Neth. J. agric. Sci. 27 (1979) 255-267

Anaerobic digestion of piggery waste. 3. Influence of temperature

A. F. M. van Velsen, G. Lettinga, D. den Ottelander

Agricultural University, Department of Water Purification, De Dreijen 12, Wageningen, the Netherlands

Accepted: 6 April 1979

Key words: anaerobic digestion, piggery waste, temperature

Summary

The effects of temperature in the range of 13 to 55 °C on the digestion of wet piggery manure were investigated in laboratory-scale digesters fed daily at a load of approx. 4 kg TS (total solids) m^{-3} day^{-1}. At a digestion temperature of 13 °C no methane was produced. In the mesophilic temperature range (20 - 40 °C) the methane production increased with temperature particularly in the range of 20 to 25 °C. In the range of 25 to 40 °C the increase of the methane production was much less pronounced and hydrolysis of undissolved manure components turned out to be the rate limiting step of the digestion process. Under thermophilic conditions (55 °C) the methane production decreased with approx. 25 % as compared to mesophilic digestion in spite of a somewhat higher degree of hydrolysis. Thermophilic digestion appeared to be more sensitive for high ammonia-nitrogen concentrations than mesophilic digestion which presumably is caused by an increase in the fraction of free ammonia with temperature (at constant pH and total ammoniacal nitrogen concentration).

From the results it was concluded that digestion under mesophilic conditions is most adequate for piggery waste stabilization. Furthermore the results of the mesophilic experiments indicated that at a load of approx. 4 kg TS m^{-3} day^{-1} the optimum temperature with respect to the net energy recovery is 27 - 30 °C when high-grade fuel is required to elevate the temperature and 35 - 40 °C when sufficient waste energy is available.

Introduction

The interest in anaerobic digestion of animal wastes is strongly increasing at present because of environmental concerns such as the abatement of odour nuisance and energy considerations. A very useful fuel, methane gas, is formed upon digestion of organic matter. On the other hand the digestion process consumes energy as well, viz for pumping and mixing and generally also for heating the manure and maintaining the digester at the desired temperature. In temporate climates like in Western Europe the greater part of the energy consumption is used for heating purposes (Mills, 1979).

As in these areas evidently the energy requirements of the process chiefly depend on the applied digestion temperature, knowledge of the influence of the temperature on the gas production is indispensable for determining the optimum process temperature with respect to the net energy recovery.

Anaerobic digestion of animal wastes can be conducted at mesophilic temperatures (20 - 40 °C) and at thermophilic temperatures (40 - 65 °C). Although thermophilic digestion of manure may have benefits over mesophilic digestion, such as higher rates of digestion, greater conversion of waste organics to gas, faster solid-liquid separation and minimization of bacterial and viral pathogens, the mesophilic temperature range should be preferred for animal waste digestion at farm-scale application because of practical reasons.

For digestion in the mesophilic range commonly a temperature of 33 - 35 °C is used. This temperature originates from the practice of sewage sludge digestion. However, the optimization of the sewage sludge digestion process has been primarily directed at a maximum stabilization of the sludge – and therefore at a maximum gas production – rather than at a maximum net energy recovery. Our studies were performed to investigate the effects of the temperature on the digestion of wet piggery manure. The main objectives of the study were (1) to assess the digestion temperature at which the maximum gas yield is obtained and (2) to collect sufficient information for optimizing the net energy recovery in the mesophilic temperature range (20 - 40 °C).

Materials and methods

Analyses

The total solids concentration (TS) was determined by drying a 10-ml sample in a 105 °C stove overnight. Volatile solids (VS) concentration was estimated by determining the weight losses at ignition at 600 °C for 4 hours. Chemical oxygen demand (COD) analyses were conducted according to Standard Methods (1965). Supernatant COD was determined after centrifugation at 14 000 *g* for 10 minutes.

Ammonia-nitrogen was determined by distillation at pH 7.3 into a boric acid solution and titration with a standard acid solution. The total nitrogen concentration was determined by the same method preceded by a Kjehldahl type destruction (boiling a 10-ml sample in concentrated sulfuric acid, with Selenium Mixture GR as a catalyser, up to clearness of the sample) and neutralization with concentrated NaOH before distillation.

The volatile fatty acids (VFA) analyses were performed on a gas chromatograph with a packed glass column (1 m × 0.4 cm i.d.) filled with Tween 80 on Chromosorb W-AW 80/100. Column temperature was 115 °C and the carrier gas, N_2, was saturated with formic acid.

Gas analyses were performed with a portable combustile gas meter calibrated for methane.

Experimental procedure
The influence of temperature on the digestion of wet piggery manure was investigated in three series of experiments, designated as series A, B and C. In each series three different temperatures were tested. Table 1 shows the temperatures investigated together with the loads applied.

After seeding the digesters with digested piggery manure from a 30 °C digestion unit the temperatures to be investigated were adjusted immediately. The digesters were fed daily or bidaily (in the weekends) by discharging a calculated amount of the digester contents. Then fresh manure was added at appropriate amounts.

The experiments were continued for a period of at least 25 days after the digestion process had reached a steady state with respect to the gas production and the VFA concentration.

Apparatus
The experiments of series A and B were performed in three 45-litre insulated steel vessels. The digestion units were heated electrically and the temperature was regulated by means of a thermocouple in the digester contents. Mixing was accomplished by mechanical stirring at approx. 100 rev/min for 15 s every 4 min. The stirring device was provided with a propellor fan at the bottom of the digester and a scum-breaker at the liquid-gas interphase. The stirring capacity in the digesters was not sufficient to mix the digester contents completely. The manure feed was added near the bottom of the digester and the effluent was discharged at the upper part. The gas production was determined with a wet gas meter. The experiments of series C were conducted in four 5-litre perspex digesters. Digestion temperature was regulated by circulating thermostated water through a jacket. The digesters were thoroughly mixed by mechanical stirring at 100 rev/min for 15 s every 4 min.

The fresh manure was added at the top of the digester whereas the effluent was discharged at the bottom. Also in these experiments the gas production was determined by means of a wet gas meter.

Materials
All digestion units were seeded with well digested sludge obtained from experimental digesters fed with 6 % TS piggery manure and operated at 30 °C. The VFA concentration of the seed material was less than 200 mg l^{-1}. The three series

Table 1. Experimental scheme.

	Series of experiments			
	A	B	C	
Load (kg TS m^{-3} day^{-1})	3.3	4.2	3.6	
Detention time (days)	22.5	15	20	
Temperatures investigated (°C)	20	27	13	
	25	32	35	
	30	40	55	(in duplicate)

Table 2. Manure characteristics.

	Exp. A	Exp. B	Exp. C
TS (g/litre)	74.0	63.3	71.6
VS (g/litre)	56.2	42.5	55.1
COD supernatant (mg/litre)	22 770	17 490	16 020
COD total (mg/litre)	67 500	64 350	65 000
COD of the VFA (mg/litre)	15 890	9 625	10 243
VFA (meq/litre)	176.2	107.2	115
Ammonia-nitrogen (as mg N/litre)	2 320	1 840	1 730
Total nitrogen (as mg N/litre)	3 850	—	3 810
pH	7.1	7.2	6.9

of experiments were not conducted simultaneously so that the manure used in the various series differed with respect to origin and composition. The manure characteristics are summarized in Table 2.

The manure used in series A originated from an experimental pig housing unit. The pigs were fed here ad libitum so that the manure may contain some spilled feed rests. The series B experiments were conducted with manure from a pig-fattening farm and those of series C with manure from an experimental farm where the manure solids and the manure liquid were discharged separately. Both fractions were combined in appropiate proportions before supplying it to the digester. The manure in this case partly consisted of saw dust and other litter material.

Results

The experimental results of series A, B and C are shown in Tables 3, 4 and 5 respectively. The data presented in these tables concern the average values of the

Table 3. Experimental results of series A (detention time 20 days; load 3.3 kg TS m^{-3} day^{-1}).

	Exp. A_1	Exp. A_2	Exp. A_3
Duration of experiment (days)	95	95	95
Temperature (°C)	20	25	30
Gas production (m^3/kg TS)	0.242	0.351	0.379
Gas composition (% methane)	71.1	70.1	69
Methane production (m^3 CH_4/kg TS)	0.172	0.246	0.262
(m^3 CH_4/kg VS)	0.226	0.324	0.345
pH	7.4	7.55	7.6
VFA concentration (meq/litre)	18.9	3.2	2.7
Acetic acid concentration (meq/litre)	14.7	3.2	2.6
Propionic acid concentration (meq/litre)	3.8	0	0.1
COD of the VFA (mg/litre)	1 429	205	171
COD supernatant (mg/litre)	7 020	7 220	5 180
Ammonia-nitrogen (as mg N/litre)	2 870	2 990	2 990
Total nitrogen (as mg N/litre)	3 950	3 680	3 650

Table 4. Experimental results of series B (detention time 15 days; load 4.2 kg TS m^{-3} day^{-1}).

	Exp. B_1	Exp. B_2	Exp. B_3
Duration of experiments (days)	90	90	90
Temperature (°C)	27	32	40
Gas production (m^3/kg TS)	0.234	0.255	0.268
Gas composition (% methane)	74.0	72.8	73.5
Methane production (m^3 CH_4/kg TS)	0.173	0.186	0.197
(m^3 CH_4/kg VS)	0.258	0.277	0.293
pH	7.6	7.65	7.7
VFA concentration (meq/litre)	3.4	1.1	6.5
Acetic acid concentration (meq/litre)	3.1	1.1	4.8
Propionic acid concentration (meq/litre)	0.3	0	1.5
COD of the VFA (mg/litre)	231	71	502
COD supernatant (mg/litre)	7 230	5 760	7 930
Ammonia-nitrogen (as mg N/litre)	2 330	2 255	2 273
Total nitrogen (as mg N/litre)	—	—	—

results during the last 25 days of the experiments when the digestion process had reached a steady state. In Tables 3 and 4 the values of TS, VS and total COD are not presented as they are inadequate due to the incomplete mixing of the digester contents in these series.

The gas production obtained in the reference approx. 30 °C experiments of each

Table 5. Experimental results of series C (detention time 20 days; load 3.6 kg TS m^{-3} day^{-1}).

	Exp. C_1	Exp. C_2	Exp. C_3 (in duplicate)	
Duration of experiment (days)	73	73	80	80
Temperature (°C)	13	35	55	55
Gas production (m^3/kg TS)	0	0.384	0.315	0.332
Gas composition (% methane)	—	65.0	58.5	59.0
Methane production (m^3 CH_4/kg TS)	0	0.249	0.184	0.196
(m^3 CH_4/kg VS)	0	0.324	0.239	0.255
pH	6.7	7.4	7.8	7.7
TS (g/litre)	72.6	52.4	57.1	55.8
VS (g/litre)	56.3	36.1	40.0	39.4
VFA concentration (meq/litre)	181.7	1.6	84.5	81.0
Acetic acid concentration (meq/litre)	113.1	1.5	19.7	18.9
Propionic acid concentration (meq/litre)	38.1	0.1	41.6	36.4
COD of the VFA (mg/litre)	16 740	115	10 240	10 220
COD supernatant (mg/litre)	20 640	5 630	18 080	17 160
COD total (mg/litre)	60 060	37 700	50 000	49 000
Ammonia-nitrogen (as mg N/litre)	1 820	2 061	→ 2 430	→ 2 400
Total nitrogen (as mg N/litre)	3 790	3 643	3 740	3 450

→ increasing to.

series differed considerably from each other. This should be mainly attributed to the use of manure of different origin and composition. Therefore, but also because of the application of different loading rates in the three series (between 3.3 and 4.2 kg TS m^{-3} day^{-1}) the interpretation of the results should be primarily related to the data obtained within each separate series.

The results in Table 5 indicate that methane production is nihil at a process temperature of 13 °C under the conditions applied. This cannot be attributed to a lack of adequate substrate for the methane formers because of the high VFA concentration in the digester mixed liquor. The VFA concentration even increased from 115 meq/litre in the manure feed to 181.7 meq/litre in the 13 °C experiment.

However, at 20° C an active methane fermentation takes place (Table 3) which results in a sharp decrease in the VFA concentration of the digester contents with respect to fresh manure. The results presented in Table 3 also reveal that the activity of the bacterial sludge is considerably higher at 25 °C (methane production 0.324 m^3/kg VS) than at 20 °C (methane production 0.226 m^3/kg VS). However, an increase of the temperature from 25 to 30 °C does not further improve the methane production very significantly, viz only from 0.324 m^3/kg VS at 25 °C to 0.345 m^3/kg VS at 30 °C. Accordingly the results of series B (Table 4) show that the methane production increases only slightly and almost linearly with the digestion temperature in the range from 27 to 40 °C. The results of the separate experiments within this series are very similar except that the VFA concentration and the COD of the supernatant solution in the 32 °C experiment are clearly lower than that in the 27 °C and 40 °C experiments.

The digestion at 55 °C was investigated in two experiments, which showed very similar results (Table 5). A raise in temperature from 35 to 55 °C apparently adversely affects the gas production because the methane production at 55 °C (0.243 m^3/kg VS) is only 75 % of that at 35 °C (0.324 m^3/kg VS). Furthermore the methane content of the gas produced under thermophilic conditions is somewhat lower.

In previous experiments (not published) extensive efforts were made to initiate thermophilic digestion at 55 °C of piggery manure having an ammonia-nitrogen concentration of approx. 3000 mg/litre. Under these circumstances methane production did not start. As it was believed that the main reason for the poor results of the latter experiments was the stronger inhibiting action of ammonia-nitrogen on the digestion process under thermophilic than under mesophilic conditions the following two experiments were carried out: (1) after finishing series C one of the 55 °C digesters was continously operated at 55 °C and fed with 6 % TS manure at a 30 days detention time (reference digester); (2) an other similar digestion unit was seeded with 5 litres of well digested piggery manure, acclimated at an ammonia-nitrogen concentration of 3000 mg/litre at 30 °C. The second digester was operated similarly to the reference digester except that 5.1 g ureum/litre manure was added to increase the ammonia-nitrogen concentration in the digester contents to approx. 3800 mg/litre.

The results of the additional thermophilic experiments presented in Table 6 indicate that at an ammonia-nitrogen concentration of 3800 mg/litre gas produc-

Table 6. Thermophilic digestion at different ammonia-nitrogen concentrations (temperature 55 °C; detention time 30 days; manure concentration 65 g TS; load 2.2 kg TS m^{-3} day^{-1}).

	Manure	Reference	Ureum added
Duration of experiment (days)		50	50
Gas production (m^3/kg TS)		0.276	0.038
Gas composition (% methane)		63	39
Methane production (m^3/kg TS)		0.174.	0.015
(m^3/kg VS)		0.235	0.021
pH	7.2	7.9	7.7
COD of the VFA (mg/litre)	3 870	5 380	12 900
Acetic acid concentration (meq/litre)	33.6	22.8	133
Propionic acid concentration (meq/litre)	7.6	16.2	17.5
VFA concentration (meq/litre)	46.6	50.3	164.4
COD of the supernatant (mg/litre)	8 000	—	—
Ammonia-nitrogen (mg as N/litre)	1 200	1 500	3 800

tion ceases almost completely and does not recuperate in the experimental period of 50 days whereas the methane production in the reference digester is very similar to that obtained in the 55 °C experiments of series C.

Discussion

The most obvious digestion characteristic for evaluating the influence of the temperature is the methane production, especially when energy recovery is the main objective for applying the digestion process. However, the methane production only represents the final degree of conversion and does not reveal the step in the process which is rate-limiting. To gain a better insight in the course of the digestion process which is necessary to optimize the process, the degree of conversion as obtained in three separate steps (hydrolysis, acid formation and methane formation) has been calculated.

In this calculation it is assumed that (1) in the hydrolysis step only undissolved organic matter is converted into dissolved fragments, (2) that VFA, hydrogen and carbon dioxide are exclusively formed by the acid-forming organisms and (3) that all methane originates from the end-products of the acid formation.

The degree of hydrolysis, acid formation and methane formation at the end of

Table 7. Influence of temperature on the degree of hydrolysis, acid formaton and methane formation (in % of the manure COD).

	Manure	13 °C	35 °C	55 °C
Hydrolysis	24.6	31.8	76.1	78.5
Acid formation	15.8	25.7	67.7	67.2
Methane formation	0	0	67.5	51.5

the experiments (steady state) can now be calculated by the following equations (van Velsen, 1977):

hydrolysis (%) $= 100\,(G + S)/M$
acid formation (%) $= 100\,(G + V)/M$
methane formation (%) $= 100\,G/M$

in which G = COD removed via methane gas (g/litre)
S = COD of the supernatant (g/litre)
M = total manure COD (g/litre)
V = COD corresponding with the VFA concentration in the digester (g/litre).

The results of these calculations have been plotted versus the temperature in Fig. 1 for experimental series A en B and are presented in Table 7 for experimental series C.

Digestion at 13 °C

Literature data concerning the digestion of solid wastes such as sewage sludge indicate that methane production still takes place below 10 °C though at a very slow rate. Contrary to these reports no gas is produced in the 13 °C experiment under the process conditions applied. The absence of methane production in this experiment may indicate that environmental factors such as the high ammonia-nitrogen concentration and the high pH levels in piggery manure together with the low temperature create conditions which are unfavourable for the methanogenic organisms.

Contrary to the results of experiments conducted in our laboratory indicating that methane-forming organisms accomodate well to changes in temperature between 10 and 45 °C (Lettinga, 1979) the gas production in a piggery manure digester evidently ceases at a fall in temperature from 30 to 13 °C.

Heukelekian et al. (1948) and Speece & Kem (1970) also reported that at the digestion of sewage sludge the gas production did not continue immediately after a sudden decrease in temperature in this range.

The cessation of the methane production in combination with the application of a 20-day detention time immediately after the start of the experiments may have caused a wash-out of methanogenic bacteria. Therefore better results may be expected when more time is taken to acclimate the bacterial population to the change in temperature.

The results in Table 7 also indicate that hydrolysis is very incomplete. This may be attributed (1) to the low activity of the hydrolytic enzyme complexes at this temperature and/or (2) to an inhibition of the hydrolysis by the end-products of the acid formation, such as VFA and hydrogen, which accumulate in the digester contents.

Digestion at mesophilic temperatures (20 - 40 °C)

As appears from Fig. 1 all three separate steps of the digestion process (hydrolysis, acid formation and methane formation) are affected to about the same extent by the temperature in the range of 20 to 40 °C. Hence it can be concluded that changes

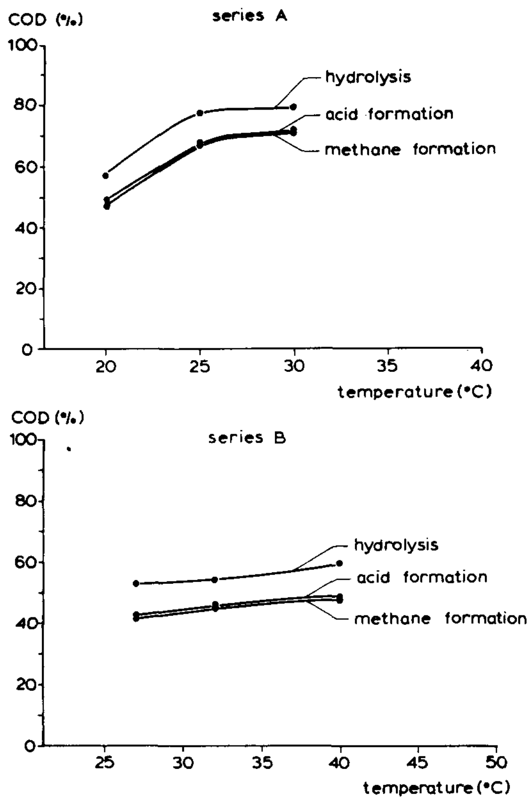

Fig. 1. Influence of temperature in the mesophilic range (20 to 40 °C) on hydrolysis, acid formation and methane formation.

in the methane production at the different temperatures investigated should be attributed mainly to changes in the rate of hydrolysis. The fact that in the digestion of solid wastes hydrolysis frequently is the rate-limiting step was already observed by Pfeffer (1974), in investigating the effect of temperature on the digestion of domestic refuse and by van Velsen (1977) in digestion experiments with piggery manure at different loading rates at 30 °C. Evidently the methane production in the underlying experiments reflects in fact the influence of temperature on the rate of hydrolysis.

Fig. 1 reveals that the rate of hydrolysis strongly increases when the temperature is raised from 20 °C to 25 °C. The combined results of series A and B indicate that the rate of hydrolysis – and therefore the gas production – increases almost linearly with the temperature in the range of 25 to 40 °C. The average rate of increase in gas production amounts to approx. 1 % per °C.

Correspondingly Fair & Moore (1934), in summarizing the results of batch experiments concerning the influence of temperature on the digestion of sewage solids, concluded that it was possible to approximate the relation between the relative rate of digestion and the temperature in the range of 25 to 40 °C by a straight line and that only little could be gained by raising the digestion temperature above 25 °C. Also Golueke (1958) reported a linear relationship between temperature (30 - 40 °C) and gas production at the digestion of raw sewage sludge at a load of 1.45 kg VS m^{-3} day^{-1}.

In establishing the effect of the temperature on the digestion an important factor to be considered should be the detention time. At a shorter, and therefore more critical, detention time the differences in methane production at different temperatures presumably are more significant. Hobson et al. (in press) conducted experiments with pig slurry at a 10-day detention time and reported an increase in the gas production from 0.30 m^3/kg TS at 30 °C to 0.42 m^3/kg TS at 40 °C which corresponds to an average increase in the gas production of 4 % per °C.

Digestion at 55 °C

The increase of the digestion temperature from 35 to 55 °C resulted in a decrease in the gas production of approx. 25 % in spite of a slight increase in the degree of hydrolysis (Table 7), which has to be attributed to an improved conversion of carbohydrates and nitrogenous substances such as proteins.

Table 8, which contains a rough estimate of the relative breakdown of carbohydrates at digestion temperatures of 13, 35 and 55 °C, indicates that the conversion of both cellulose and hemicellulose increases at increasing temperatures. The breakdown of nitrogenous components can be more or less followed by the ammonia-nitrogen concentration before and after digestion. These analyses give only an impression of the overall process because apart from the release of ammonia-nitrogen during the breakdown of nitrogenous substances, part of the ammonia-nitrogen is incorporated in new cell material. Furthermore some ammonia-nitrogen may be lost from the digestion liquor with the gas. The ammonia-nitrogen concentration in the experimental series C increased significantly with increasing temperature, i.e. from 1820 mg/litre at 13 °C to 2400 mg/litre at 55 °C, which points to an increased conversion of nitrogenous components at 55 °C.

The both higher VFA concentration and supernatant COD at thermophilic as compared to mesophilic digestion has also been observed by Buhr et al. (1977), Golueke (1958), Garber et al. (1975), Pohland & Bloodgood (1963). Apparently the observed decrease in the gas production in the underlying experiments is due to both a less complete acid and methane formation.

Earlier investigations on the effect of temperature on anaerobic digestion of wastes gave rather conflicting results. Heukelekian (1930) and Fair & Moore (1932) found in batch experiments with sewage sludge both a higher gas production

Table 8. Rough estimate of the reduction of hemicellulose and cellulose as observed in digestion experiments with wet piggery manure at different temperatures (in % of the manure concentration). Lignine is used as an internal standard.

	13 °C	35 °C	55 °C
Hemicellulose	38	43	53
Cellulose	34	39	52

and gas production rate at increasing temperatures up to 60 °C, whereas Maly & Fadrus (1971) found in similar experiments that this only holds for the gas production rate. Continuous experiments at different temperatures were conducted with municipal sewage sludge (Golueke, 1958; Pohland et al., 1963; Malina, 1961; Garber et al., 1975) and shredded domestic refuse (Pfeffer, 1974). Garber et al. (1975) and Pfeffer (1974) reported an increase in the gas production with increasing the temperature from the mesophilic to the thermophilic range. On the other hand the reports of Golueke (1958), Pohland & Bloodgood (1963) and Malina (1961) showed a similar or somewhat lower gas production at thermophilic as compared with mesophilic temperatures. These discrepancies in the reports may be caused either by differences in the acclimation procedures followed or by the influence of some yet unidentified inhibitory agent for thermophilic methanogenic organisms.

Anyhow, the results obtained in the additional experiment conducted in the present study where the ammonia-nitrogen concentration was increased from 1500 mg/litre to 3800 mg/litre, clearly show that ammonia-nitrogen severely inhibits the methane formation under thermophilic conditions. In fact such an inhibition also occurs under mesophilic conditions but recent results (van Velsen, 1979a) have shown that the digestion process can acclimate in that case to ammonia-nitrogen concentrations up to 3500 mg/litre as applied in the present experiment. Apparently this does not occur in the 55 °C experiment.

The increasing inhibitory effect of ammonia-nitrogen on the digestion process with increasing temperature is presumed to be caused by an increase in the fraction of undissociated ammonia at increasing temperature (at constant pH and total ammoniacal nitrogen concentration).

The fraction of free ammonia under a given set of conditions can be calculated by Eq. 1.

$$NH_3\text{-}N = NH_4^+\text{-}N \, \frac{10^{pH}}{k_b/k_w + 10^{pH}} \qquad (1)$$

in which

NH_3-N = concentration of undissociated ammonia-nitrogen (mg/litre)
NH_4^+-N = concentration of total ammoniacal nitrogen (mg/litre)
k_b = dissociation constant of aqueous ammonia
k_w = ionization constant for water.

For a total ammoniacal nitrogen concentration of 3500 mg/litre a calculation shows that at pH = 8 the free ammonia-nitrogen is 970 mg/litre at 55 °C (k_b = approx. 1.905×10^{-5} (Weast, 1964)) and only 260 mg/litre at 30 °C ($k_b = 1.820 \times 10^{-5}$ (Weast, 1964))!

As it is presumed (McCarthy et al., 1961) that undissociated ammonia-nitrogen is the inhibiting agent for the methane-formation, it is clear that the effect of ammonia-nitrogen should be considerably greater under thermophilic than under mesophilic conditions.

Determination of the optimum digestion temperature

The experimental results reveal that the mesophilic temperature range is most adequate for the digestion of wet piggery manure. At a submaximum load of 4.0 kg TS m^{-3} day^{-1}, which is imperative when the abatement of odour nuisance is focussed (van Velsen, 1979b), the gas production increases almost linearly in the temperature range from 25 to 40 °C.

Starting from the results of experimental series B a raise in temperature from 27 to 40 °C causes an increase in the methane production from 0.024 m^3/kg TS (Table 4) which corresponds to a heating value of 0.865 MJ/kg TS. On the other hand the heating of 6 % TS manure from 27 to 40 °C theoretically demands 0.91 MJ/kg TS, indicating that, apart from higher radiant losses at 40 °C, the extra methane production is not sufficient to heat the manure from 27 to 40 °C, even not at a 100 % efficiency of the energy conversion.

The energy balance might be more positive when more concentrated manure is digested. However, the gas production per kg TS decreases at increasing manure concentrations above 6 % TS (van Velsen, 1977). Therefore, when the heat requirements of a digester have to be supplied exclusively with high-grade fuel, for example part of the methane produced, the optimum temperature with respect to the net energy recovery is at the lower part of the mesophilic range, i.e. between 27 and 30 °C. On the other hand when sufficient waste energy, for example cooling water of a gas motor/generator set, is available the optimum process temperature for energy recovery may be at the upper part of the mesophilic range, i.e. 40 °C, when the maximum gas production is obtained.

Conclusions

– Digestion under mesophilic conditions is most adequate for piggery waste stabilization. At a load of approx. 4 kg TS m^{-3} day^{-1} gas production increases almost linearly with temperature in the range of 25 to 40 °C. At these temperatures hydrolysis is the rate limiting step in the process.

– The optimum temperature with respect to the net energy recovery is approx. 27 - 30 °C in case high grade fuel is required to elevate the temperature. However, when sufficient waste energy is available the optimum digestion temperature may be approx. 40 °C.

– A continuous digestion of piggery waste at a temperature of 13 °C is unsuccessful, because the methane production is nihil under these conditions.

– Thermophilic digestion of manure at an ammonia-nitrogen concentration in the range of 1700 to 2400 mg/litre results in a slightly increasing hydrolysis and in a significantly decreasing methane production, i.e. by approx. 25 % as compared to mesophilic digestion. At increased ammonia-nitrogen concentrations (3800 mg/litre) the gas production at 55 °C ceases almost completely, presumably due to the occurrence of increasing concentrations of free ammonia at increasing temperatures.

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