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Biogas Digester: A Discussion on Factors Affecting Biogas Production and Field Investigation of a Novel Duplex Digester

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Abstract: Utilisation of biogas has gained importance in recent years, mainly due to the availability of cheap raw materials and environmental compatibility. Further, with an increase in the cost of petroleum products, biogas can be an effective alternative source of energy for cooking, lighting, food processing, irrigation and several other requirements. In essence, a biogas digester involves anaerobic fermentation in which different groups of bacteria act upon complex organic materials in the absence of air to produce biogas. Thus, it is essential to evaluate the effects of various parameters that influence the performance of a digester, and it is one objective of this article. Results available in published literature and those from experiments (laboratory- and field-level) performed at IIT Guwahati are presented to illustrate the effects of various parameters on the performance of the existing models of biogas digester. The field investigation of a novel duplex digester have also been presented and discussed. The novel duplex digester is shown to have enhanced biogas production mainly due to agitation of its contents and, therefore, is promising for practical applications.

Keywords:

Introduction

There is a worldwide concern because the rate of consumption of fossil fuels far exceeds the rate of their formation. This concern has stimulated researchers to develop economically viable and environmental friendly alternatives such as biogas [1-3]. Biomass is a key renewable energy resource of the future at both small- and large-scale levels [1]. Recently, emphasis is being given to produce biogas from cattle dung and other waste materials because of increasing cost of diesel and petrol. Biomass already supplies 14% of the world's energy and several projects are being assessed that, if implemented, will increase the role of biomass in the overall energy system. On an average, biomass produces 38% of the primary energy in

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developing countries (90% in some countries), where it is the single largest energy source. There is a growing recognition that the use of biomass energy in large commercial systems based on sustainable, already accumulated resources and residues, can help improve natural resource management [4].

Biogas Digester

Over the years a number of biogas plant designs have been developed. These can be classified in several ways depending upon the design and mode of operation. One common way of classification is movable drum type and fixed dome type. These two models in India are popularly known as the KVIC model (or the conventional type) and the *Janata* model (or *Deenabandhu* model), respectively. Both these types have their merits and demerits. Biogas plants can also be classified as batch- or continuous-fed. The movable drum (KVIC model) type basically comprises an underground brick masonry digester connected with an inlet and outlet, and covered by a movable steel gasholder for gas collection. The gasholder moves up and down, and is guided by a central guide pipe depending upon the accumulation and discharge of gas. The movable gasholder made of mild steel (MS) alone accounts for approximately 40% of the total plant cost and, therefore, these biogas plants are much more expensive than the fixed dome type. Maintenance costs of movable drum type plants are also higher due to the need to paint the gasholder every year to prevent corrosion [5]. Hence, this model is not found to be much effective in view of raw material cost (mainly MS holder) and frequent maintenance requirements, even though this model provides consistent gas pressure. The fixed dome model such as *Janata* and *Deenabandhu* have been installed in different parts of India, but the performance of these plants depends on the location of their installation. The fixed dome model consists of an inlet or mixing tank, an outlet tank and a fermentation chamber or digester pit. In this design, there is no separate gasholder and upper portion of the digester pit itself acts as the gasholder. Displaced level slurry provides requisite pressure for release of gas for its subsequent use [6].

Anaerobic digestion is an important process for biogas production. The major parameters affecting methanogenic reactions in a digester are the C/N ratio, temperature, pH value, presence of volatile substance, biological oxygen demand (BOD), chemical oxygen demand (COD) etc. Effects of these important factors and some other factors on biogas production have been discussed in this article. The rate of biogas production depends on the ambient temperature of a particular region—it decreases considerably if the ambient temperature falls below 15°C or if it exceeds 45°C. The fluctuation of temperature is very high in north-eastern India. During winter, the temperature of this region falls below 15°C, and hence, biogas production becomes very small and digestion period increases. Therefore, there is a need to design and develop new biogas digesters for such regions. Results from the experimental investigation of a new digester have been presented later in this article. The duplex digester proposed here is shown to have enhanced biogas production mainly due to agitation of its contents and, therefore, is promising for practical applications.

Anaerobic Digestion

The subject of anaerobic digestion for production of biogas has received attention from several scientists and farming communities during the last century. Anaerobic digestion takes place with the help of different micro-organisms. Animal origin and waste plant material consists mainly of carbohydrates, lipid, proteins and inorganic material. In the first stage,

acidogenic bacteria degrade these materials to form alcohols, organic acid and long chain fatty acid. In the second stage, acetogenic bacteria breaks down the fatty acid and produces acetate, CO_2 and hydrogen. In the last stage, methanogenic bacteria convert the fatty acid into methane. In order to complete all the stages, the anaerobic bacteria should get a suitable environment for the above-mentioned processes.

The development of microbiology as a science led to research by Bushwell and Hatfield [7] in the 1930s to identify anaerobic bacteria and the conditions that promote methane production. Some advanced studies on this aspect have been reported [8, 9]. Moser discussed the present and future developments of anaerobic digester [10]. Digesters of plug-, high mixing-, contacting- and packed bed-type have been used [11-13]. In most cases, temperature of digester was increased by using heat exchanger or heat pipe and the performance was found to be enhanced in the mesophylic temperature range [14]. Lopez et al. [11] reported studies on slurry preparation. The effect of the maintenance of pH value of slurry on biogas production has also been discussed in some literature [10, 15, 16]. Rahman [12] studied the functional design of mixed-feed system and developed a relation between gas production rates with concentration of different mixed biomasses. Sinha [13] discussed strategic modelling of biomass. It has also been observed that biogas production is a strong function of digestible content in cow excreta [16]. To facilitate a good rate of biogas production, it must be ensured that above parameters are favourable to the bacteria involved in digestion process [17, 18].

Factors Affecting Biogas Yield

Carbon/Nitrogen (C/N) Ratio

The relationship between the amount of carbon and nitrogen present in organic materials is expressed by the carbon/nitrogen (C/N) ratio. A suitable C/N ratio plays an important role for the proper proliferation of the bacteria for the degradation process [16]. Depending upon the relative richness in carbon and nitrogen content, feed material can be classified as nitrogen- or carbon-rich. It is generally found that during digestion, micro-organisms utilise carbon 25 to 30 times faster than nitrogen, i.e. carbon content in feedstock should be 25 to 30 times of the nitrogen content [19-21]. To meet this requirement, constituents of feedstock are chosen in such a way to ensure a C/N ratio of 25:1 to 30:1 and concentration of dry matter as 7-10%. Even in situations where C/N ratio is close to 30:1, the biomass can undergo efficient anaerobic fermentation only if waste materials are also biodegradable at the same time [22, 23].

Temperature

Most digesters installed in the field lack mechanisms for temperature control and removal of dissolved oxygen. Hence, efficiency of these digesters is reported to be low, particularly during the winter months. There are different temperature ranges during which mesophilic and thermophilic bacteria are most active causing maximum gas yield. Generally, mesophilic bacteria are most active in the temperature range 35-40°C and thermophilic bacteria in the range 50-60°C. Choice between the mesophilic and thermophilic fermentations is governed by the natural climatic conditions in which the plant is located. Though, it is possible to create conditions for thermophilic fermentation by external heat, but such a method is generally uneconomical. Length of fermentation period is linked with the digester temperature.

The methanogens are inactive in extreme high and low temperatures, while the optimum temperature is 35°C [16]. When the ambient temperature decreases to 10°C, gas production

virtually stops. Satisfactory gas production takes place in the mesophilic range (30-40°C). Proper insulation of digester helps to increase gas production during the cold weather [16]. When the digester operates at a temperature of 15°C it takes nearly a year for the digestion cycle to complete. However, if the temperature is approximately 35°C, the cycle can be easily completed in less than a month [22]. When the digester temperature is maintained at 25°C, it takes approximately 50 days for digestion of cattle waste. But, if the temperature ranges between 32 and 38°C, digestion is complete within 28 days. Mahanta et al. [24] carried out experiments to analyse the effect of temperature variation on anaerobic fermentation of cattle wastes. Smith et al. [25] suggested that at low temperature, biogas plants with some design modifications could also function quite effectively as in a warm climate.

The average minimum ambient temperature in north-eastern India falls below 13.5°C during the winter season, which lasts for about 4-5 months in a year [26]. Further, temperatures during the day and night differ significantly in this region. The bacteria cannot survive under such extreme temperature variations as well as at low temperature. To overcome such problems, a biogas digester with design modification has been proposed. Laboratory experiments at IIT Guwahati [27] show that for a given capacity, a digester under controlled temperature provides a significantly larger biogas production compared to a digester without controlled temperature (Figs. 1 and 2).

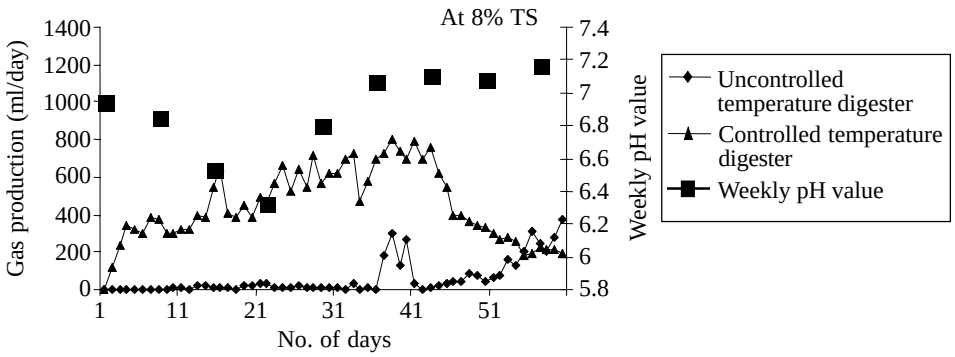


Fig. 1. Effect of pH value on biogas production.

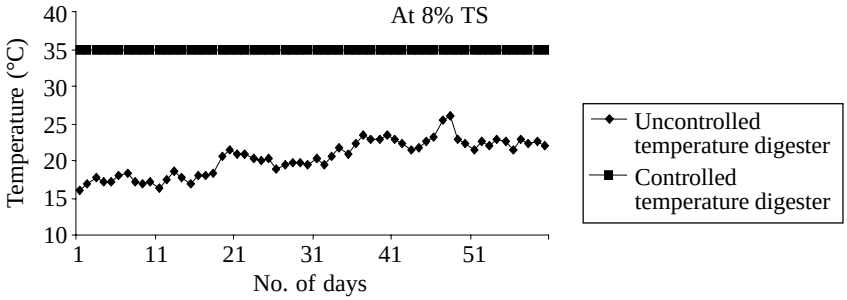


Fig. 2. Variation of digester temperature.

pH Value

It is essentially a measure of the acidity and alkalinity of a solution before feeding to a digester. A pH value of 7 is regarded as neutral, less than 7 as acidic and more than 7 as

alkaline. Augenstein et al. [14] suggested that during anaerobic fermentation, micro-organisms require a natural or mildly alkaline environment for efficient gas production. An optimum biogas production is achieved when the pH value of input mixture in the digester is between 6.25 and 7.50 [16, 27, 28]. The pH value in a biogas digester is also a function of the retention time. In the initial period of fermentation, as large amounts of organic acids are produced by acid forming bacteria, the pH value inside the digester can decrease below 5. This inhibits or even stops the digestion or fermentation process. Methanogenic bacteria is very sensitive to pH value and do not thrive below a value of 6.5. Later, as the digestion process continues, concentration of NH_4 increases due to the digestion of N_2, which can increase the pH value to above 8. When the CH_4 production level is stabilised, the pH range remains between 7.2 and 8.2. According to studies in China, during the period when ambient temperature varies between 22 and 26°C, it takes approximately 6 days for pH value to acquire a stable value [29]. Similarly, during the period when ambient temperature ranges between 18 and 20°C, it takes approximately 14-18 days for pH value to attain a stable value [28]. Recent experiments performed at IIT Guwahati [27] showed that normally pH value stabilises as fermentation proceeds (Fig. 1).

Dilution and Consistency of Input

All waste materials fed to a biogas plant consist of solid substance—volatile organic matter and non-volatile matter (fixed solids)—and water. During anaerobic fermentation process, volatile solids undergo digestion and non-volatile solids remain unaffected. According to a finding by The Energy and Resources Institute (TERI) [30], fresh cattle waste consists of approximately 20% total solid (TS) and 80% water. TS, in turn, consists of 70% volatile solids and 30% fixed solid. For optimum gas yield through anaerobic fermentation, normally, 8-10% TS in feed is required [30]. This is achieved by making slurry of fresh cattle dung in water in the ratio of 1:1. However, if the dung is in dry form, the quantity of water has to be increased accordingly to arrive at the desired consistency of the input (i.e., ratio could vary from 1:1.25 to even 1:2). If the dung is too diluted, the solid particles will settle down into the digester and if it is too thick, the particles impede the flow of the gas formed at the lower part of the digester. In both cases, gas production will be less than optimum [30]. It is also necessary to remove inert materials such as stones from the inlet before feeding the slurry into the digester. Otherwise, the effective volume of digester will decrease.

Loading Rate

Loading rate is defined as the *amount of raw materials fed per day per unit volume of digester capacity*. It is an important parameter that affects gas yield. If the plant is overfed, acids will accumulate and methane production will be inhibited since micro-bacteria cannot survive in acidic situation. Similarly, if the plant is underfed, the gas production will also be low because of alkaline solution, which is also not a favourable condition for anaerobic bacteria [30].

The effect of daily and alternate day loadings on biogas yield was also studied [31]. It was found that a 50 kg charge on daily basis and 100 kg charge on alternate day basis produced 2.9043 and 2.9285 m^3 of gas, respectively. Also, for a particular size of plant, there is an optimum feed of charge rate that will produce maximum gas and further quantity of charge will not proportionately produce more gas. According to Moharao [32], a daily loading rate of 16 kg of volatile solids per m^3 of digester capacity produces 0.04-0.074 m^3 of gas per

kg of raw dung fed. He further recommended loading rates for plants working on night soil ranging from 1.04 to 2.23 kg of volatile solids per m^3 of digester capacity [33]. Higher loading rates are recommended only in cases where mean ambient temperature is high.

Srivastava and Chynoweth [34] developed a mathematical model to describe gas yield as a function of organic loading rate corresponding to two different digester designs, viz. a continuously stirred tank and non-mixed vertical flow reactor. Analysis of the digester operation with the help of the model indicated that optimum gas yield could be achieved by selecting a digester design and an operating technique that will increase solid conversion through longer solids and micro-organisms retention. Pre-treatment of feed was identified as one of the contributing factors for increasing the biogas yield.

Hydraulic Retention Time

Hydraulic retention time (HRT) is the *average period that a given quantity of input material remains in the digester to be acted upon by the methanogens.* In a cattle-dung plant, the retention time is calculated by dividing total volume of the digester by volume of input added daily. From the results of experiments at IIT Guwahati, it is observed that the rate of gas generation is initially high and then, gradually, declines as the digestion approaches completion [27]. Thus, the time required for 70-80% digestion is considerably less than that needed to achieve complete digestion. HRT is chosen to achieve at least 70-80% digestion. Langrage [35] suggested that HRT depends upon the interior temperature of the digester—higher the temperature of the digester lower the retention time. HRT varies between 20 and 120 days, depending upon the design and operating temperature of the digester. For digesters operating in countries of tropical region such as India, HRT is usually taken as 40-60 days and in countries of colder region such as China, digesters are designed for HRT of about 100 days [36]. Boodoo et al. [37] studied the effects of different retention times employed in the anaerobic fermentation of slurry from cattle kept on slatted floors and those fed primarily by sugarcane and its by-products.

Toxicity

Mineral ions, heavy metals and detergents are some toxic materials that inhibit the normal growth of pathogens in the digester. Small quantity of mineral ions (e.g., sodium, potassium, calcium, magnesium, ammonium and sulphur) also stimulates the growth of bacteria, while very heavy concentration of these ions leads to toxic effects. For example, presence of NH_4 from 50 to 200 mg/l stimulates the growth of anaerobic microbes, whereas, its concentration above 1500 mg/l produces toxicity. Similarly, heavy metals such as copper, nickel, chromium, zinc, lead etc., in small quantities are essential for the growth of bacteria but their higher concentration has toxic effects [32]. Detergents including soap, antibiotics, organic solvents etc. also inhibit the activity of methane producing bacteria and hence addition of these substances in the digester should be avoided [32].

Other Factors Affecting Biogas Yield

Agitation

Agitation or mixing of digester contents significantly helps to ensure intimate contact between micro-organisms, which leads to improved fermentation efficiency. Coppinger [38] suggested that effect of varying degrees of mixing of digester contents improves biogas production.

The major problem associated with the different designs of biogas plant such as KVIC, *Deenabandhu* etc. is that a thick layer of scum formation appears at the top of the digester which blocks the gas from coming out of the upper free portion of the digester. Thus, no gas is available at the utility point. The effects of recirculation of gas to break the scum formation were investigated by Mahanta et al. [24]. They found that recirculation of gas improves the biogas yield. A recent experiment at IIT Guwahati showed that recirculation of gas increases the biogas production by three times [27]. Figure 3 presents a comparison of gas production with recirculation and without recirculation from experiments performed at IIT Guwahati. The gas production with circulation is much more than that without recirculation at the same pH value.

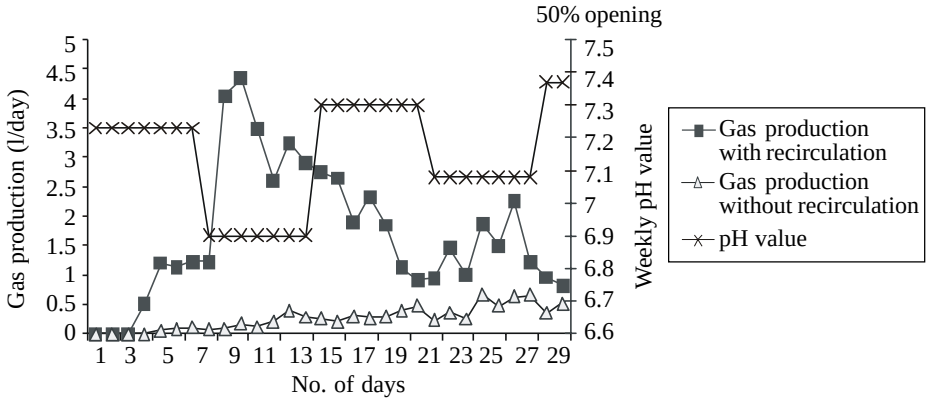


Fig. 3. Variation of gas production at 8% TS.

Additives

The additives seem to play an important role in biogas yield. Addition of 5% commercial charcoal to cattle dung slurry on dry weight basis raised the yield by 17 and 35% in batch and semi-continuous processes, respectively. Madamwar and Mithal [39] performed two sets of experiments: one at controlled temperature of 38°C and the other at ambient temperature of 15°C to find the impact of adding pectin to cattle dung slurry as feed on biogas yield. Pectin not only enhances gas yield but also imparts process stability during the periods of fluctuating temperature. The impact of adding inert materials such as vermiculite, charcoal and lignite bovine excreta as feed on biogas yield has also been reported [40]. These additives increased biogas yield by 15-30%. Pebbles, glass marbles and plastic mesh when suspended in digester slurry reportedly led to an increase in the gas yield by 10-20%.

Prasad [41] studied the effects of adding bagasse, Gulmohar (*Delomix ragia*) leaves, wheat straw, groundnut shells and leguminous plant leaves as additives to cattle dung on the biogas yield, gas composition and extent of bio-degradation. These additives were separately mixed with cattle dung in the ratio of 1 part (oven dry) to 10 parts of fresh dung containing 19.2% of TS on weight basis. Anaerobic fermentation was carried out under batch process in bottles in laboratory at ambient temperature between 30 and 32°C for 9 weeks. The volume of biogas generated in 24 h was measured everyday and gas composition analysed periodically. It has been concluded that addition of additives is advantageous for obtaining high gas yield [41].

Field Investigation of a Novel Duplex Model

It is evident that the efficiency of anaerobic digestion essentially depends on intensity of bacterial activity, which is influenced by several factors such as ambient temperature, digester temperature, loading rate, hydraulic retention time, pH value of digester content etc. Therefore, for efficient performance of a biogas plant, it is necessary to regulate all the above factors in a suitable range. A series of laboratory and field experiments were carried out at IIT Guwahati to evaluate the performance of a biogas digester. Effects of the operating parameters on biogas production have also been investigated [27]. Based on the investigations, a novel duplex digester has been designed and developed. This duplex digester is constructed in such a way that it will provide 5 m^3 of biogas production per day as compared to 3 m^3 *Deenabandhu* biogas plant. The construction cost of the duplex digester is approximately 25% more than that of *Deenabandhu* biogas plant. Figure 4 shows the schematic diagram of the duplex digester.

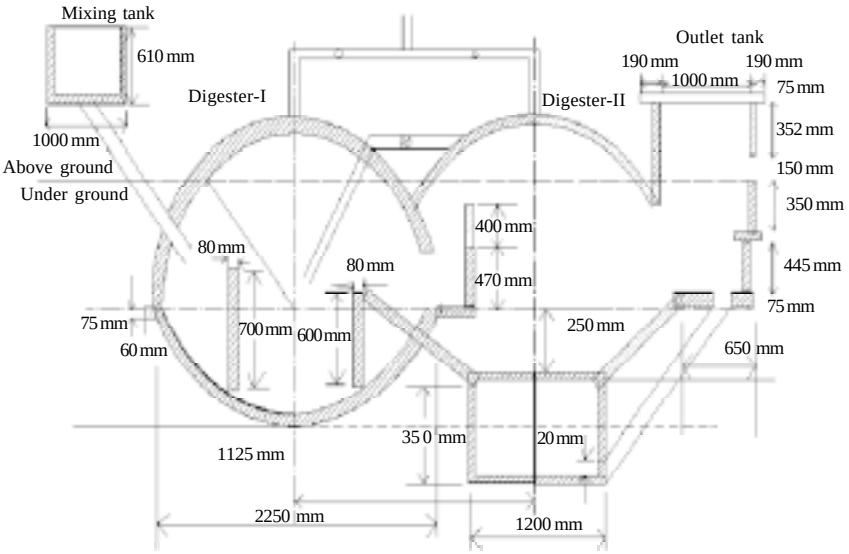


Fig. 4. Schematic diagram of duplex digester.

The duplex digester has an inlet tank or mixing chamber, an outlet tank, two fermentation chambers, two manholes for cleaning with necessary pipelines and valves (Fig. 4). The first fermentation chamber is facilitated with two partitioned walls to provide higher digestion rate as the micro-organisms occupy more surface area to develop and multiply. This leads to an increase of micro-organisms activity, and as a result, the biogas production rate increases. The second fermentation chamber has no partitioned walls—the reasons will be explained later. The two fermentation chambers are interconnected with flexible pipes to cause an agitation effect. The bottom of the first fermentation chamber is made bowl-shaped while the bottom of the second chamber is cylindrical in shape. The slurry is discharged to the outlet tank through a pipe connected in between the cylindrical based digester and outlet tank. For periodic cleaning of the digester, two manholes are provided in both the chambers. For a complete digestion, the undigested part of the input material goes to the second chamber by the phenomenon of slurry displacement. The cylindrical base of the second fermentation

chamber helps in discharging the completely digested slurry through a discharge pipe attached to the base of the second fermentation chamber. Finally, the slurry is discharged to the outlet tank.

A comparison of daily gas production of duplex digester and a 3 m^3 *Deenabandhu* digester is shown in Figs. 5 and 6 taken for a period of two months (December 2004 and January 2005). The digesters were installed at IIT Guwahati (in north-eastern India 25°06 N, 91°35 E) at the same ground level. The loading rate of the digesters was maintained at 60 kg/day. The variation of pH value during the two months was found to be similar for the two digesters. The outlet pH value in case of the duplex digester was found to be 8.03 and 8 in December and January, respectively, whereas, for the same period the *Deenabandhu* digester showed 8.10 and 8.13.

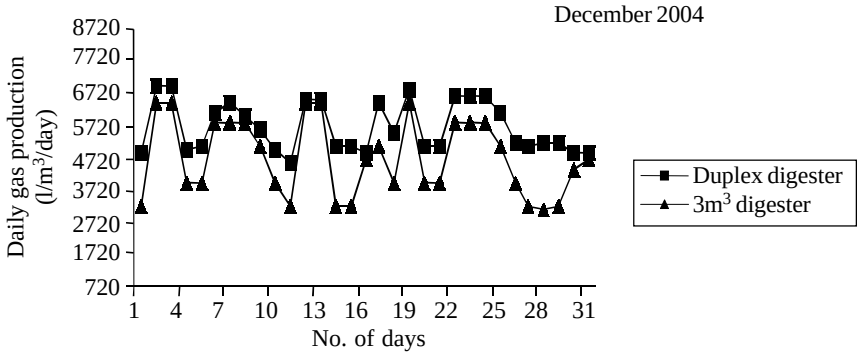


Fig. 5. Variation of gas production.

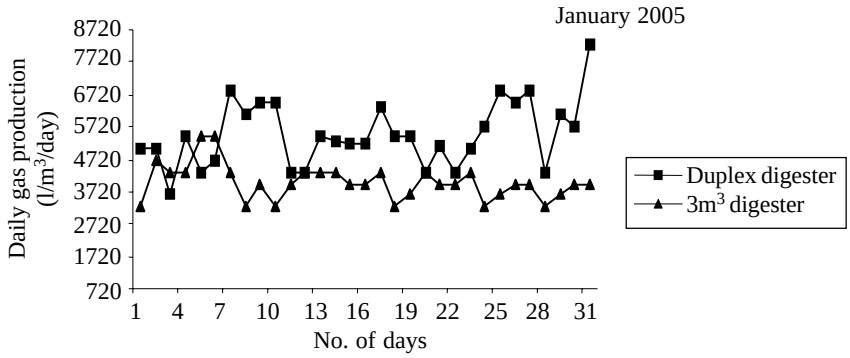


Fig. 6. Variation of gas production.

The duplex digester shows uniform temperature variation in comparison to *Deenabandhu* digester (Fig. 7). For each of the digesters, cattle dung-water mixture with TS = 8% was used as feed and C/N ratio maintained at 25.6. The comparison of gas production (Figs. 5 and 6) illustrates the fact that average daily gas production of duplex digester is much higher than the Deenabandhu model. This may be attributed to the complete digestion of feed material and a strong activity of micro-organisms in the former. The first fermentation chamber of duplex digester, i.e. partitioned walls helps in complete digestion of input material and the second fermentation chamber helps in discharging the digested slurry through the pipe.

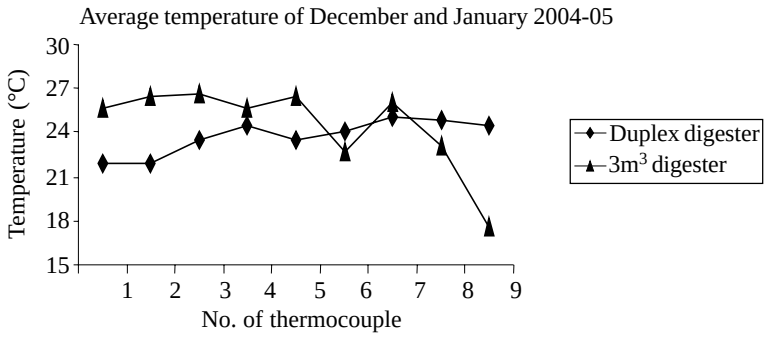


Fig. 7. Variation of temperature.

Conclusions

Biogas technology has significant potential to mitigate several problems related to ecological imbalance, minimising crucial fuel demand, improving hygiene and health, and thus, resulting in an overall improvement in the quality of life in rural and semi-urban areas. Biogas obtained by anaerobic digestion is a type of bacterial degradation of organic matter that occurs in the absence of oxygen and produces primarily, methane and carbon dioxide. It is evident from the above discussion that efficiency of anaerobic digestion essentially depends on intensity of bacterial activity, which is influenced by several factors such as ambient temperature, temperature of digester material, loading rate, hydraulic retention time, pH value of digester content etc. Therefore, for efficient performance of a biogas plant, it is necessary to regulate all the above factors suitably. The rate of biogas production also depends on the ambient temperature of a particular region. The fluctuation of temperature is very high in north-eastern India. During winter, the temperature of the region falls below 15°C, thereby reducing the gas production. Based on the information in published literature, and investigations carried out at IIT Guwahati, a novel duplex model of digester has been designed and developed. This duplex model is found to be very effective to provide a consistent biogas production provided the operating parameters are regulated to the suitable levels.

References

1. Singh, R.B., 1974, Bio-gas Plant, Generating Methane from Organic Wastes, Gobar Gas Research Station, Ajitmal, Etawah, Uttar Pradesh, India.
2. Singh, J., Myles, B.R. and Dhussa, A., 1987, *Manual on Deenabandhu Biogas Plant*, Tata McGraw-Hill Publishing Company Limited, New Delhi.
3. Khandelwal, K.C. and Mahdi, S.S., 1986, *Biogas Technology*, Tata McGraw-Hill, New Delhi, India, **Vol. 1**, pp. 51-60.
4. Hall, D.O., Rosillo-Calle, F., Williams, R.H., Johansson, J.T.B., Kelly, H. and Reddy, A.K.N., Woods, Biomass for Energy: Supply Prospects. Renewable Energy: Sources for Fuels and Electricity, London, Earthscan Publications Ltd., pp. 593-651, 1993.
5. NAS, 1977, Methane Generation from Human, Animal and Agricultural Wastes, Report of an Ad Hoc Panel of the Advisory Committee on Technology Innovation, *National Academy of Science*, Washington DC.
6. Bahadur, S. and Singh, K.K., 1978, *Janata Biogas Plants*, Planning Research and Action Division, State Planning Institute, Lucknow.

7. Bushwell, A.M. and Hatfield, W.D., 1936, Anaerobic Fermentations, *Bulletin 32 Urbana*, State of Illinois, Department of Registration and Education, U.S.A.
8. Qasim, S.R. and Stinehelfer, M., 1982, Effect of a Bacterial Culture Product on Biological Kinetics, *Journal of Water Pollution Control Federation*, **Vol. 54**, pp. 255.
9. Qasim, S.R., Warren, K. and Udomsinrot, K., 1985, Methane Gas Production from Anaerobic Digestion of Cattle Manure, *Energy Sources: An Interdisciplinary International Journal of Science and Technology*, **Vol. 7**, No. 4, pp. 319-341.
10. Lusk, P. and Moser, M., 1996, Anaerobic Digestion: Yesterday, Today and Tomorrow, *Ninth European Bioenergy Conference*, Copenhagen, Denmark, Pergamon Press, UK, pp. 284-289.
11. Lopez, M., Montalvo, S., Freyges, A., Ruiz, M. and Correa, O., 1996, Behaviour of Presolubilized Sludge in Anaerobic Digestion, *Environmental Biotechnology: Principles and Applications*, Cuba.
12. Rahman, M.H., 1996, A Study on Biogas Technology in Bangladesh, *Proc. 22nd WEDC Conference*, New Delhi, India.
13. Sinha, B.P., 1984, Basic Principles of Digester Design, *Proc. Seminar on Biogas from Human Excreta*, Sulabh International, Patna, Bihar, India.
14. Augenstein, D.C., Wise, D.L., Wentworth, R.L. and Cooney, C.L., 1976, Fuel Gas Recovery from Controlled Landfill of Municipal Wastes, *Resources Recovery Conserve*, **Vol. 2**, p. 103.
15. *Report No. ETSU B 1129*, 1986, A Microbiological Study into Processes, Department of Microbiology, University College, Cardiff.
16. *Report No. ETSU B 1118*, 1986, Research into the Development of Prototype Units for the Production of Biogas Methane from Farm Wastes and Energy Crops, Department of Microbiology, University College, Cardiff.
17. Sambo, A.S., Barga, B. and Danshehu, B.G., 1995, Effect of Some Operating Parameters on Biogas Production Rate, *Renewable Energy*, Elsevier Science Ltd., **Vol. 6 (3)**, pp. 343-34.
18. Abubakar, M.M., 1990, Biogas Generation from Animal Wastes, *Nigerian Journal of Renewable Energy*, **Vol. 1**, pp. 69-79.
19. Barnett, A., Pyle, L. and Sibramaniam, S.K., 1978, *Biogas Technology in the Third World: A Multidisciplinary Review*, International Development Research Center (IDRC), Ottawa, Canada, p. 51.
20. Fry, L.J. and Merrill, 1973, Methane Digesters for Fuel Gas and Fertilizer, *Newsletter No. 3*, New Alchemy Institute, Santa Cruz, California.
21. Singh, R.B., 1974, *Biogas Plant: Generation of Methane from Organic Wastes*, Gobar Gas Research Station, Ajitmal, Etawah, p. 33.
22. SPOBD, 1979, Biogas Technology and Utilization, *Chengdu Semina*r, Sichuan Provincial Office of Biogas Development, Sichuan, People's Republic of China.
23. NAS, 1977, Methane Generation from Human, Animal and Agricultural Wastes, Report of an Ad Hoc Panel of the Advisory Committee on Technology Innovation, *National Academy of Sciences*, Washington, DC.
24. Mahanta, P., Dewan, A., Saha, U.K. and Kalita, P., 2004, Effect of Temperature and Agitation on the Performance of Biogas Digesters, In *Proceedings of 2nd BSME-ASME International Conference on Thermal Engineering*, Bangladesh, **Vol. II**, pp. 871-879.
25. Smith, P.H., Frank, J.R. and Smith, W.H., Strub, A., Charter, P. and Schleser, G. (Eds.), Biomass Feedstocks for Methane Production, 1982, In *Proceedings of 2nd E.C. Conference*, Applied Science Publishers, New York, pp. 122-126.
26. Mahanta, P. and Kalita, P., 2002, Some Studies on Evaluation of Solar Radiation Data, *All India Seminar on Advances in Solar Energy Technologies*, Allied Publication Pvt. Ltd., New Delhi, pp. 241-246.
27. Mahanta, P., Dewan, A., Saha, U.K. and Kalita, P., 2004, Influence of Temperature and Total Solid Concentration on the Gas Production Rate of Biogas Digester, *Journal of Energy in Southern Africa*, **Vol. 15 (4)**, pp. 112-117.
28. Wise, D.L., 1987, *Global Bioconversions*, CRC Press, Florida, **Vol. IV**, pp. 178-189.

29. SPOBD, 1979, Biogas Technology and Utilization, *Chengdu Seminar*, Sichuan Provincial Office of Biogas development, Sichuan, P.R. China.
30. TERI, 1987, *Fixed Dome Biogas Plants: A Design*, Construction and Operation Manual, TERI, New Delhi, p. 3.
31. Gore, J.A., 1981, More Gas from Gobar Gas Plants, *Indian Farming*.
32. Moharao, G.J., 1975, Aspects of Night Soil Digestion, Sewage Farming and Fish Culture, *A Working Paper*, All India Institute of Hygiene and Public Health.
33. Moharao, G.J., 1974, Scientific Aspects of Cow Dung Digestion, *Khadi Gramodyog*, **20 (7)**, pp. 340-347.
34. Srivastava, V.J. and Chynoweth, D.P., 1987, Kinetic Analysis of Biogasification of Biomas, Waste Blend and Its Engineering, *Significant Energy from Biomass and Wastes*, Elsevier, pp. 1021-1034.
35. Langrage, B., 1979, Biomethane 2: Principles – Technique Utilization, *EDISUD*, La Calade, 13100 Aix-en-Provence, France.
36. *UN Guidebook on Biogas Development*, 1980, United Nations, New York, p. 99.
37. Boodoo, A., Delaitre, C. and Preston, T.R., 1979, The Effect of Retention Time on Biogas Production from Slurry Produced by Cattle Fed Sugarcane, Mauritius.
38. Coppinger, E.R., June 1979, *The Operation of a 50,000 Gallon Anaerobic Digester at the Monroe State Dairy Farm*, Ecotope Group, 2332, East Madison, Seattle, WA.
39. Madamwar, D.B. and Mithal, B.M., 1986, Effect of Pectin on Anaerobic Digestion of Cattle Dung, *Biotechnology and Bioengineering*, **Vol. 28 (4)**, pp. 624-626.
40 Geeta, G.S., Raghavendra, S. and Reddy, T.K.R., 1986, Increase of Biogas Production from Bovine Excreta by Addition of Various Inert Materials, *Agricultural Wastes*, **17 (2)**, pp. 153-156.
41. Prasad, C.R., 1985, Utilisation of Organic Wastes in Biogas Plant, *Khadi Gramodyog*, pp. 514-518.