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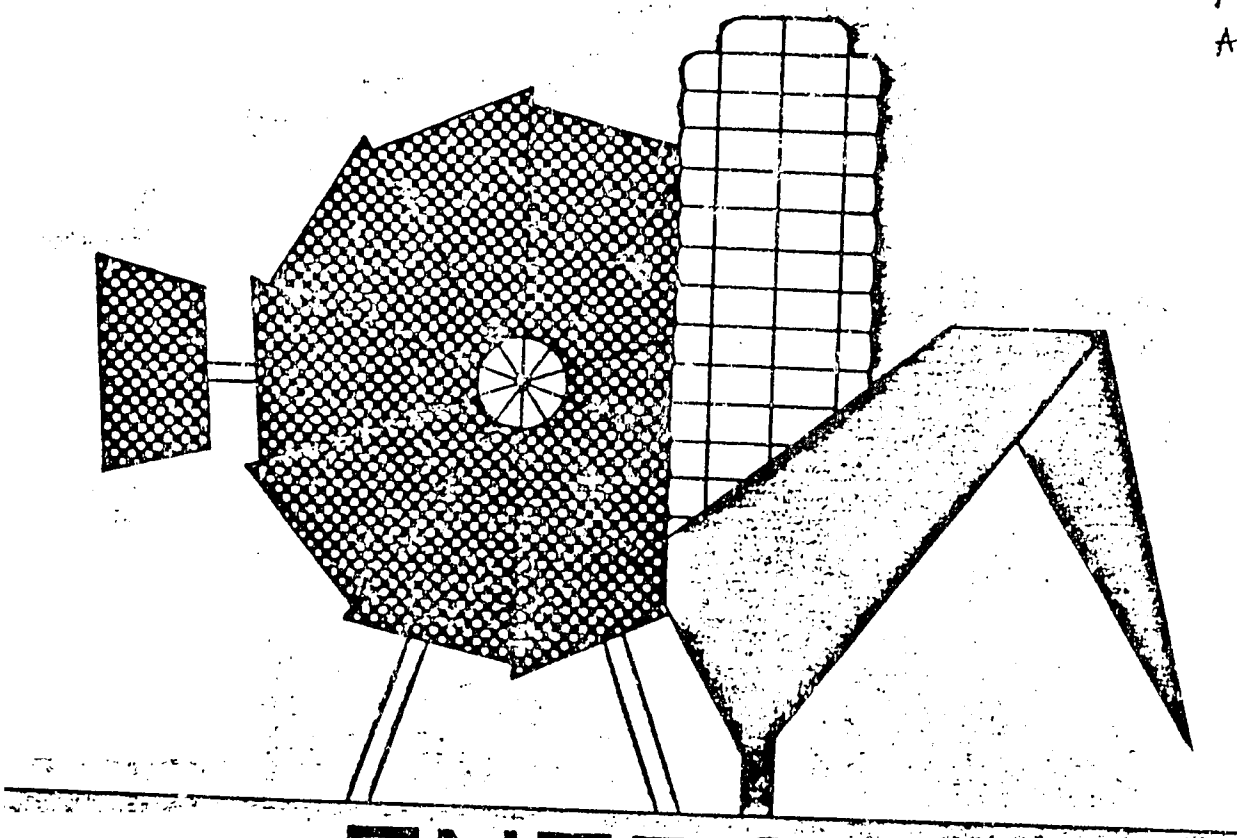

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EVALUATION OF THE PERFORMANCE OF TWO RURAL BIOGAS UNITS OF INDIAN AND CHINESE DESIGN

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ABSTRACT

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In the context of endeavours to develop biogas technologies appropriate to Egyptian rural areas, Indian and Chinese designs appear to be the foremost candidates. The aim of the present work is to assess the performance of two family-sized prototype units, one Indian and one Chinese version, with particular reference to their potential suitability to prevailing village conditions.

The Chinese unit used is 5 m^3 in size and is almost an exact duplicate of the original Chinese shallow and wide cylindrical model. The second prototype, on the other hand, is a modified version of the horizontal vertical Indian model. It holds about 7 m^3 of slurry. Both units were operated over sufficiently long periods to allow an evaluation under reasonably comparable conditions which fairly closely represented those anticipated in the actual village circumstances.

Water-buffalo dung at a solids concentration of 9—11% was used as feedstock. The experimental program encompassed the study of seasonal variations of digester temperature, as well as the effect of the inherent design features of the digesters, operating temperature, retention time and internal flow patterns on the gas production rate.

The slurry temperatures obtained in the digesters during one year of operation reflect the effect of continuous seasonal variation of ambient temperature. The temperature curve exhibits a minimum value during February and a maximum during August. The slurry temperature changed over the range from 17 to 29°C.

The gas production rate increased exponentially with increase in temperature in the range studied. The gas production rates from both the Chinese and Indian-type digesters are almost the same under the same operating conditions.

Internal mixing and flow patterns in the digesters were evaluated by a novel tracer technique. A large amount of dead space was noticed in both types. The mean actual retention times obtained using the pulse tracer technique were less than half the theoretical retention time.

Two new digester designs are proposed to overcome most of the difficulties and limitations associated with the Chinese and Indian technologies in the rural Egyptian setting.

INTRODUCTION

The application of biogas technology in rural areas of Egypt appears to

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have good prospects (Hamad and El Halwagi, 1981; El Halwagi, 1982). The extent of its probable spread, however, will depend on a myriad of interacting factors. Foremost among these is the appropriateness of the adopted technologies to local village conditions.

The Chinese and Indian types of technologies seemed to be most suitable and readily adaptable. Two family-sized prototype units were therefore constructed and operated at the National Research Centre (NRC) extension site for pilot experimentation and performance testing. The first unit is almost an exact duplicate of the most popular type of Chinese digester. The second unit is a modified version of an Indian design. Both units were tested under natural environmental conditions and over periods long enough to allow a reasonable assessment of their basic operating features.

EXPERIMENTAL SET-UP

In addition to the digesters proper, the experimental assembly encompassed the normal measuring devices for temperature, pressure and gas flow rate. A pressure regulation system (Hamad et al., 1982) was also incorporated in conjunction with the Chinese unit in order to operate it at constant pressure.

Two family-sized digester units were constructed for the study: one of the Chinese and the other of the Indian type.

Chinese-type digester

The circular and shallow digester type was taken as the prototype for this study. The basic feature of this type is its fixed roof. The unit is built completely underground. The base of the digester is made of concrete and is shaped like a dish which allows for saving of construction materials and

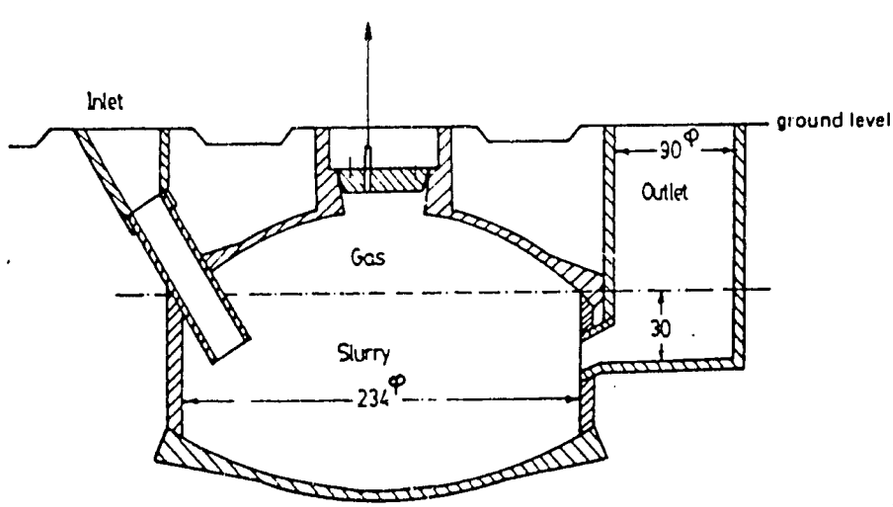

Fig. 1. Chinese prototype digester (dimensions in cm).

counteracts the uplift pressure of underground water. The cylindrical shell of the side wall as well as the digester dome are built of bricks. At the apex of the dome is a manhole for the initial loading and periodic discharge of digester contents. Two chambers are connected to the cylindrical part, one used as inlet and the other as outlet. The digester is illustrated in Fig. 1. Its volume is 5 m^3, while the slurry volume is about 4.2 m^3. Details of the Chinese design have been reported in some previous publications (Intermed. Technol. Publ., 1979; Sichuan Prov. Off. Biogas Dev., 1979; Abdel Dayem and Hamad, 1980).

Modified Indian-type digester

A horizontal type digester was constructed since it is deemed more suitable for the high water-table conditions prevailing in Egypt. It consists of two parts, a vertical shallow cylindrical part and a tubular horizontal part. Both are under ground. The tubular section is a ready-made concrete pipe fabricated especially for sewer work. A tube of 1 m diameter and 3 m length is used. The pipe is laid with a slight slope (1:20) to help the liberated gas to flow to the cylindrical vertical compartment. The vertical section is made of masonry with ledges to support the gas holder. The gas holder is constructed of mild steel sheets, angles and flats according to the original Indian design (Srinivasan, 1978).

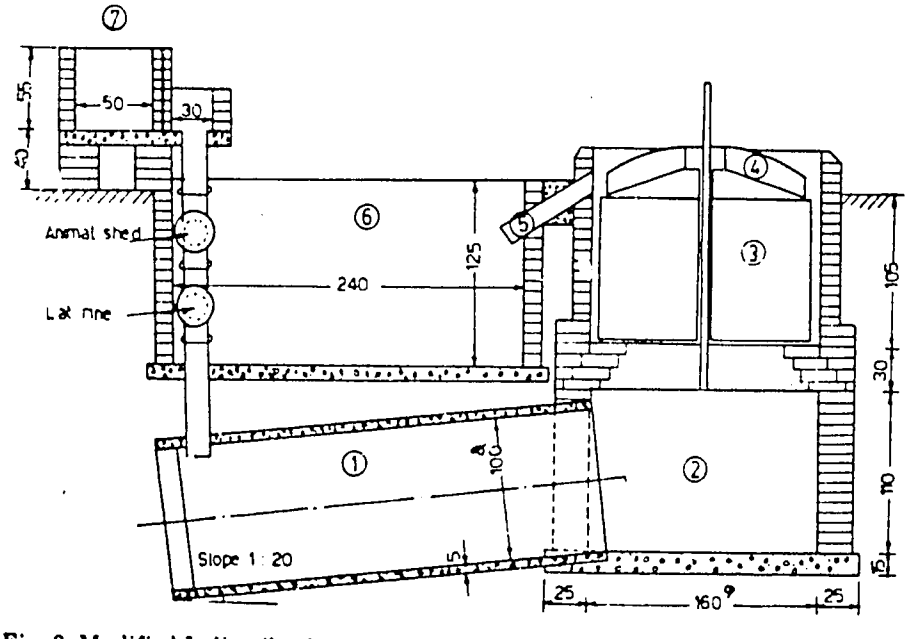

Fig. 2. Modified Indian (horizontal-vertical) prototype digester (dimensions in cm); 1, horizontal part; 2, vertical part; 3, gas holder; 4, solar heater; 5, effluent pipe; 6, effluent storage reservoir; 7, feed mixing chamber.

A small reservoir was constructed over the horizontal part of the digester to serve as a storage place for the effluent and also as a post-composter.

Details of this prototype are given in Fig. 2. The volume of the digester is 7.1 m^3.

OPERATION OF DIGESTERS AND EXPERIMENTAL CONDITIONS

The manure used as feedstock for the digestion process was obtained from the National Research Centre animal farm. Two rations were used in feeding the water buffalos. That used in winter consisted mainly of fresh clover plus some cotton-seed meal and wheat straw, whereas the summer ration consisted of cotton-seed meal, maize, rice bran, wheat bran and wheat straw. The digester was started by feeding it with low concentration slurry. Then the slurry concentration was gradually increased until the required concentration was reached. Thereafter the digester was fed daily with the required amount of slurry according to the selected retention time. The feed was prepared by mixing the fresh dung with an equal volume of water. Accordingly, the slurry concentration varied in the range of 9—11% total solids. The organic matter was in the range 70—77% while the C/N ratio was about 20 to 25:1.

The two prototype units were constructed side by side at the National Research Centre extension site. They were operated under similar conditions to those expected in rural areas. However, the two units were not operated simultaneously. The Chinese unit was operated during 1980 while the Indian unit was operated mainly during 1981. Both units were operated without any external heating.

The key parameters affecting the performance characteristics of the Indian and Chinese-type digesters were studied and evaluated on a comparative basis. They included: the digester temperature and its variation with natural ambient conditions; inherent design features; and the effects of temperature, retention time and internal flow patterns on gas production rates and organic matter digestibility.

RESULTS AND DISCUSSION

Digester temperature

Variation of temperature inside the digester with natural ambient conditions was followed for long enough periods to indicate the major seasonal effects. The temperature measurements in the Indian prototype were taken at the centre of the vertical section; those in the Chinese prototype were made in the middle of the digester. Results are shown in Fig. 3.

The temperatures obtained in the Indian-type digester during one whole year of operation reflect the effect of the continuous seasonal variations of ambient temperature. The curve exhibits a minimum value during February and a maximum during August. The slurry temperature changed over the

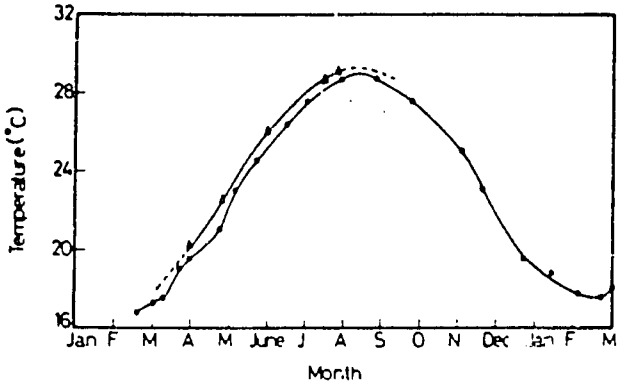

Fig. 3. Seasonal variation of temperature inside the digester; △, Chinese type (1980); ○, Indian type (1981).

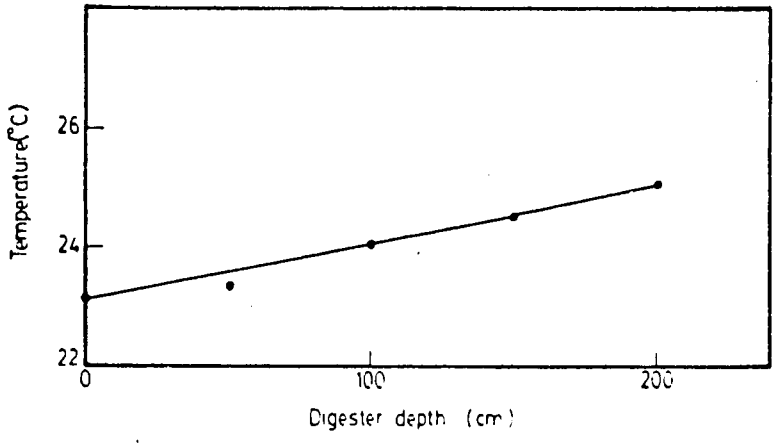

Fig. 4. Axial temperature profile in the Indian-type digester.

range from 17 to 29°C. Thus, the mean temperature during the year is about 23°C.

During the test period, the daily average ambient temperature ranged between 10 to 22°C for the cold winter season and 33 to 40°C for the summer season. The soil temperature varied in the range 16—26°C during the same period. Such sharp daily fluctuations, particularly throughout the winter season, are believed to have an adverse effect on gas production by the digester.

The shapes of the curves are similar for the Chinese and Indian types (Fig. 3). However, the temperatures attained in the Chinese-type digester are slightly higher than those for the Indian type, the difference being about 0.5—1°C. Though the measurements were not made in the same year but in two consecutive years, these results tend to indicate the comparatively better insulation properties of the Chinese-type digester.

The distribution of temperature in the vertical section of the Indian type was measured in the centreline at different elevations. The axial temperature profile obtained is shown in Fig. 4. The temperature was lowest at the bottom

and increased steadily with increasing height. About 2°C difference was observed. A lower variation of about 1°C was found in the Chinese-type digester.

Effect of design and operating parameters on gas production rate

Effect of digester design

The gas production rates of the Indian and Chinese-type digesters are illustrated in Fig. 5. The Indian type was operated at a retention time of 38.4 days and a pressure of 12 cm water column. The Chinese-type digester was operated under similar conditions. The retention time was 35.4 days. Though the normal Chinese-type digester is characterized by its variable gas pressure, for comparative purposes it was operated under a constant pressure of 7 cm water column.

The gas production rates per unit slurry volume were calculated on the basis of the active slurry volume, which is defined as that confined volume which contributes to the daily gas production rates. Thus, the slurry volume exposed to the atmosphere was not considered.

The results obtained at different temperatures for both types, as depicted in Fig. 5, show that production rates from the two types at the same temperature are almost the same. The small difference can be attributed mainly to slight differences in operating pressures and retention times.

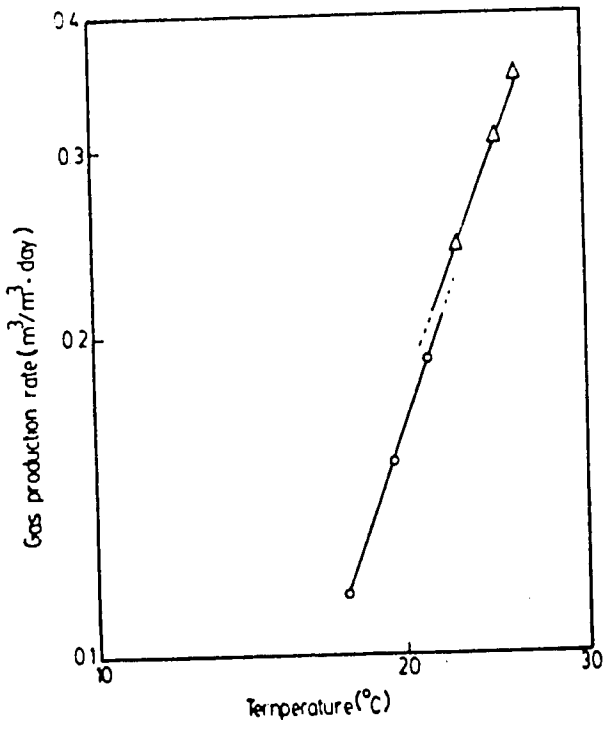

Fig. 5. Gas production rates of Indian and Chinese-type digesters; △, Chinese type; ○, Indian type.

The results obtained help to clarify the controversial issue of whether gas production rates of Chinese-type digesters are lower than those of the Indian types. It seems that, at the same temperature, differences are due only to differences in active slurry volumes. Since the Chinese-type digesters operate normally under variable pressure, their active slurry volume would not be constant, but would vary with pressure. The effect of pressure on gas production rate was studied earlier (Hamad et al., 1982). This particular work showed that the increase in gas pressure is accompanied by an increase in the gas losses, and a decrease in the active slurry volume. Therefore the total gas production rate decreases with increasing pressure. It was also noted that gas losses can be minimized by a small modification in the outlet chamber design.

The gas production rate of the Janata-type digester, which is an Indian modification of the fixed-roof Chinese-type digester, was reported (Biogas Newsl., 1981) to be less than that of the moving gas holder type by about 20—26%. The relatively high difference in production rate seems to be related mainly to the design of the outlet chamber of the digester.

Effect of retention time

The Indian-type digester was operated at three retention times: 38.4, 57.5 and 95 days. Long retention times were studied because of their relevance to two major features of Egyptian conditions; firstly the prevailing relatively low temperatures of fermentation, and secondly the frequent lack of raw materials in rural areas. These two features necessitate long retention times in order to obtain the maximum possible conversion of organic matter.

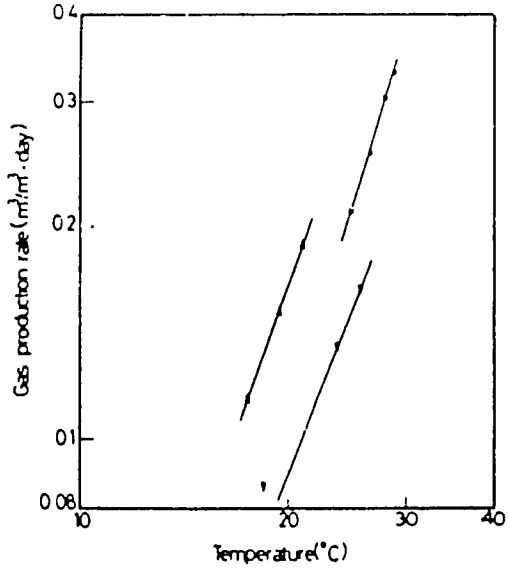

Fig. 6. Effect of operating parameters on gas production rate for Indian-type digester. Retention time: △, 38.4 days; ○, 57.5 days; ▽, 95 days.

The digester was operated continuously and the retention time was changed periodically. Steady state was assumed to be attained after one retention time. Measurements were carried out at steady-state conditions for a sufficient period to explore the effect of temperature which changed slowly as a result of ambient temperature variations. It is worth mentioning that, due to the continuous temperature change, a true steady state could never be reached. However, the assumed "practical" steady state, which can be reached after one retention time is more valuable, as it reflects the actual case for operation of such digesters in rural areas.

The gas production rate per unit slurry volume decreased with increasing retention time from 38.4 to 95 days as illustrated in Fig. 6. However, the amount of gas liberated per unit weight of organic matter increased with increasing retention time.

Effect of temperature

The gas production rate increased sharply with increasing temperature. This can be noted from Figs. 5 and 6 for both the Indian and Chinese-type digesters. This has also been reported previously by many investigators (Pfeffer, 1974; Hashimoto, 1981).

Results could be empirically correlated by the relation:

$$v_g \propto T^x$$

where v_g = volume of gas liberated ($m^3/m^3 \cdot day$); T = temperature of slurry in the digester (°C). The exponent x varied in the range 2.5—2.9 according to the digester type and retention time; this variation may be due to the high sensitivity to temperature and the temperature gradient present in both digesters. Thus, a mean value of 2.7 can be taken as exponent for this relation.

Gas composition

Some typical gas compositions in the Indian-type digester under different operating conditions are given in Table I. The methane content varied in the range 52—66%; carbon dioxide 37—48%; and hydrogen 0—0.9%. The gas composition for the Chinese-type digester was found to depend on gas pressure (Hamad et al., 1982). For the actual situation of operating under variable pressure, the gas composition varied in the range 53—58% methane, 37—43% carbon dioxide and 0—3% hydrogen.

Because of the overlapping of different parameters in this study, it was difficult to assess the influence of other variables. It should be noted, however, that Jewell et al. (1981) found that the methane content of the produced gas decreased with increasing retention time.

TABLE I

Performance characteristics of the Indian-type digester

Operation conditions		Gas production rate			Organic matter conversion (%)	Gas composition		
Temperature (°C)	Retention time (days)	$m^3/m^3 \cdot day$	m^3/kg dig·day	m^3/kg solids fed		CH_4	CO_2	H_2
17.3	38.4	0.107	0.2	0.04	27.8			
19.5	38.4	0.152	0.25	0.056	32.1	66.48	36.97	0.55
27.5	57.5	0.305	0.43	0.143	46.7	56.71	43.29	0
28.7	57.5	0.330		0.155				
18.5	95	0.086	0.18	0.08	33	57.0	43.0	0
22	95	0.11	0.13	0.098	51.8			

Organic matter digestibility

The apparent efficiency of organic matter digestibility for the Indian-type digester is given in Table I. However, these results are only indicative because of the interaction of other factors relating to variations in digestion temperatures and feed material. Nearly similar results were obtained for the Chinese-type digester (Abdel Dayem and Hamad, 1980).

Residence time and internal flow patterns

Actual flow patterns and mixing characteristics of real digesters would vary considerably according to their design. A valuable approach to the characterization of internal flow behaviour and to assessment of deviation from the two ideal extremes of either perfect mixing or plug flow is provided through determination of residence-time distribution. Anomalous flow behaviour can result from numerous sources of deviation from ideal models. The major problems are channeling, dead volume and bypassing. Determination of the residence times in the exit stream is a useful indicator and one which is applied in biological reactor design and analysis. Exit-age distribution is also of particular importance in connection with the effect of anaerobic digestion on pollution control and kill rate of pathogens.

A number of stimulus—response techniques can be used to determine age distributions (Danckwerts, 1953; Kramers and Alberda, 1953; Levenspiel and Bischoff, 1963). Pulse—response experiments were carried out in this work employing a novel tracer and monitoring technique which is simple and readily applicable to tests undertaken under rural conditions.

A plastic material whose specific gravity is approximately the same as that of the digester (1.05) was used as the tracer. It consisted of cylindrical beads, each having a length of about 7 mm and weight of 0.015 g. On mixing with the slurry, these beads could be uniformly spread without exhibiting noticeable settling or floating over long periods of time. Thus, this material reasonably fulfills the requirements of a tracer as it does not react in the digester and at the same time is detectable in small concentrations without disturbing the transport and physical properties of the digester contents.

At the beginning of the experiment, a pulse of 1.66% tracer concentration was injected into the feed stream. The concentration of the tracer in the effluent was subsequently followed for a period of about two theoretical retention times. On a daily basis, the plastic beads in the effluent were collected by sieving and washing, after which they were dried and weighed to determine the exit tracer concentration. Thus, experimental data on exit-age or residence-time distribution would take the form of discrete values of tracer concentration measured at successive 1-day intervals after the introduction of the tracer.

The actual mean residence time ($\bar{t}_a$) can then be determined from the

following equation:

$$\bar{t}_a = \frac{\Sigma\, t\, C(t)\, \Delta t}{\Sigma\, C(t)\, \Delta t}$$

where t is real time (days); $C(t)$ = tracer concentration in the effluent at time t (g/l); Δt = time increment (days). The effective digester volume V_e (m^3) can then be calculated using the equation:

$$\bar{V}_e = \bar{t}_a\, v$$

where v = the volumetric flow rate (m^3/day).

It should be noted that $\bar{t}_a$, the actual mean residence time, is different from the nominal or theoretical retention time $\bar{t}$ calculated on the basis of the total digester volume V by the equation:

$$\bar{t} = \frac{V}{v}$$

The effective digester volume $\bar{V}_e$ is expected to be smaller than the actual digester volume V because of the gas holdup and internal dead volumes. It is estimated (Perry, 1976), that only about one-third of the volume is used for actual digestion in the case of sewage treatment plants. The remainder of the space is occupied by stabilized solids, supernatant fluid, scum, and gas.

The exit-age distribution (E curve) for the Chinese prototype digester is shown in Fig. 7. This represents a pulse- response curve in which the dimensionless tracer concentration in the effluent C/C_0 is plotted against dimensionless time $\theta = t/\bar{t}$, where C is the exit tracer concentration at time t; C_0 is the initial tracer concentration; θ is the number of residence times (or the reduced time); $\bar{t}$ is the nominal or theoretical retention time (35.4 days).

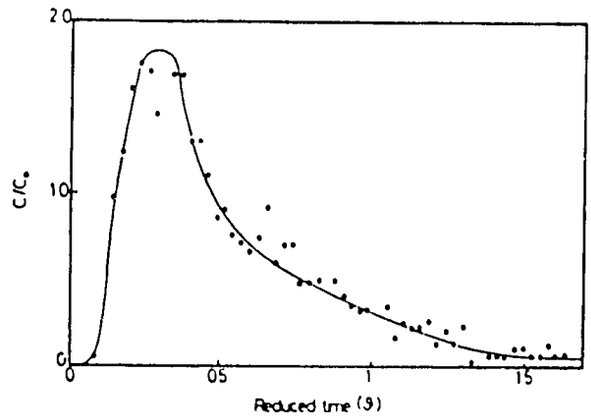

Fig. 7. Effluent tracer concentration from the Chinese-type digester operated at 35.4 days retention time.

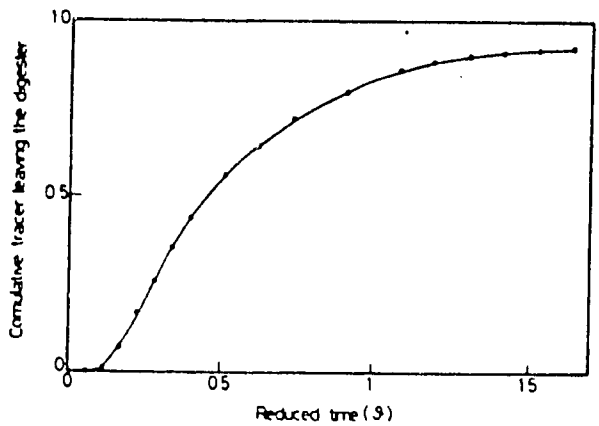

Fig. 8. F curve for plastic tracer passing through the Chinese-type digester operated at 35.4 days retention time.

The actual mean residence time $\bar{t}_a$ was calculated to be about 14 days, which is only about 0.4 of the theoretical retention time. Such a large difference can be explained in terms of the presence of relatively large amounts of dead space which decrease the effective volume of the digester. In addition to the effects of gas holdup, sediments and the scum layer, the geometrical configuration of the digester itself, relating to such aspects as feed inlet, site of product withdrawal, corners and internal structural elements, leads to stagnation zones.

The residence-time distribution (F curve) is shown in Fig. 8. This is calculated from the exit tracer concentration—time data by graphical integration. Such information can be used directly for modeling mixing effects on digester performance. Otherwise, various combinations of ideal models may be employed in simulation of non-ideal behaviour. A reasonable model for the Chinese prototype could involve a combination of a dispersed plug-flow reactor with a large dead volume occupying about 0.6 of the digester volume.

The E and F curves for the modified Indian prototype are shown in Figs. 9 and 10. The actual mean residence time was calculated to be about 26 days, or around 0.45% of the theoretical retention time. Thus, the dead volume—though lower than in the Chinese digester—is still considerable. Because of the more complex nature of this digester, being a composite design, the exitage distribution exhibits an anomalous shape. There appears to be more than one peak, which is indicative of channeling or short-circuiting. Simulation of this type of digester would, therefore, necessitate a more elaborate model involving dispersed plug-flow, channeling and a dead volume.

In essence, and though these tracer studies and their analysis and treatment entail a certain degree of oversimplification, they do reveal a very important finding, viz. the very large dead volume in both types of digester. Since the initial investment cost is a function of the size of the digester, and since only a fraction less than half the volume of the digester is actively utilized, it appears that design modifications are strongly needed to promote biogas technology in rural areas.

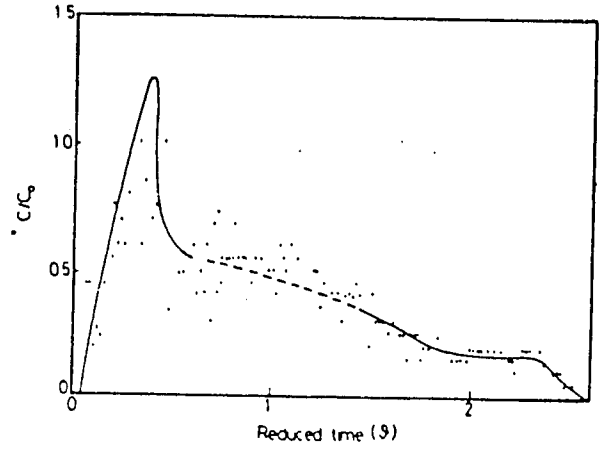

Fig. 9. Effluent tracer concentration from the Indian-type digester operated at 57.6 days retention time.

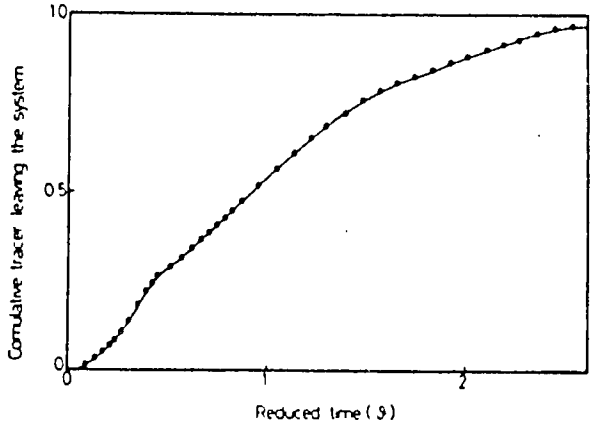

Fig. 10. *F* curve for plastic tracer passing through the Indian-type digester operated at 57.6 days retention time.

SUITABILITY OF CHINESE AND INDIAN TECHNOLOGIES FOR EGYPTIAN CONDITIONS

The main advantage of these two technologies is the possibility of constructing small units suitable for Egyptian rural families. Though the Chinese type is cheaper than the Indian, it is more difficult to construct and operate.

The major limitations of these technologies with regard to their appropriateness and therefore their potential use under Egyptian conditions can be summarized as follows:

(1) Fluctuation of the slurry temperature depending on the season. This leads to a sharp drop in the gas production rate during winter to less than half its value during summer.

(2) The relatively large underground depth needed. This causes constructional difficulties because of the presence of a high water table in most of the

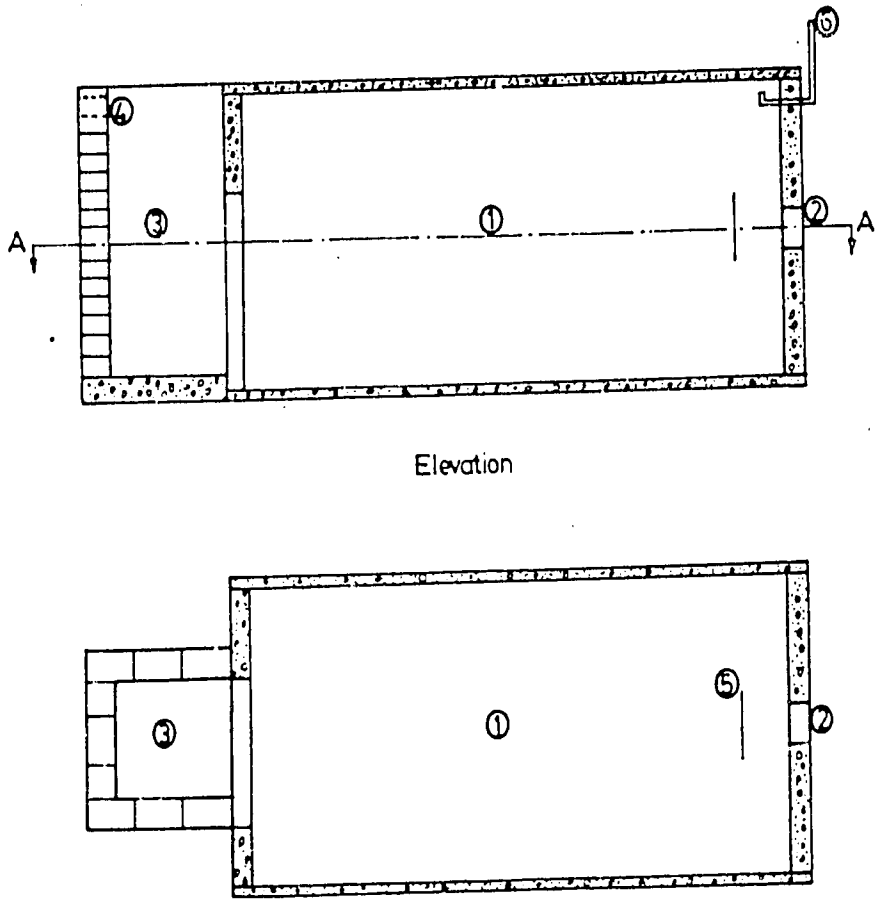

Fig. 11. Plug-flow digester; 1, digester; 2, inlet pipe; 3, outlet chamber; 4, outlet pipe; 5, buffle; 6, gas pipe.

rural areas. This prevailing high water table, also decreases the heat insulation capabilities of such digesters.

(3) The presence of relatively large amounts of dead space which results in lower conversion efficiencies.

(4) Both types of digester require a comparatively large space for unit construction and effluent treatment, which may not be available in most of the rural houses.

In order to overcome these main difficulties and limitations, two new designs which may be promising are now under development.

The first is what may be called the plug-flow digester. This digester is just a horizontal large pipe of concrete or plastic material as available, with an inlet from one side and an outlet from the other side. The pipe is embedded in the earth. The upper part of the pipe is slurry-free for gas separation. The

gas produced can be stored either in rubber tyres or in a conventional floating gas holder. Details of a family-sized unit of this type are illustrated in Fig. 11. The digester can be located totally under the animal shed and accordingly there will be no need for a large free space for its construction. If needed, and especially for large digesters, the unit can be connected with a solar heater for maintaining the temperature at a reasonable level.

The second is the thermophilic mini-digester with a volume of about 0.5 m^3. This is estimated to produce more than 1 m^3/day, which is sufficient for a small rural family. A gas production rate of 2–3 $m^3/m^3 \cdot$day can be obtained easily by operating in thermophilic regimes. For this reason the digester is to be furnished with a solar heater. The heating medium circulates by natural convection. The main advantages of this digester are:

(1) Only a small area is required for the erection of the unit.

(2) Constant and sufficient gas is produced during summer and winter.

(3) The high operating temperature would result in an almost complete elimination of parasites and pathogens, thus rendering the effluent suitable for animal feeding.

CONCLUSIONS

Gas production rates from Chinese and Indian-type digesters are almost the same, if the units are operated under the same conditions.

A sharp drop in slurry temperature was noticed during the winter season, and accordingly the gas production rates decreased to less than half those prevailing during the summer season.

A large amount of dead space was noticed in both types. The mean actual retention times obtained using the pulse tracer technique were found to be less than half the theoretical retention time.

Two digester designs are proposed to overcome most of the difficulties and limitations associated with both the Chinese and Indian types of technology in the rural Egyptian setting.

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