

Design Considerations of a Flexible Biogas Digester System for Use in Rural Communities of Developing Countries

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Abstract

Several challenges are associated with the development, adoption and deployment of biogas digesters in developing countries. Amongst these challenges is a comprehensive and systematic procedure for the design of digesters suitable for rural communities. This paper proposes the Flexible Biogas Digester System (FBDS) as a viable option for rural communities in developing countries and provides a detailed step-by-step procedure for its design. The biogas production process is a function of the digester operating factors which may be grouped into physical, process and performance parameters. The physical design parameters include the digester volume, the volume of the biogas storage tank, and the volume of the installation pit. The process parameters include total solid content of the slurry (TS), organic loading rate (OLR), digester operating temperatures, pH of the slurry inside the digester. The performance parameters include biogas production rate, biogas productivity and biogas quality. The Net Present Value and the Levelised Cost of Energy are presented for simple economic evaluation of the FBDS.

Keywords

Flexible Biogas Digester System, Design Parameters, Biogas in Rural Communities, Biogas in Sub-Saharan Africa, Digester Design Factors

1. Introduction

Biogas technology has been identified as a means to increase access to clean and

modern energy carriers in developing countries, especially Sub Sahara Africa [1] [2] [3]. Several types of biogas digesters exist and have been in use in many parts of the world. Amongst the types of biogas digesters which have been developed and used worldwide, only the Nepali GGC 2045 and Chinese fixed dome have been in limited use in Sub-Saharan Africa. The limited development and use of digesters in Sub-Saharan Africa may be attributed to the many challenges associated with the development, adoption and deployment of these types of digester in rural communities of developing countries [1] [3] [4].

One major challenge associated with the development of digester is the insufficient literature on a comprehensive and systematic procedure for the design, implementation, and performance evaluation of digesters suitable for rural communities.

The objective of this paper is to fill the knowledge gap on digester design. The Flexible Biogas Digester System (FBDS), also known as the plastic digester, is proposed as a viable option for both rural and urban households in developing countries and provides a step-by-step detailed procedure on how to design the digester. The design, implementation and performance evaluation of the FBDS will help to improve access to clean and modern energy carriers through the use of renewable local resources to meet energy needs for cooking in what is termed “need-resource matching” [5].

2. Energy Production Using the Flexible Biogas Digester System

The energy carrier produced by the FBDS is biogas. Biogas is a renewable and clean energy carrier with a calorific value of 21 - 37.5 MJ/m³ and is made up of a composition of several gases, namely: Methane (CH₄), Carbon dioxide (CO₂), Hydrogen Sulphide (H₂S), Water vapour (H₂O), Ammonia (NH₃), Carbon monoxide (CO), Nitrogen (N₂), Oxygen (O₂) and Hydrogen (H₂) [6] [7]. It is produced from the digestion of organic waste by microorganisms via the anaerobic process. The anaerobic process is made of four stages: hydrolysis, acidogenesis, acetogenesis and methanogenesis [6] [8] [9]; with different groups of microorganism participating at each stage of the process [9]. The principle of the anaerobic process is influenced by environmental conditions, solid content of organic material used, and the type of physical technology used. Thus the process and technology may be grouped into categories [2] [10] [11] based on:

- solid content (% TS) *of influent*: the digester/process could be Wet Anaerobic Digestion where the % TS of the influent is less than 10% or Dry Anaerobic Digestion where the % TS is greater than 10%.
- operating temperatures: the digester/process may be operated under thermophilic (40°C -70°C), mesophilic (20°C - 45°C) or psychrophilic (0°C - 20°C) temperatures.
- feeding mode: the digester may be a batch, continuous, semi-continuous feed.
- mixing mode in the digester: the mixing mode of material within the digester may be plug/cross flow as in the tubular digesters, complete mix as in the

fixed-dome and floating drum digesters, leaching bed digesters.

Various types of organic materials (waste) could be used for the production of biogas. These include cow dung, chicken manure, night-soil, pig manure, vegetable residue, kitchen waste (peelings from preparation of food), food waste (fruit, food crops), water hyacinth, fallen leaves of trees, organic municipal waste and industrial organic waste [6] [7] [12] [13] [14] [15].

3. Design Factors

A biogas digester is a bioreactor which is used to decompose organic materials for the production of biogas through the anaerobic process. The anaerobic process occurs in four main stages as previously described, by the action of different groups of microorganisms. The biogas production process is a function of the activities of these microorganisms. The activities of the microorganisms depend on the digester operating factors which include: digester size, temperatures, total solid content, organic loading rate, pH and mixing of the digester content [16] [17] [18] [19].

4. Description of the Flexible Biogas Digester System (FBDS)

The FBDS consists of a cylindrical digestion tank and the gas storage (herein referred to as the digester), gas outlet, a gas convey pipeline, control stop corks and a biogas burner. The digester is installed in a pit for its operation; making the pit an integral part of the FBDS. By design, the digester is a sealed tubular structure with an inlet for the introduction of organic material into the digestion tank and an outlet to expel digested organic material. The inlet is made from a 60 cm long PVC pipe and the outlet is made from a 40 cm long PVC pipe. The digestion tank, where the biogas production process takes place, makes up 75% and the gas storage makes up 25% of the total volume of the unit respectively [20]. Although, other materials may be considered for use in the design, it is recommended that the digester be made from high-density polyethylene plastic (trampoline) material to take advantage of the strength of this material. The FBDS is as shown in **Figure 1**.

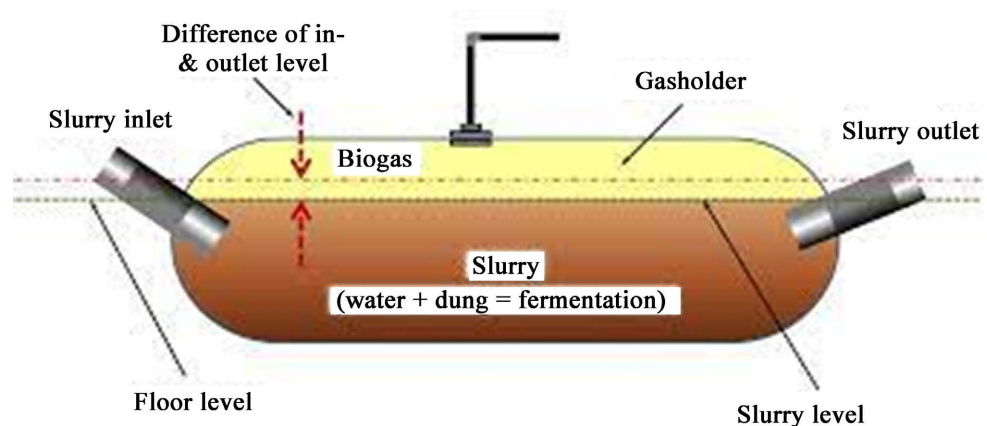


Figure 1. The flexible biogas digester system (FBDS).

5. Design Parameters of Flexible Biogas Digester System

The Flexible Biogas Digester System (FBDS) comprises two main elements: the digester unit and the installation pit, in which resides the digester. In order to design and implement an FBDS, knowledge is required of the key parameters of both the digester and pit. Equally important is the necessity to match the digester size with the installation pit size for an efficient biogas production process. In this section, we present and describe the FBDS parameters for consideration during the design process. These parameters are grouped as Physical and Process Parameters. Additionally, Performance Parameters are introduced and described, which will serve as indicators of operation status of the FBDS.

5.1. Physical Parameters

The physical parameters which must be considered in the design of the FBDS relate to the digester with its associated elements and the installation pit. These include the volume of the digester, the volume of the biogas storage tank, the size of the inlet and outlet tubes, the volume of the installation pit, and the biogas convey pipeline. Since the digester resides in the installation pit, for practical design flexibility, the volume of the installation pit is the last design step after the digester has been designed, constructed and its various dimensions measured. The digester proposed here is a cylindrical tube. Determination of the volume of the cylindrical tube begins with determining the length of the tube from a given cross-sectional area of the tube. The volume of the digester and the biogas storage volume may be determined by one of two methods: 1) using the amount of feedstock available or 2) using the amount of energy (biogas) required daily [17] [21] [22].

Based on the amount of feedstock available, the length of the tube is determined using equations 1 to 4. The require length of the FBDS is calculated using Equation (1) [21].

$$\text{length}(l) = \frac{\text{total volume}(V_T)}{\text{cross sectional area of the tube}(A)} \quad (1)$$

The total volume (V_T) consists of the volume of the digester (V_d) (liquid phase) and the gas storage (gas phase).

The liquid phase makes up 75% of the total volume and is calculated using Equation (2).

$$\text{volume of liquid phase}(V_l) = \text{volume of mixture per day} * \text{retention time} \quad (2)$$

where

volume of mixture = quantity of fresh feedstock mixed with water in a given ratio [m^3/d]

volume of liquid phase (V_l) = Volume of the digester (V_d) [m^3]

retention time: the retention time (Equation (12)) of the slurry in the digester is determine according to the local ambient temperature.

The volume of the gas phase (gas store) make up 25% of the total volume, V_T ,

and may be calculated using Equation (3).

$$\text{volume of gas phase (gas storage)} = V_T - V_d = 25\%V_T \quad (3)$$

The length of the unit can now be determined from Equation (1), using Equation (4).

$$\text{volume}(V_T) = \pi r^2 * \text{length}(l) \quad (4)$$

Based on the quantity of energy needed the household, the volume of the digester may be determined using Equations (5) and (6). The quantity of daily biogas need of the household may be determined using Equation (5).

$$D = n * h * b \quad (5)$$

where

D [m³] = daily biogas requirement.

n = number of burners used in cooking

h [hours] = numbers of hours required for cooking

b [m³ per hour] = biogas burning rate of each burner

The biogas storage is 25% of the total volume of the digester, hence the total volume may be determine using Equation (6).

$$V_T = \frac{D}{25\%} \quad (6)$$

The length of the digester unit may now be calculated using Equation (4).

Dimensioning the Installation Pit

The dimensions of the installation pit are its length, width and depth, as shown in **Figure 2**.

Given the length of the digester as determined using Equation (4), the width of the installation pit is determined using Equation (7) [21].

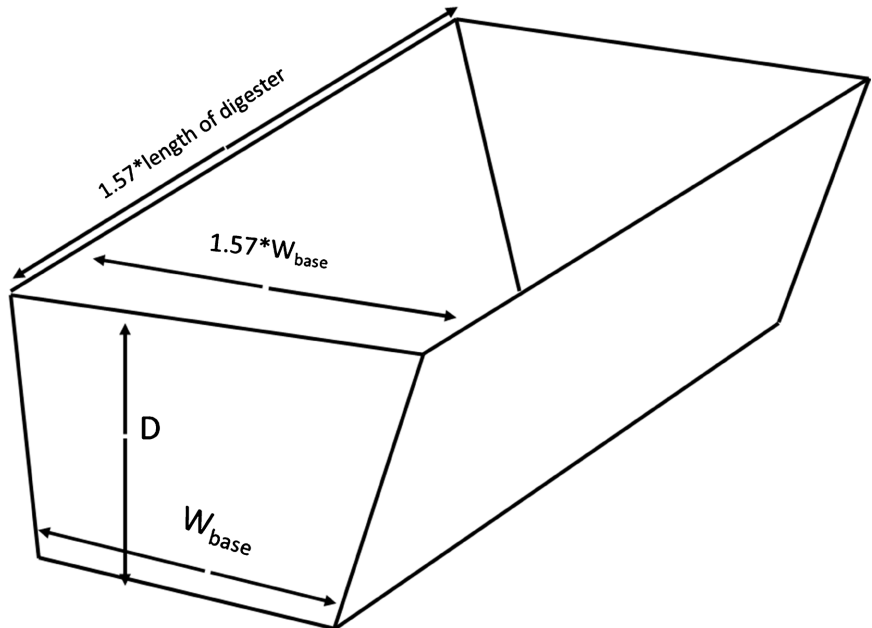


Figure 2. Dimensions of the installation pit.

$$W_{base} = 0.9 * d \quad (7)$$

where:

W_{base} = width of the installation pit at the base, and d = diameter of digester

The width at the top of the installation pit is $1.57 W$, in order to get the inclination as shown in **Figure 2**.

Similarly, the depth of the installation pit is determined by Equation (7) and the length of the Installation pit is determined from Equations (8a) and (8b).

$$D = 0.9 * d \quad (8a)$$

D = Depth of the installation pit, and d = diameter of digester

$$L = 1.04 * l \quad (8b)$$

L = Length of the installation pit, and l = calculated length of digester

5.2. Operating or Process Parameters

The parameters of the anaerobic digestion process include: total solid content of the slurry (TS), organic loading rate (OLR), digester operating temperatures, pH of the slurry inside the digester and mixing of the digester content. [19] [23] [24]. The process parameters which must be considered in the design of the FBDS are describe in the following sections.

5.2.1. Total Solid Content of the Slurry (TS)

The TS of the slurry fed daily into the digester determines whether the digester is operated in the wet or the dry regime. Usually, the tubular digester is operated in the wet regime wherein the TS is less than 10% of the influent. The TS is determined using Equation (9) [1].

$$TS = \%TS * \text{mass of slurry} \quad (9)$$

$\%TS$ = percentage of total solid content of the feedstock

5.2.2. Organic Loading Rate (OLR)

The OLR is the quantity of volatile solids fed into the digester and may be measured in kilograms (kg). In order to determine the OLR, the total solids (TS) fed into the digester must be determine alongside with the corresponding volatile solids, from **Table 1**. The OLR can be determined using Equation (10).

Table 1. Emperical values of % TS and % VS for feedstock common in rural areas.

Feedstock	%TS	%VS
Fowl dung	25	85
Cow dung	22.5	85
Pig dung	17	80
Goat dung	28	80
Garden weed	18	82
Sorted food waste	33	-

$$\text{OLR} = \% \text{TS} * \% \text{VS} * m \quad (10)$$

where

m = mass of feedstock fed into the digester, kilogram per day [kg/d]

%VS = percentage volatile solids in the influent

The relationship between %TS and %VS is an empirical one, depending on the nature of material (feedstock) used for biogas production. Typical values commonly available for feedstock in rural areas are presented in **Table 1** [10].

Alternatively, the OLR (in cubic meter per day) may be determined using the digester volume and the retention time using Equation (11) [25].

$$\text{OLR} \left[\frac{\text{m}^3}{\text{d}} \right] = \frac{V_d}{R} \quad (11)$$

where

OLR = Organic Loading Rate [m^3/day]

V_d = volume of the liquid phase of the digester [m^3]

R = retention time [day] is the time the influent remains in the digester before it is ejected.

Hydraulic Retention Time (R)

The Hydraulic Retention Time is the time the influent remains the digester before it is ejected. It may be calculated using Equation (12).

$$R = \frac{V_d}{Q} \quad (12)$$

The design value of R is such that it is at least twice the growth rate of the methanogenic bacteria in order to avoid washing them out of the digester. These bacteria are the slowest growing amongst the consortium of microorganism involved in the anaerobic process [20].

5.2.3. Operating Temperature

The consortium of anaerobic bacteria is affected by temperature within the digester. Different groups of bacteria survive within specific temperature range [1] [26]. The FBDS is designed to operate within the mesophilic range of temperature (20°C - 45°C). In order to insulate the digester from wide temperature fluctuations at low cost, the digester is placed in an excavated installation pit in the ground. Part of the digester is exposed to the ambient environment in order to receive heat. However, the digester is designed to operate at ambient temperature [20].

5.2.4. pH Values

The pH in the digester influences the methane production ability of the consortium of microorganisms involved in the anaerobic process. The optimum pH of the digestion process is 6.5 - 7.5. [27]. The pH is maintained by the type of substrate used and the operating temperature and OLR. For small-scale digesters, this parameter is often not important in the design of the digester [20].

5.3. Performance Parameters

The performance parameters of the biogas digester system include the biogas production rate, biogas productivity, biogas quality, and biodegradation rate. For application in rural communities, the quantity of biogas produced, biogas production rate and the biogas productivity are essential to evaluate the functioning of the FBDS.

To determine the quantity of biogas produced daily, under the determined local conditions, a gas flow meter is often installed in the gas convey pipeline. The reading is taken at every 12-h interval, usually during the feeding of the digester.

The biogas production rate of the digester is determined using Equation (13).

$$\text{Biogas production rate} = \frac{\text{quantity of biogas produced} \left[\text{m}^3_{\text{biogas}} \right]}{\text{days} [\text{d}]} \quad (13)$$

The productivity the digester is determined from the daily measurement of the biogas produced per day (in m^3 per day) and the amount of volatile solid (kg_{vs}) per day fed into the digester by using Equation (14).

$$\text{Biogas productivity} = \frac{\text{biogas production rate} \left[\frac{\text{m}^3_{\text{biogas}}}{\text{d}} \right]}{\text{Amount of volatile solids in the influent} [\text{kg}_{\text{vs}}]} \quad (14)$$

6. Economic Analysis of the Flexible Biogas Digester System

The economic analysis of the biogas digester system aims at evaluating the economic viability of the system and to compare the system to other energy systems used by the household. Prevalent metrics for economic analysis often include: 1) Investment Cost of the system, 2) Operation and Maintenance (fixed and variable), 3) Net Present Value (NPV), 4) Pay Back Period, and 5) Levelised Cost of Energy (LCOE) [28] [29].

6.1. Investment Costs

The investment cost includes cost for: digester tube (PVC tarpaulin), inlet/outlet pipes, biogas delivery pipe, safety valves, biogas burner, excavation of the installation pit, initial feedstock to start the digester, system installation labour cost, and cost of other accessories [13] [21].

6.2. Operation and Maintenance (Fixed and Variable)

These costs are often difficult to determine especially for small scale biogas systems; and generally, often assumed to be within 2% of the Investment Cost.

6.3. Net Present Value

The NPV is the present discounted value of all future cashflow over the life an investment. It is used to determine the value of a business, investment, capital

profit and anything which involve cash flows [19]. Small-scale digesters, such as the FBDS, do not often involve physical cash flows. However, savings from purchase of firewood or other energy carriers, displaced by biogas may be considered as cash flows in addition to the investment cost of installation of the FBDS. The NPV is determined using Equation (15).

$$\text{NPV} = -C + \sum_{i=1}^l \frac{I_i}{(1+r)^i} \quad (15)$$

where

C = initial capital investment

I = annual savings from use of biogas

l = life span of the FBDS

r = local discounting rate

6.4. Levelised Cost of Energy (LCOE)

The levelized cost of energy (LCOE) is often used to compare the cost of energy from the biogas system and cost of energy from other sources of energy for cooking in the household. The LCOE is determined using Equation (16).

$$\sum_{n=1}^N \frac{c_n}{(1+d)^n} \div \sum_{n=1}^N \frac{E_n}{(1+d)^n} \quad (16)$$

where

- N [years] = the life span of the digester
- C_n [\$] = the annual operation cost of the digester over (including the annuities of the investment cost and maintenance cost)
- E_n [MWh] = the projected annual energy production
- d [%] = the local discounting rate, assuming the investment of the digester was obtaining through a loan
- The annual operation and maintenance cost of the digester is often assumed to be 2% of the initial investment cost

7. Discussions and Conclusions

7.1. Discussions

The development, adoption and promotion of biogas technology to increase access to clean energy carriers in rural communities as well as urban households in developing countries could be achievable through the design of suitable digesters. The proper design and operation of the digester are important to win the confidence and trust of the users. The design considerations included both physical and process parameters. In the design of the physical parameters of the digesters the inlet and outlet have not been emphasized. They could be made from the PVC pipes of diameter 90 - 100 mm. The length of the outlet should range from 60 - 100 cm while the inlet should be a bit longer by 20 - 30 cm. The biogas convey pipeline is a function of the distance of the digester from the biogas consumption point (kitchen). The biogas convey pipeline should include two

stop cork: one at the digester tank and the second at the biogas consumption point. This is to ensure safety. A pressure release valve may be included in the biogas convey pipeline to release some biogas out of the storage tank should the pressure become too high. The feedstock should be analyzed to determine its % TS and %VS which will aid in the design of the OLR.

7.2. Conclusions

The FBDS could be a suitable alternative technology for the production of biogas for use in rural communities as well as urban households in SSA. A step-by-step procedure for its design has been proposed. The design parameters which must be considered in the design of this digester include the physical, and operating or process parameters. The physical parameters relate to the digester with its associated elements and the installation pit. The physical parameters include: the volume of the digester, the volume of the biogas storage tank, the size of the inlet and outlet tubes, the volume of the installation pit, and the biogas convey pipeline. The operating or process parameters which must be considered include total solid content of the slurry (TS), organic loading rate (OLR), digester operating temperatures, and the pH of the slurry inside the digester. In addition to these design parameters, some performance parameters and economic analysis technique for evaluation of the digester has been presented. The essential performance parameters include the biogas production rate and biogas productivity, biogas quality in terms of the percentage content of methane. The NPV and the LCOE have been presented for the economic analysis of the digester.

The implementation and performance evaluation of this design procedure within specific local environmental conditions will be considered in the subsequent study.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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