7.8
	15	33220	333	1.0	31110	602	1.9	6740	513	7.6	6630	463	7.0
	10	34390	436	1.8	32210	368	1.1	6740	398	5.9	6240	330	5.3
	5	35100	293	0.8	33830	214	0.6	6210	278	4.5	6790	267	8.9

[a] Values are the average of 20 determinations.
Influent total solids = 65870 mg/L.
Influent ash = 11910 mg/L.
CSTR = continuous stirred tank reactor.
NMR = no-mix reactor.
STD = standard deviation.
CV = coefficient of variation (in percent).

Table 5
The Effluent Volatile Solids (mg/L) at Various Temperatures and Hydraulic Retention Times[a]

Digester type	Hydraulic retention time, d	Volatile solids 25°C mg/L	%	35°C mg/L	%
CSTR	25	33460	77.93	31650	76.93
	20	36160	77.40	33720	76.87
	15	40490	79.51	38500	79.94
	10	43790	80.95	41340	79.21
	5	47470	82.09	44830	81.72
EER	25	17320	74.48	16130	73.01
	20	22840	76.10	21460	77.29
	15	26480	79.70	24480	79.17
	10	27650	80.34	25950	80.56
	5	28890	82.31	27040	79.92

[a]Values are the average of 20 determinations.
Influent volatile solids = 53960 mg/L.
CSTR = continuous stirred tank reactor.
MNR = no-mix reactor.

fixed solids in the effluent could be a result of the precipitation of some minerals into the bottom of the digester. Calcium and phosphorous may have been precipitated as $CaCO_3$ and Ca_2 (PO_4). The absence of these materials in the effluent lends support to this. Similarly, the fixed solids concentration in the effluent of the NMR was not affected by the hydraulic retention time nor the temperature, although there was a significant reduction in the fixed solids. Since the digester was not mixed, the reduction in the fixed solids may be a result of the precipitation of some minerals with the suspended solids into the bottom of the digester. This is supported by the fact that higher fixed solids concentrations were found in the sludge obtained from the bottom of the digester. The total and volatile solids reductions (in percent) for the four digesters were calculated at all hydraulic retention times and temperature. These reductions were higher as both the hydraulic retention time and temperature were increased for both types of digester as shown in Fig. 7.

The results clearly indicated that the NMR is superior in terms of solids reduction compared to the CSTR, at all temperatures and hydraulic retention times. This is probably owing to the high microbial population found in the sludge of the NMR. The influent manure was received in the inlet side compartment where settlement of solids and growth of microbial cells began. Slight mixing induced by the inflow of the influent was achieved in this compartment, thereby improving the conversion efficiency. The partially settled liquid was then received in the outlet side compartment

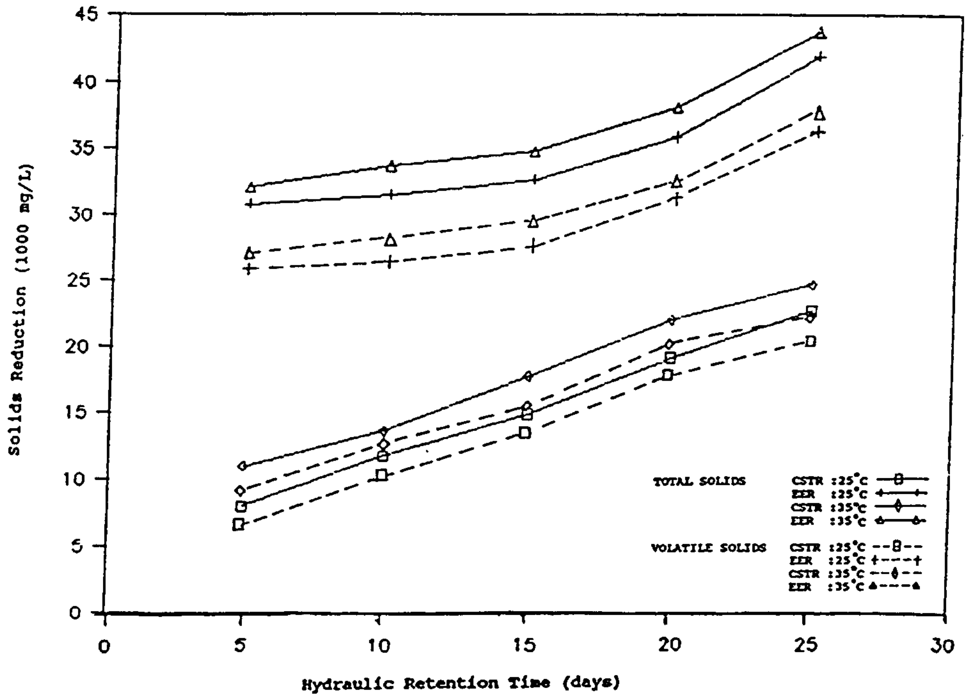

Fig. 7. The solid reductions at various temperatures and hydraulic retention times.

where further settlement of solids and growth of microbial cells took place. Because no mixing takes place in this compartment, loss of microbial cells with the effluent was minimized. The accumulated sludges at the base of the two compartments were periodically removed (at the end of each experimental run), thereby ensuring that the effective volume of the digester, and, hence, the hydraulic retention time was not significantly effected.

Sludge Characteristics

The chemical oxygen demand, nitrogen and solids analyses were performed on the sludge samples obtained from the input and output chambers of the no-mix reactors at the end of each hydraulic retention time. The results are shown in Table 6.

The total COD of the sludge obtained from the NMR was significantly higher than that of the influent manure, whereas the soluble COD of the sludge obtained from the reactor was less than that of the influent manure. This suggested that the sludge was partially stabilized. Both the temperature and hydraulic retention time had no significant effects on the COD of the sludge obtained from the energy efficient reactor. However, higher values of the COD were observed in the sludge obtained from the input chamber compared to that of the output chamber.

Table 6
The COD, Nitrogen, and Solids Concentrations of the Sludge Obtained from the No-Mix Reactor at Various Temperatures and Hydraulic Retention Times[a]

	Hydraulic retention time, d	COD				Nitrogen				Solids			
		Total		Soluble		TKN		AM-N		Total		Volatile	
		25°C	35°C	25°C	35°C	25°C	35°C	25°C	35°C	25°C	35°C	25°C	35°C
Input side	5	202800	203000	23000	23340	8520	9650	550	560	100820	110350	85310	94350
	10	202890	203100	23000	23350	8530	9650	550	560	100910	110450	95350	94440
	15	202970	203150	23050	23360	8530	9690	560	560	101130	110640	95390	94630
	20	202990	203440	23100	23390	8550	9700	560	560	101170	110640	85400	94640
	25	203130	203830	23350	23450	8590	9700	560	560	101370	110880	85430	94860
Output side	5	160440	163000	17810	19690	7850	8860	550	560	96000	98440	81820	83240
	10	160500	163000	17840	19810	7860	8860	560	560	96880	98600	81880	83380
	15	160590	163080	17840	19870	7860	3870	550	560	96890	98680	81880	83390
	20	160750	163150	18030	19930	7870	8870	560	560	97220	98810	82040	83500
	25	160910	163360	18210	20010	7890	8900	550	560	97350	98960	82160	83450

[a]Values are the average of 4 determinations.

The total, fixed, and volatile solids of the sludge obtained from the no-mix reactor were all significantly higher than those of the influent manure. The hydraulic retention time appeared to have no significant effect on the concentration of the total, fixed, and volatile solids. However, higher values of all these solids components were observed at 35°C (compared to those at 25°C) and in the sludge obtained from the input chamber (compared to those of the sludge obtained from the outlet chamber). It appears that most of the coarse materials in the influent manure settled in the input chamber.

The total kjeldahl nitrogen (TKN) concentrations of the sludges obtained from the two chambers of the no-mix reactor were significantly higher than that of the influent manure. This was because of the precipitation of solid material containing organic nitrogen and the buildup of microbial population in the sludge. However, higher values of TKN were observed at 35°C (compared to those at 25°C) and in the sludge obtained from the input chamber (compared to the outlet chamber). Neither the temperature nor the hydraulic retention time had any effect on the concentration of ammonium nitrogen of the sludge obtained from both the input and outlet chambers. The ammonium nitrogen concentration of the sludges obtained from the two chambers were similar in value to that of the influent manure.

pH and Temperature

The pH and temperature of the effluent were measured on a daily basis for the four digesters during the steady state operation of each hydraulic retention time. The results indicated that the pH of the four digesters were in the optimum range (from 7.1 to 7.4). Similar pH values were reported in the literature (*3–6*). The temperature of the continuous stirred tank reactor was 1–2°C higher than the temperature in the no-mix reactor due to heat generated by mixing.

CONCLUSIONS

The gas production of both types of digester was affected by both the temperature and the hydraulic retention time; the higher the temperature and/or the lower the hydraulic retention time, the higher was the biogas production rate.

The no-mix reactor (NMR) was superior in terms of biogas production and productivity when compared with the continuous stirred tank reactor (CSTR) at all temperatures and hydraulic retention times. The biogas produced by the CSTR ranged from 8.95 to 23.88 L/digester/d, whereas that produced by the NMR ranged from 13.95 to 36.25 L/digester/d. The biogas productivity of the CSTR ranged from 0.074 to 0.223 m^3 biogas/kg VS added, whereas that of the NMR ranged from 0.082 to 0.369 m^3 biogas/kg VS added. The biogas produced by the NMR at 25°C was much higher than that produced by the CSTR at 35°C for all retention times.

The composition of the biogas produced by both types of the digester was almost the same. The methane concentration in the gas mixture was in the range of 58.08–59.55%.

The NMR achieved higher total and soluble COD reductions (compared to the CSTR) at all temperature and hydraulic retention times. The total COD reduction of the CSTR ranged from 4.8 to 33.3%, whereas that of the NMR ranged from 37.5 to 70.6%. The soluble COD reduction of the CSTR ranged from 5.2 to 47.5%, whereas that of the NMR ranged from 38.5 to 65.4%.

The NMR achieved higher solid reductions as compared to the CSTR at all temperatures and hydraulic retention times. The total solids reduction of the CSTR ranged from 12.2 to 37.5%, whereas that of the NMR ranged from 46.7 to 66.5%.

The sludge obtained from the bottom of the NMR had higher concentrations of total COD, solids, and total kjeldahl nitrogen than those of the influent manure. The value of these components were dependent on the temperature and hydraulic retention time used.

Both types of digester operated at an optimum pH (7.1–7.4) at all temperatures and hydraulic retention times. The liquid temperature in the CSTR was higher (1–2°C) than that of the liquid in the NMR because of mixing effect.

REFERENCES

1. Ghaly, A. E., Ben-Hassan, R. M., and Dahel, S. (1986), ASAE Paper No. 85-4545, St. Joseph, MI.
2. Ben-Hassan, R. M., Ghaly, A. E., and Singh, R. K. (1985). CSAE, Paper No. 85-408, Ottawa, Ontario.
3. Cowley, I. D. and Wase, D. A. U. (1981), *Proc. Biochem.* **16**(5), 28–33.
4. Lapp, H. M., Schulte, D. D., Sparling, A. B., and Buchanan, L. C. (1974), CSAE, Paper No. 74-213, Ottawa, Ontario.
5. Anderson, G. K., Donnelly, T., and McKeown, K. J. (1982), *Proc. Biochem.* **17**(4), 28–32.
6. Persson, S. P. E., Barott, H. D., Branding, A. E., and Regan, R. W. (1979), Bulletin 827, Agricultural Experimental, College of Agriculture, The Pennsylvania State University, University Park, PA.
7. Lyons, E. J. (1967), *Suspension of solids in mixing theory and practice,* vol. II, Uhi, W. W. and Gray, J. B., eds., Academic Press, New York.
8. APHA (1980), *Standard method for the examination of water and wastewater,* Fifteenth ed., American Public Health Association, Washington, DC.
9. Blanchard, J. P. and Gill, T. A. (1984), *Trans. ASAE* **27**(2), 535–540.
10. Cournoyer, M. S. and Chagnon, R. (1984), ASAE Paper No. 84-4562, St. Joseph, MI.

11. Hills, D. J. and Mehlschan, J. J. (1984), *Trans. ASAE.* **27**(3), 889–893.
12. Lo, K. V. and Liao, P. H. (1984), ASAE Paper No. 84-4560. St. Joseph, MI.
13. Lo, K. V., Liao, P. H., Bulley, N. R., and Chieng, S. T. (1984), *Can. Soc. Agric. Eng.* **26**(1), 73–78.