Performance evaluation of a biogas stove for cooking in Nigeria

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Abstract

A biogas stove was designed, constructed and its performance evaluated using a 3 m^3 continuous-flow Indian type biogas plant at the Teaching and Research Farm, University of Agriculture, Makurdi, Nigeria. The biogas plant was operated with cattle dung as feedstock in the ratio of 1 part of dung to 2 parts of water at a retention time of 30 days and daily loading rate of 100 kg of slurry. The performance of the stove was evaluated by boiling water, cooking rice and beans and the time taken to perform specific tasks determined from a stop watch. The amount of biogas used in boiling and cooking was determined from the operating pressure of the plant measured from a manometer that was placed between the stove and the plant. The results obtained showed that 0.14 l of water was boiled in 1 minute while 5.13 g of rice and 2.55 g of beans cooked in a minute. The biogas consumption for boiling water, cooking rice and beans was 0.69m^3/min, 2.81m^3/min and 4.87m^3/min respectively. The efficiency of the stove in boiling water, cooking rice and beans was 20%, 56% and 53% respectively.

Keywords: biogas stove, Nigeria, cooking, performance evaluation

Introduction

The rural energy problem in many developing countries like Nigeria has not changed in the last 20 – 30 years, and millions of people still lack enough energy inputs to sustain economic development (Stout and Best, 2001). The average consumption of energy per capita is at the level attained in Europe and North America a century ago (Smil and Knowland, 1980). Fossil energy, which is the main energy stay of Nigeria is estimated to be declining, a trend that will intensify after the year 2000 (Pimentel et al, 1998). This is because the world supply of oil is projected to last approximately 50 years at the current production rate; a projection that is based on current consumption rate and population.

It is estimated that if the world population continues to grow at the rate of 15% and if all people in the world were to enjoy a standard of living and energy consumption rate similar to that of the average American, then the world's fossil fuel reserves would last only about 15 years (Pimental et al, 1999). In order to address this anticipated energy crisis, the World Energy Council and the Food and Agricultural Organization have called on governments to promote renewable and sustainable technologies in rural areas (Stout and Best, 2001).

In Nigeria, large quantities of animal waste are produced annually (Table 1) and are under-utilised, which can be gasified to produce heat (Jekayinfa and Omisakin, 2005). The biological gasification of biomass materials is one of the affordable methods of providing energy for in-situ application on Nigeria farms and villages.

Biogas is a methane-rich gas that is produced from the anaerobic digestion of organic materials. It's a colourless, blue burning gas that can be used for cooking, heating and lighting. It has a heating value of 22MJ/m^3. It is odourless and can be obtained from various feedstocks such as cattle dung, poultry and piggery wastes. Typically a kilogram of cow dung yields about 0.09m^3 of biogas per day (Sasse, 1988). The use of biogas for heating and cooking has been in practice for a long time

Table 1: Prospects of biogas production from various waste types in Nigeria
Source: Itodo and Kucha, 1997

Waste type	*Biogas yield (m^3/kg)*	*Population (million)*	*Fresh waste production (kg/day)*	*Feedstock production (million kg/day)*	*Biogas production (million m^3/day)*
Cattle	0.025	12.10	9.0	108.9	3.27
Pig	0.045	1.30	4.0	5.20	0.26
Poultry	0.075	160.0	0.04	6.40	0.51

in countries like India, China and Nepal. Biogas technology is unavailable and not in use in Nigeria despite its numerous advantages, particularly applicable to rural Nigeria where the majority of Nigerians live. The gas is a cheap source of energy for rural application and can be used in agro-processing activities such as gari-frying and bread baking.

The quality of biogas (its methane content) depends on production factors such as the carbon-to-nitrogen ratio of the feedstock, pH of the slurry from which the gas is produced, retention time of the slurry in the digester and the loading rate of the slurry into the digester. Other factors include temperature, total solids content of the feedstock and the presence of materials toxic to the anaerobes. The gas is produced from complex types of anaerobic micro organisms. Figure 1 is the biogas production process.

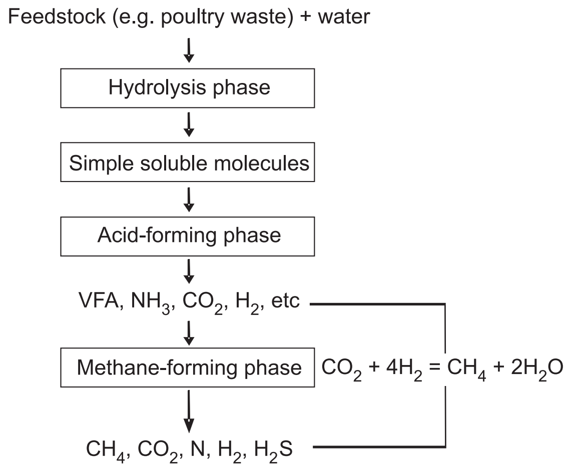

Figure 1: Flow diagram of biogas production process

The main influencing factors in using biogas as a combustible gas are gas/air mixing rate, flame speed, ignition temperature and gas pressure. Compared to liquefied petroleum gas, biogas needs less air per cubic metre for combustion. This means that for the same amount of air more gas is required. Therefore, gas jets are larger in diameter when using biogas. About 5.7 litres of air are required for total combustion of 1 litre of biogas, while for butane it is 30.9 litres and for propane 23.8 litres (Sasse *et al*, 1991).

The use of biogas for cooking and heating begins with an efficient stove. Biogas stoves are relatively simple appliances which can be manufactured by local blacksmiths or metal workers. Stoves may be constructed from mild steel or clay. Clay burners are widely used in China and their performances have been satisfactory. However, a cooker is more than just a burner. It must satisfy certain aesthetic and utility requirements, which vary widely from region to region. Thus, there is no such thing as an all round biogas burner.

All gas burners follow the same principle. The gas arrives with a certain speed at the stove, a speed created by the given pressure from the gas plant in the pipe of a certain diameter. The jet at the inlet of the burner increases this speed thus producing a draft which sucks air (primary air) into the pipe. The primary air must be completely mixed with the biogas by widening the pipe to a minimum diameter, which is in constant relation to the diameter of the jet. The widening of the pipe again reduces the speed of the gas. This diffuse gas goes into the burner head. The burner head is formed in such a way as to allow equal gas pressure everywhere before the gas/air mixture leaves the burner through the orifices at a speed only slightly above the specific flame speed of biogas. More oxygen (secondary air) is supplied by the surrounding air to enable final combustion.

If combustion is perfect, the flame is dark blue and almost invisible in daylight. Stoves are normally designed to work with 75% primary air. If too little air is available, the gas does not burn fully and part of the gas escapes unused. If too much air is supplied, the flame cools off thus prolonging the working time and increasing the gas demand (Sasse *et al*, 1991).

The 2-flame burners are the most popular type (Werner et al, 1989). There are several types of biogas stoves in use across the world. An example is the Peking stove that is widely used in China and the Jackwal stove widely used in Brazil. The Patel Ge 32 and Patel Ge 8 stoves are widely used in India, and the KIE burner is used in Kenya (Sasse, 1988). The efficiency of using biogas is 55% in stoves, 24% in engines and 3% in lamps (Sasse *et al*, 1991).

The research conducted evaluated the performance of a designed and constructed biogas stove for cooking using the gas produced from a $3m^3$ floating drum Indian type biogas plant.

Materials and methods

Description of the stove

Figure 2 is a schematic diagram of the burner. The main components of the stove are the injector, the air/gas mixing chamber and the burner. The injector is held in position by a nut and washer that is welded to the frame of the stove. The injector tapers into a nozzle of about 0.01 mm^2, which enters into the air/gas mixing chamber. The air/gas mixing chamber opens into the burner head. The burner head has 35 jets each of 0.03 cm^2 from which the gas can be ignited. The air/gas chamber is held in position by two brackets welded to the frame. The combustion of biogas is regulated by moving the injector into and out of the air/gas chamber, which regulates the amount of air that enters into the chamber.

If the injector is moved deeper into the air/gas mixing chamber, the drift of oxygen into the burner is reduced thus reducing combustion. On the contrary, when the injector is moved out of the air/gas mixing chamber more oxygen enters into the burner thereby increasing combustion. Table 2 contains the specifications of the burner. The frames and the stands are made from angle bars. A wall made from metal sheet welded round the frame serves as wind breaker. The stove is connected to the gas holding unit of the biogas plant by a rubber hose which convey biogas from the gas holder of the plant to the stove.

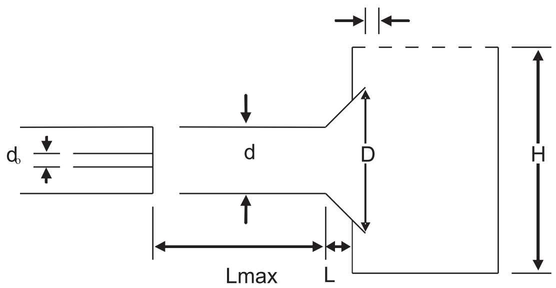

Figure 2: Schematic diagram of the burner

Design analysis of the stove

The design analysis of a biogas stove involves the determination of the following important dimensions:

1. Diameter of the jet (d_o)
2. Length of the air intake holes measured from the end of the jet (L_{max})
3. Length of the mixing pipe (L)
4. Number and diameter of flame port holes (d_H)
5. Height of the burner head (H)

The procedure of design of biogas burners by Sasse *et al* (1991) was employed in the design of the stove.

Table 2: Specification of biogas burner

Component	Symbol	Specification
Jet diameter	d_o	1.6
Diameter of mixing pipe	d	9.7
Length of air intake hole		
Maximum	L_{max}	67.9
Minimum	L_{min}	13.1
Diameter of mixing chamber	D	12.6
Length of mixing chamber	L	14.6
Number of holes	n	35
Diameter of flame port hole	d_H	0.25
Note: All dimensions in cm		

Jet diameter

The jet diameter (d_o) was estimated from equation 1

$$d_o = 2.1\sqrt{V_f / \sqrt{h}}\,(mm) \tag{1}$$

Where:

V_f is fuel flow rate (m^3/hr) and obtained from equation 2

$$Q = V_f = c\sqrt{\Delta p d^5 / SL} \tag{2}$$

d is diameter of the rubber hose = 1.30 cm
Δp is measured from the manometer
S is air density = 1.2 kg/m^3
L is distance between the manometers
h is prescribed gas pressure (cm W.C) which is 0.9 cm
W. C was determined from the manometer to be 0.01
V_f was calculated to be 5.93 m^3/hr

Diameter of the mixing pipe

The diameter of the mixing pipe (d) was determined from equation 3

$$d = 6d_o\ (mm) \tag{3}$$

Length of air intake holes

The length of air intake hole measured from the end of the jet was estimated from equation 4.

$$L_{max}\ (mm) = 7d \qquad L_{min}\ (mm) = 1.35d \tag{4}$$

For a floating drum biogas plant that is required to operate at a gas pressure of 0.10 m W.G, the other dimensions of the burner were determined as follows:

Diameter of mixing chamber

The diameter of the mixing chamber (D) was determined from equation 5.

$$D\ (mm) = 1.30d \quad (5)$$

Length of mixing chamber
The length of the mixing chamber (L) was determined from equation 6

$$L = 1.50d \quad (6)$$

Number of holes
The number of holes on the burner was estimated from equation 7

$$n = 20d_o^2 \quad (7)$$

Diameter of flame port hole
The diameter of flame port hole (d_H) for a floating drum biogas plant was taken as 2.5 mm (Sasse *et al*, 1991).

Performance evaluation of the stove
The performance evaluation of the stove was carried out by boiling water, cooking rice and beans, and the time taken for the various tasks was determined from a stop watch. Boiled water was determined by observing bubbling and steam rising from the boiling water while the cooked material was determined by pressing the rice and beans between two fingers and crushing. The quantity of rice and beans used was determined by weighing using an electronic weighing device.

One litre of water was used in the evaluation. Boiling of the water and cooking of the rice and beans were replicated thrice. The time taken for all the 35 jets of the stove to burn was also determined from a stop watch. A manometer was placed between the biogas plant and the stove (Figure 3) to enable the measurement of pressure at which biogas entered into the stove. The cooking rate (C_r) was determined from equation 8. The biogas consumption rate (Q) was determined from equation 9 (Sasse, 1988) and the efficiency (η) of the stove was computed from equation 10.

$$C_r = \frac{qty \text{ of commodity (g or l)}}{time \text{ taken (min)}} \quad (8)$$

$$Q\left(m^3/_h\right) = c\sqrt{\frac{\Delta p(cm)d^5(cm)}{SL(m)}} \quad (9)$$

where
Q is quantity of gas flow (m^3/h)
c is pressure drop in the pipe, which for smooth plastic pipe is 2.80
Δp is pressure drop allowed
d is diameter of hose
S is air density
L is distance between manometers

$$\eta = \frac{C_r}{Q} = \frac{equation\ 8}{equation\ 9} \times 100\% \quad (10)$$

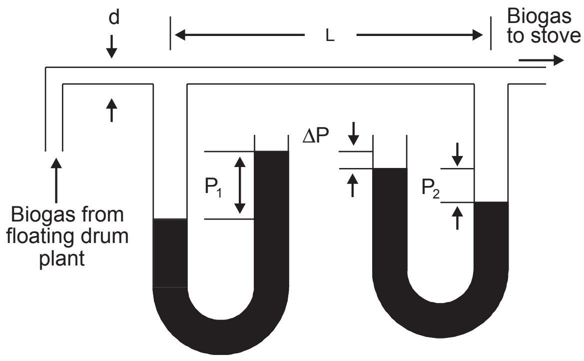

Figure 3: Set-up of the experiment

Results and discussion

Table 3 (overleaf) is the summary of the performance of the biogas stove for boiling water, cooking rice and beans. The table provides the cooking rate, biogas consumption rate and efficiency of the stove. The boiling rate was 0.14 l/min while the cooking rate was 5.13 g/min and 2.55 g/min for rice and beans respectively. The biogas consumption rates were 0.69 m^3/min, 2.87 m^3/min and 4.87m^3/min for boiling water, cooking rice and beans respectively. The corresponding efficiency of the stove was 20%, 56% and 53% for boiling water, cooking rice and beans respectively. The time taken for all the 35 jets of the burner to ignite was 1.17, 1.33 and 1.17 seconds during water boiling, cooking rice and beans respectively.

Table 4 (overleaf) illustrates cooking and biogas consumption rates for boiling water, cooking rice and beans compared to results obtained from other countries and sources. The cooking rate for water and rice was lower for this stove than the values obtained from India and the other sources. This resulted in higher biogas consumption rates for this stove when compared to the values obtained from India and the other sources. The degree of boiling water was determined by observing bubbling and steaming while that for the rice and beans was determined by pressing a cooked sample between two fingers and crushing. This also played a major role in the biogas consumption rate as it determined the duration of the cooked material on the stove.

Conclusion

1. The stove boiled 0.14 l of water in 1 minute while 5.13g of rice and 2.55g of beans cooked in a minute. The biogas consumption for boiling water, cooking rice and beans was 0.69m^3/min, 2.81m^3/min and 4.87m^3/min respectively. The efficiency of the stove in boiling water, cooking rice and beans was 20%, 56% and 53% respectively. The re-igniting of the stove resulting from the flame dying off may have been responsible for the comparatively low cooking and high biogas consumption rates.

Table 3: Summary of performance of biogas stove

Parameter	*Water*				*Rice*				*Beans*			
	1	*2*	*3*	*mean*	*1*	*2*	*3*	*mean*	*1*	*2*	*3*	*mean*
Qty. of material (l; g)	1.0	1.0	1.0	1.0	146.3	147.5	146.2	146.6	123.5	123.8	122.8	123.3
Time taken (min)	7.0	7.0	7.0	7.0	29.0	29.0	28.0	28.6	48.0	48.0	48.0	48.3
Time taken for all the 35 jets to ignite (sec)	1.5	1.0	1.0	1.0	2.0	1.0	1.0	1.33	1.0	1.5	1.0	1.17
Wind effect (No. of times re-ignited)	Stable flame throughout the period				0	3	3	2	2	3	1	2
Cooking rate (l/min; g/min)	0.14	0.14	0.14	0.14	5.04	5.09	5.22	5.13	2.52	2.58	2.58	2.55
Biogas consumption rate (m^3/min)	0.69	0.69	0.69	0.69	2.87	2.87	2.87	4.87	4.87	4.87	4.87	4.87
Efficiency of stove (%)	20				56				53			
Method of observation	Water bubbling and steaming indicates boiling				Pressing cooked sample in between two fingers and crushing							

Table 4: Comparative cooking and biogas consumption rates of the University of Agriculture Makurdi stove
Source: Werner et al, 1989

Commodity	*Cooking rate*			*Biogas consumption rate (m^3/min)*	
	UAM	*India*	*OEKOTOP*	*UAM*	*India*
Water	0.14 l/min	0.10 l/min	3.33 l/min	0.69	0.005
Rice	5.13 g/min	16.67 g/min	12.5 g/min	2.87	0.005
Beans	2.55 g/min			4.87	

2. The potential of this stove can be maximized by improving the air/gas regulating mechanism.
3. Biogas is an affordable energy source for in-situ application on Nigerian farms and villages where over 70% of the population lives and the use of this technology depends on a good stove.
4. Further work will be to:
   a. Affect the air/gas regulating mechanism by improving the method of moving the injector into and out of the air/gas mixing chamber.
   b. Design and construct a 2-flame burner deriving from the experience of the single – flame burner evaluated in this study.

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