Environment Protection Engineering

Vol. 6 1980 No. 4

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OPERATING EXPERIENCES WITH A SOLAR-HEATED ANAEROBIC DIGESTER

A 0.57 m^3 anaerobic digester was constructed and tested over a six-month period using dairy cow manure. This horizontal, cylindrical digester used a plug flow design which required no mixing, and was heated by the sun via a greenhouse structure built over it. The digester produced about 0.5 m^3 of gas per day when loaded with a 12% solids manure slurry containing 2.2 kg of solids per day. The biogas, containing 60% methane and 40% carbon dioxide, was used for cooking in a specially-designed burner at the rate of 0.25 m^3 per hour. It was estimated that one day's gas production would be sufficient for the daily cooking needs of a small family.

1. INTRODUCTION

The energy crisis in this country involves dwindling supplies of petroleum fuels at ever increasing prices. Yet for the developing world where more than one-third of the people live, another kind of energy crisis is being experienced as a result of the scarcity and cost of wood fuel for cooking. As much as one to two tons of wood per person per year is used for cooking in countries such as Thailand, Tanzania, and Gambia (ECKHOLM [2]). Furthermore, the efficiency of using wood for cooking is low, particularly where open fires are used. MAKHIJANI [6] reported that in Bolivia twelve tons of firewood were used by a typical six-person family in one year. The efficiency of converting the energy in this firewood to useful cooking and heating energy was estimated at only 5%. The costs of firewood and charcoal are climbing in Africa, Asia, and Latin America. ECKHOLM [2] reported that in Upper Volta, West Africa, 20–30% of a family's income is spent for firewood. These higher prices are the result of wood scarcity caused by the deforestation that is occurring in the semi-arid zones of the developing world. ECKHOLM [2] reported that the removal of forest cover from these semi-arid lands results in serious erosion problems, and subsequent reductions in agricultural yields. Compounding this problem is the burning of dried animal dung where firewood is not available. Between 300 to 400 million tons of animal dung are burned each year in India, thus robbing farmlands of badly needed nutrients and organic matter (ECKHOLM [2]).

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Anaerobic digestion is a process that converts the energy in animal manures to methane gas, a clean-burning fuel suitable for cooking, lighting, and heating. Additionally, the fertilizing value of the manure is not destroyed in the process. A National Academy of Science Study [7] reported that, not surprisingly, India has pioneered the use of family-sized methane generator units as an alternative to burning the dung. Other Asian countries have also made extensive use of anaerobic digestion for providing cooking fuel and fertilizers on farms where there are sufficient animal numbers. LAPP [5] reported that anaerobic digesters in *Nepal costing U.S. $450* and requiring the daily wastes from four water buffalo produced enough methane gas for two lights and the cooking needs of a family. He also reported that the gas was utilized at 60% efficiency compared with 5% efficiency of wood burning. A study tour by FAO (1978) reported the use of *one million biogas plants in the Peoples Republic of China*. Here the digesters were loaded with a mixture of night soil (human feces), animal dung, waste vegetation, and water. The biogas (a mixture of 60% methane and 40% carbon dioxide) was used chiefly for cooking and lighting in rural areas. The cost of the Chinese digester for a family household was reported to be only *U. S. $25*, excluding labor. Other countries which have made extensive use of small digesters for cooking and lighting include Korea (27,000 at a cost of U. S. $140 apiece) and Taiwan (7,500 using hog manure) (BARNETT et. al. [1]).

A limitation of these simple digesters is that they are unheated, and can only be used in warmer climates where the ambient temperature rarely drops below 20°C. SMIL [10] reported that due to this limitation the Chinese digesters were mainly concentrated in the southern parts of the country.

This paper describes a digester design using the sun to maintain temperature for efficient fermentation of the animal manure. The author began experimentation with a solar-heated digester in New York State. SHARPSTEN and WILLIAMS [9] reported that this digester maintained its temperature at 12°C above the outside temperatures during the spring, when the average outside temperature was 16°C. This small digester, constructed from metal drums, had a liquid capacity of 0.38 m^3 and produced about 0.2 m^3 of gas per day.

In an attempt to improve upon the New York State research, a 0.57 m^3 anaerobic digester was constructed and tested at the University of Arizona. This digester was constructed of three — 208 dm^3 (55 gallon) metal drums, welded end-to-end to form a horizontal cylinder. The digester was loaded at one end with dairy manure, which was digested in stages as it moved to the other end of the cylinder. This design, which required no mixing, was patterned after research performed at Cornell University, and is called a "plug flow" digester. JEWELL et. al. [4] reported the successful operation of a pilot scale plug flow digester at 5.6 m^3 of liquid volume. This digester was loaded with fresh, undiluted dairy manure at 10-12% solids, and produced about 5.7 m^3 of biogas per day, using a 30-day detention time. An important finding of this study was that no mixing was required and no scum layer was formed as long as the manure added was at the higher solids content of 10-12%. The University of Arizona digester project was started with hopes of reproducing the Cornell work at a smaller scale (1/10), using low cost materials, and using the sun to maintain digester temperatures.

2. OBJECTIVES

1. To determine the potential gas production per unit of animal manure added to an anaerobic digester of the plug flow design.
2. To determine the usefulness of this biogas for cooking purposes.
3. To determine the effectiveness of a solar-heated design in maintaining optimum temperatures of the digester contents.
4. To determine the operating characteristics unique to this digester design.

3. DIGESTER DESIGN AND CONSTRUCTION

A plug flow digester has the configuration of a long, narrow container, with a length-to-width ratio of about 5:1, and either a square, or circular cross-section. In order to achieve this configuration using low-cost materials, 208 dm^3 metal drums were chosen. Three drums were welded end-to-end to form a long cylinder with dimensions, 2.67 m long by 0.58 m in diameter. The ends were removed from the interior drums, so that the whole length is hollow. A loading tank, built from a section of another metal drum, was welded to one end of this cylinder. A similar tank was also welded to the other end of the cylinder. A section was removed from the bottom of each end cover of the cylinder, so that when manure entered the digester, gas was not lost past this cover. Figure 1 shows the detail for the digester configuration. The digester was placed horizontally, and the level of slurry in the tank was determined by the height of the outlet end of the digester. When fresh slurry was added to the inlet, an equal volume of digested slurry was displaced over the top edge of the outlet tank, where a barrel was placed to collect this material.

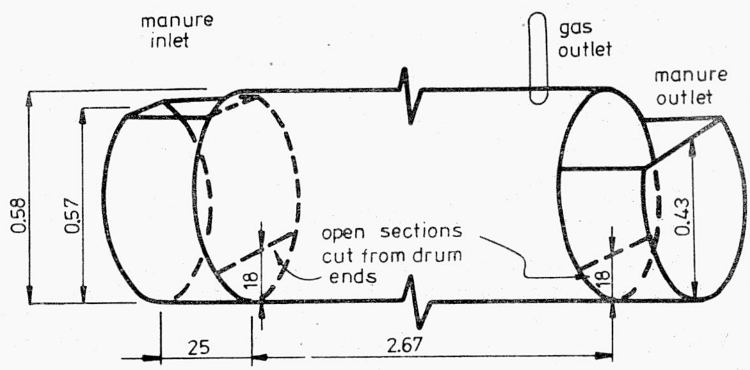

Fig. 1. Digester tank configuration (dimensions in meters)
Rys. 1. Układ komory fermentacyjnej (wymiary w metrach)

The digester was solar-heated in that the tank was painted black, and a greenhouse-type structure was built over the digester. This structure was a modified A-frame with a south-

-facing window covered with clear plastic. A hinged door covered this window, and on sunny days was opened so that the digester tank and its contents were heated by the sun. Figure 2 shows this structure and the rest of the digester apparatus. On cloudy days and at night, the door was closed to prevent loss of heat from the warm digester and its contents. The north slope and the ends of the digester house were insulated with 8 cm of fiberglass to further prevent heat loss. This passive solar-heated design required daily attention in opening and closing the doors, but its simplicity made it a trouble-free technique of heating. When the outside temperatures rose past the 40°C mark, as they frequently did in the Arizona summer, the door was left closed day and night, and the digester's temperatures remained near the 35°C optimum.

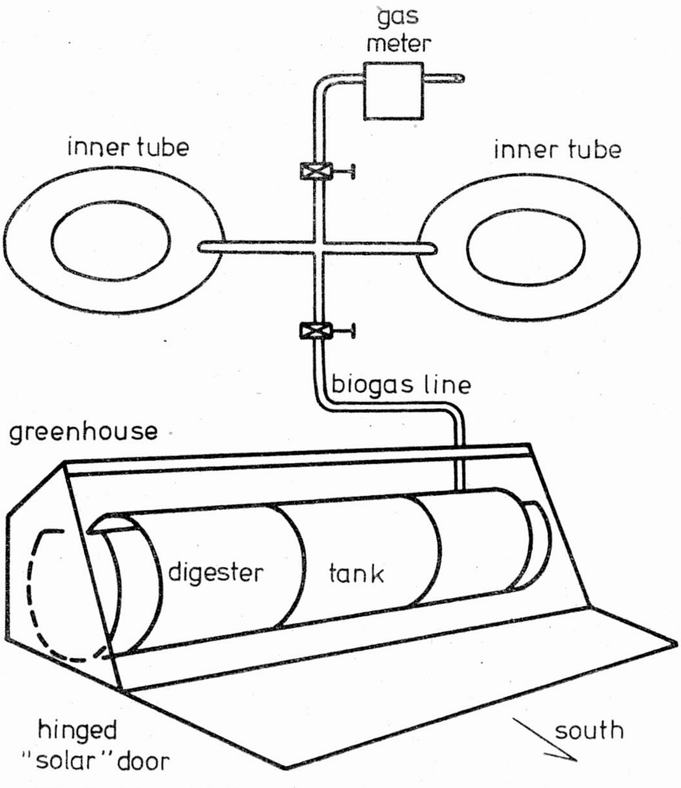

Fig. 2. Schematic diagram of solar-heated digester system
Rys. 2. Schemat ogrzewanego słońcem systemu fermentacyjnego

The biogas was piped from the top of the digester tank and stored in flexible rubber tubes. These were tractor tire inner tubes, and two were used with an inflated capacity of approximately 0.57 m^3. No gas compression equipment was necessary in that the pressure developed by the gas bubbling from the digester contents was sufficient to inflate the tubes to their capacity. The gas piping was rigid plastic pipe and flexible rubber radiator hose. A residential-type gas meter was used to measure the daily gas production.

4. EXPERIMENTAL PROCEDURE

The digester was initially loaded on February 8 with a mixture of 76 dm^3 of sludge from the Tucson City sewage anaerobic digester and 170 dm^3 of dairy manure and water slurry. The sewage sludge was rich in anaerobic bacteria and acted as a seed to facilitate gas production. During the following 30 days, manure/water slurry mixed in equal proportions was added at about 10 dm^3/day. Thereafter fresh dairy manure was collected from concrete aprons in order to obtain dirt-free material. The manure was mixed in approximately equal proportions with water to obtain a total volume of 19 dm^3 and added daily to the digester. This resulted in a 30 day hydraulic retention time. This input material had an estimated solids content of 10-12%, as recommended by the Cornell University experiments for plug flow digester operation; providing a solid loading rate of 2.2 kg per day or 3.9 kg per m^3 of digester volume per day. The digested slurry displaced by the newly-loaded input material was collected and spread on an adjacent agricultural field.

The gas production was measured daily using the following procedures: the gas valve to the digester was closed; the gas tubes were stacked and a weight was placed on top of them to add pressure; the gas valve to the gas meter was opened, and the gas volume measured and exhausted to the atmosphere. The tubes held about one-day's gas production and were convenient containers to store and transport the gas without the necessity for compression. Some of the gas was saved for use in a burner where tests on cooking efficiency and gas consumption were performed.

During the months of March through May, the solar door was opened in the morning and closed in the late afternoon. During the summer months, the solar door was kept closed because the ambient temperatures were high enough to maintain the digester temperature at the desired level. Temperatures of the digester contents were continuously recorded using two thermocouples, one in the inlet, and the other in the outlet. These thermocouples along with thermocouples recording the outside air temperature were connected to a strip chart recorder so that a continuous record of temperatures was obtained.

5. RESULTS AND DISCUSSION

5.1. DIGESTER OPERATION

The digester was operated and data were taken for the time period from early March to early September 1979. Data on loading rate, gas production, and temperatures are shown in figs. 3a, 3b, and 3c. These segments represent three distinct phases in the digester operation. Figure 3a represents the start-up period during which the digester temperature gradually rose to the optimum 35°C and daily gas production also experienced a gradual rise. The loading rate during start-up was held below the desired rate for this digester size, due mainly to the lower digester temperatures during this time period. The daily loading rate was about one kg of solids per day, or about 8.5 kg of slurry. Gas production was

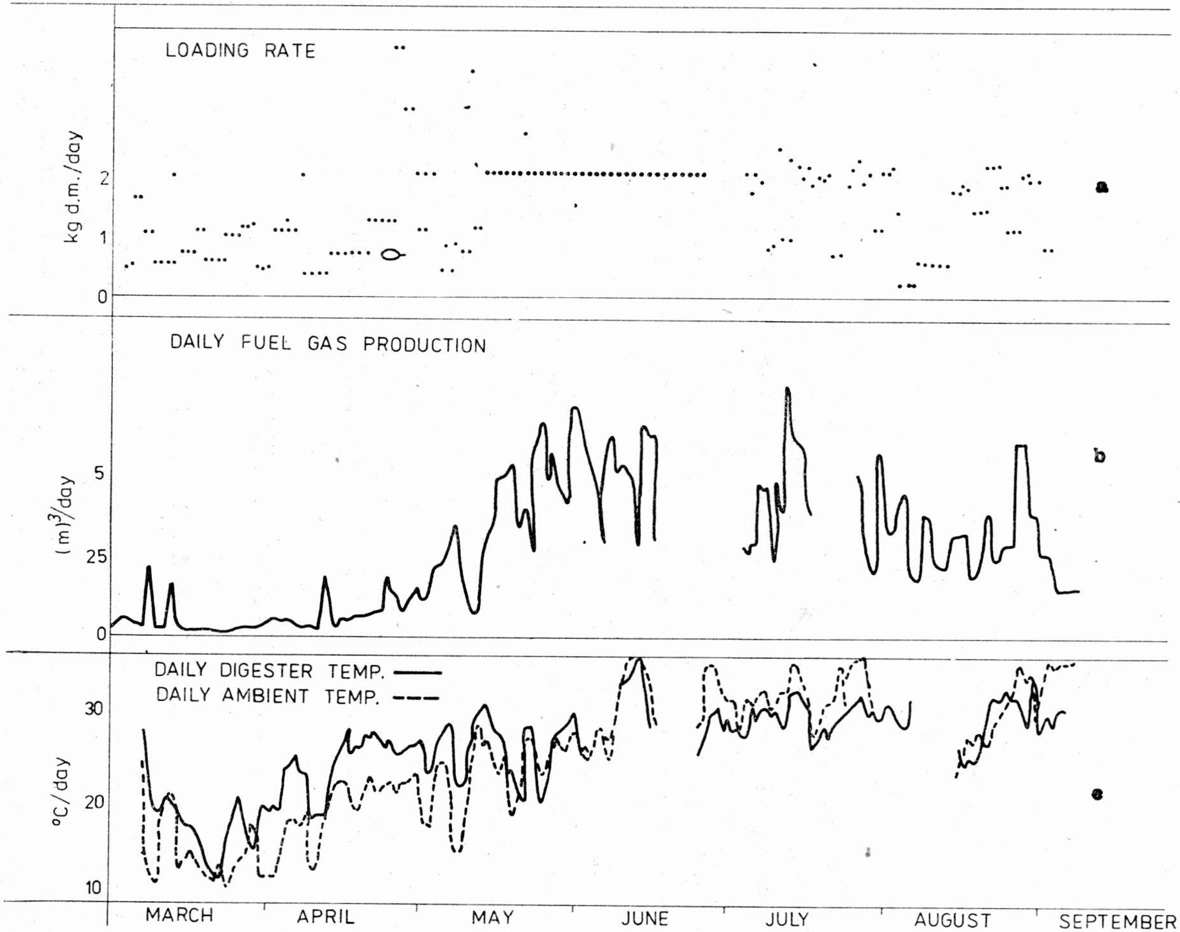

Fig. 3a. Digester start-up
Fig. 3b. Digester steady state
Fig. 3c. Digester final stage operation
Rys. 3a. Uruchomianie komory fermentacyjnej
Rys. 3b. Ustalone warunki pracy komory fermentacyjnej
Rys. 3c. Końcowy etap pracy komory fermentacyjnej

about initially 0.05 to 0.15 m³ per day, rising to almost 0.5 m³ by mid-May. The temperature data in March showed that the main reason for early low gas production was low temperatures in mid-March due to a rainy, cloudy period when the average outside temperature was only 13°C. Digester temperatures dropped from 27°C to 13°C from March 1 to March 20. From this period through mid-May, the digester temperatures rose to the desired level, due in part to the passive solar-heating nature of the digester. The average temperature difference between the digester and the outside air was a positive 5°C.

Table 1

Operating parameters of the solar-heated digester, May 15—June 15, 1979

Parametry pracy komory fermentacyjnej ogrzewanej słońcem, 15 maja—15 lipca 1979

Operating temperature		Digester volume		Retention time	Loading rate Total solids/day		Moisture content	Gas Production	
°F	°C	ft³	m³	days	1b/day	kg/day	%	ft³/day	m³/day
84	29	20	0.57	30	4.8	2.2	88	17.3	0.5

The steady state period of the digester is shown on fig. 3b. Table 1 summarizes the average operating parameters from May 15 to June 15. The loading rate was held constant at 2.2 kg of solids per day, or 18 kg of slurry. This regular loading procedure, coupled with a fairly steady temperature at 29°C, resulted in gas production of 0.5 m³ per day. The value of the solar heating feature is not evident from fig. 3b, where the outside temperatures and digester temperatures are almost equal to each other. The solar greenhouse did aid in preventing the digester temperatures from dropping too much at night. The resistance to temperature change of the liquid slurry also contributed to this finding. For example, the average nightly temperature drop of the digester from its daytime maximum was 8°C, whereas the outside air had an average temperature difference of 13.5°C. On one day in May, the outside temperature fell from 36°C to 16°C, while the digester temperature drop was from 32°C to 27°C. While this showed the value of the greenhouse in moderating temperature differences, it also showed that improved insulation of the digester could reduce the temperature losses even further. Figure 3c shows the final period of digester operation, when the loading rate fluctuated between 0.4 and 2.2 kg solids/day. Due to a gradual solids build-up in the digester tank, it became increasingly difficult to load slurry into the digester inlet. This resulted in the final shut-down of the digester in early September. In spite of these difficulties, gas production continued at a fairly high rate, averaging about 0.4 m³ per day. The break in the fuel production graph was due to a gas leak for several days in July. The digester temperatures remained at a fairly high level, about 31°C, while outside temperatures soared to an average of 35°C. During this period from July to early September, the greenhouse door was kept closed almost all the time. This prevented the digester temperatures from going beyond the upper limit at which mesophilic bacteria can exist, about 40°C.

5.2 GAS UTILIZATION

Initial attempts to use the biogas in a natural gas burner were unsuccessful. This was due to the lower energy value of the gas (22.3 megajoules per m^3 for biogas, versus 37.2 megajoules per m^3 for natural gas). The natural gas burner holes were too small and the biogas was unable to maintain a flame due to its high velocity from the burner. A burner was designed especially for the biogas using recommendations by SATHIANATHAN [8]. For efficient combustion of biogas with 60% methane, the flame port area (sum of the areas of the individual flame ports) should be 300 times the injector orifice area. To achieve this design specification a burner was built from various iron pipe fittings and is shown in ig 4. The orifice diameter was 1.6 mm (1/16 inch) and 19 flame ports were drilled with a diameter of 6.4 mm (1/4 inch) each. An air mixing hole was drilled with a diameter of 6.4 mm (1/4 inch) next to the orifice pipe. A number of tests were performed with this burner using the biogas produced from the digester as fuel. The procedure involved discon-

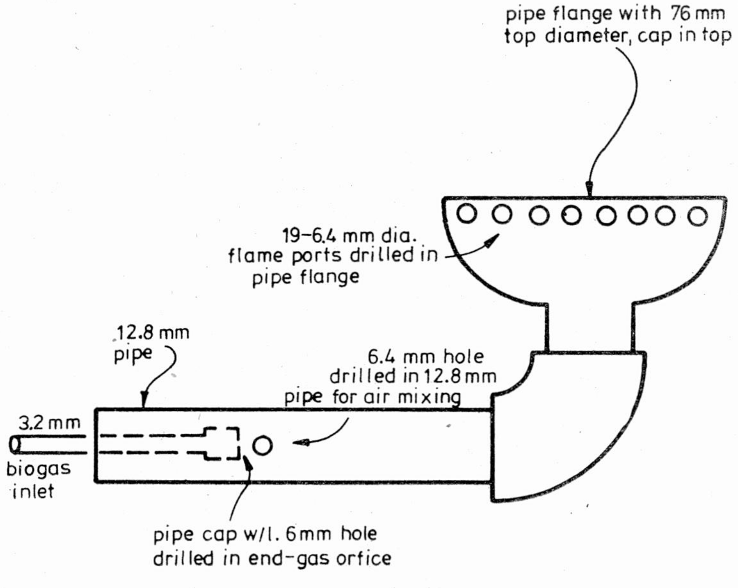

Fig. 4. Biogas burner configuration
Rys. 4. Budowa palnika biogazu

necting a tubefull of gas from the digester, and clamping the hose to the biogas inlet of the burner. A plywood board was placed on the gas tube, and weights added to obtain a pressure of between 100 mm and 200 mm (4 to 8 inches) of water. The gas burned with a very clear, light-blue flame. The large flame ports were successful in maintaining combustion with the slow-burning biogas. Some difficulties were experienced in the wind blowing out the burner. This was corrected by mounting the burner in a cast iron hibachi to shield the flame. The gas burned at a rate of 0.2 m^3 per hour to 0.3 m^3 per hour, depending on the gas pressure. The burner was also used for cooking several meals, to determine the fuel consumption during this activity. Three breakfasts were cooked, including boiled water for coffee and scrambled eggs and bacon for a familly of four, using a total of 0.23 m^3 of gas. Each breakfast required about 20 minutes cooking time and 0.08 m^3 of gas. About 12 minutes were required to bring one liter of water to a boil from an initial temperature of 25°C.

Thus, assuming that 0.5 m^3 of gas is produced daily, more than 0.4 m^3 of gas is left for cooking lunch and dinner. This would amount to almost 2 hours cooking time, and should be sufficient to handle the cooking of these two meals. SATHIANATHAN [8] reported that from 0.3 to 0.4 m^3 were required per person per day for cooking. Thus, a four-person family would require more than 1 m^3 per day. The tests described above indicate that with careful use of the gas, 0.5 m^3 per day should be sufficient to provide a small family's cooking needs.

6. CONCLUSIONS

1. Biogas was produced at an average rate of 0.5 m^3 per day in a plug flow anaerobic digester with a liquid volume of 0.57 m^3. A manure/water mixture at 10–12% solids was added at the rate of 2.2 kg of solids per day. This is equivalent to the manure production from a small dairy cow weighing 200 kg.

2. The solar heating aspect of the digester maintained its temperature at 5°C above ambient during the spring months, and held the digester temperature at an average of 29°C during a 30-day period when the outside day-night temperature difference was as much as 20°C (36° to 16°C).

3. Some operating characteristics of the plug flow digester included a relatively trouble--free loading and unloading procedure, no mixing required, and a build-up of solids in the digester after six months which had to be removed before further operation.

4. A specially-designed biogas burner used gas at the rate of 0.25 m^3 per hour and cooking tests showed that the two-hour operating time of the burner was sufficient to cook the daily meals for a small family.

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WYNIKI DOŚWIADCZEŃ Z ANAEROBOWYMI KOMORAMI FERMENTACYJNYMI OGRZEWANYMI SŁOŃCEM

Skonstruowano komorę fermentacyjną o objętości 0,57 m^3, a następnie przetestowano ją w okresie 6-ciu miesięcy stosując nawóz krów mlecznych. Ta pozioma cylindryczna komora, pracująca w układzie przepływu tłokowego bez mieszania, była ogrzewana słońcem poprzez cieplarnianą obudowę. Komora produkowała około 0,5 m^3 gazu na dobę przy obciążeniu obornikiem bydlęcym o stężeniu 12% suchej masy w ilości 2,2 kg SM/d. Biogaz, który zawsze zawierał 60% metanu i 40% dwutlenku węgla, był używany do celów kuchennych. W specjalnie zaprojektowanych palnikach biogaz spala się w ilości 0,25 m^3 na godzinę. Oszacowano, że dzienna produkcja gazu wystarczałaby małej rodzinie na codzienne gotowanie.

BEHEIZUNG EINER ANAEROBEN FAULKAMMER MIT SONNENWÄRME

Beschrieben wird eine Faulkammer von 0,57 m^3 Inhalt, die ein halbes Jahr lang getestet wurde. Der Inhalt dieser zylindrischen, horizontalen Kammer mit Propfenströmung brauchte nicht gemischt zu werden; die benötigte Prozessenergie stammte von der Wärme der Sonne die durch ein darübergebautes Gewächshaus durchdrang. Die Kammer wurde mit einem 12% Dungbrei von Milchkühen gespeist und produzierte etwa 0,5 m^3/d Gas. Der Brei entsprach einer Trockenstoffmenge von ca. 2,2 kg TS/d. Das Biogas setzte sich i. M. aus 60% Methan und 40% Kohlendioxyd zusammen und wurde für Küchenzwecke verwertet. Die Verbrennungsrate in Spezialbrennern beträgt 0,25 m^3/h und das kann den Bedarf einer kleinen Familie fürs Kochen voll decken.

РЕЗУЛЬТАТЫ ОПЫТОВ С АНАЭРОБНЫМИ БРОДИЛЬНЫМИ КАМЕРАМИ, ОБОГРЕВАЕМЫМИ СОЛНЦЕМ

Была сконструирована бродильная камера, объёмом в 0,57 $м^3$, а затем тестирована в течение шести месяцев при применении навоза от молочных коров. Эта горизонтальная цилиндрическая камера, работающая в системе поршневого течения без смешивания, обогревалась солнцем через тепличный кожух. Камера производила около 0,5 $м^3$ газа в сутки при нагрузке скотным навозом с концентрацией сухой массы в количестве 2,2 кг СМ/сут. Биогаз, содержащий 60% метана и 40% углекислого газа, использовался для кухонных целей. В специально запроектированных горелках биогаз сгорает в количестве 0,25 $м^3$ в час. Было определено, что суточное производство газа хватило бы для небольшой семьи на ежедневную варку на кухне.