

Research Article

Design and Performance Evaluation of Biogas-based ‘Injera’ Baking Stove Using Local Waste as Feedstock

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Abstract

Injera is a popular food in Ethiopia. Currently, approximately 70-80% of the primary energy for cooking in Ethiopia comes from biomass. The collection of wood for fuel and its combustion in inefficient stoves lead to local scarcity and ecological damage. This extensive use of biomass in traditional ways contributes to drought, environmental pollution, greenhouse gas (GHG) emissions, and health issues. To mitigate these problems, there is a growing emphasis on promoting alternative renewable energy sources, such as biogas technology, which is both energy-efficient and cost-effective. Currently, biogas in Ethiopia is primarily used for lighting and cooking. However, previously implemented biogas injera baking stoves have faced challenges, including uneven heat distribution, heat loss, and high fuel consumption. This study aims to analytically design and develop an improved biogas injera baking stove and its performance. This project is focusing on key parameters such as cooking time, biogas consumption, temperature, efficiency, energy requirements, and the quality of injera. The newly developed stove completed the baking process in just 120 sec. The experimental results demonstrate that the newly developed biogas injera baking stove outperforms the existing model, showing significant reductions in both baking time and biogas consumption. Additionally, this study highlights the economic feasibility of the new stove, with a positive net present value.

Keywords

Injera, Cooking Time, Stove, Biogas

1. Introduction

Biogas technology was introduced in Ethiopia as early as 1979, when the first batch type digester was constructed at the Ambo Agricultural College. In the last two and half decades around 1000 bio gas plants, ranging in size from 2.5 m³ to 200 m³, were constructed in households, community and governmental institutions in various parts of the country.

In Woliata zone biogas plant started 2003 E. C, when this technology started the study would occur in sodo zuria

woreda's then the study would be achieved after that planting started. When the biogas energy using started in sodo around woreda's, but know time five woreda's using technology and there is also total 383 biogas plant available those woreda's. They using Fixed Dome type biogas plant and 6 m³ digester, when the plant, planting for 25 years [4].

Biogas is another potentially clean source of cooking energy in social institutions. This technology has been promot-

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ed in the country for the last four decades however, only few institutions have installed biogas plants, from which they receive the gas used for cooking. In different institutions there is shortage of biogas plants like universities, Hospitals, Colleges and others. Which are under energy mix problems? Those problems are that they cost more mainly by the more for using wood fuels for cooking and baking process and also by the less combustion, the performance is less and it is time consuming. On other hand the bakers suffer different diseases due to large amount heat loss and indoor air pollution [1].

The expected impact from domestic biogas time saving and health improvement mainly for women and children, contribution to arrest environmental degradation including reduction of greenhouse gas emission, economic return for the public (economic internal rate of return of 78% for Ethiopia). Provision of quality bio-fertilizer and private sector development and bringing forth efficient biogas stove for injera production [6].

In the middle 1990s the world bank assisted cooking efficiency improvement and new fuels marketing project implemented by the ministry of mines and energy adopted the improved household "injera" (traditional flat-bread) baking stove, also known as Mirt stove, for institutional and commercial applications. The institutional Mirt stove has mainly been adopted by commercial bakers. In the way to this study, it is planned to improve the production efficiency of injera proving fuel mix.

2. Problem Statement

Many of under developed and developing countries get energy source for cooking and baking from wood. Biogas is one of the alternative energy sources produced from different waste materials, cow dung, excreta etc. Matured biogas production technology has led to the development of a number of biogas appliances for lighting, power generation, and cooking. The most promising among them is the biogas stove, to meet the energy requirement for cooking application at domestic as well as at the community level. Now days in Ethiopia, 75% energy is extracted from wood. Using fire-wood affects human and environmental problem. In order to reduce this problem different alternative energy sources are becoming on implement. From these biogas plants is one. In Ethiopia, the implemented biogas gives advantageous only for lighting and cooking purposes. However, previously implemented biogas stove used for Injera baking have a problem of Heat loss due to the gaps between the base of burner stove and the edge of mitade and also bakers affected by heat due to loss of heat and height of the stove.

3. Objectives

3.1. General Objective

To design a biogas stove which has a better performance

in utilizing the biogas resource and the ability to solve the short comings of previous researchers.

3.2. Specific Objective

- 1) To design biogas stove for injera baking
- 2) To evaluate the performance of the stove using locally available biogas fuels
- 3) To improve consuming time from traditional ones
- 4) To modify the burner cover for improve the wastage of heat loss
- 5) To reduce the bakers exertion by minimizing the height of the stove

4. Materials and Methods

Design components are:-

1. Design of burner cover

Design of Injera mitade

Design of biogas burner stove, the part of biogas burner which designed:

1. Design of injector orifice or "Jet"
2. Determination of throat size (mixer tube)
3. Determination of burner port
4. Determination of flame height

Design of mitade cover

Design of rack and pinion gear

Design of shaft

Biogas Stove design considerations

1. Efficiency > 55%
2. User comfort (position of the tap, gas flow regulation capacity of the tap, primary air intake regulation)
3. Stability of the frame, distance burner - frame support
4. Stability of the cooking vessel on the pan supports
5. Distance bottom cooking vessel - flame ports burner, 25 - 30 mm
6. CO emissions
7. Manufacturing simplicity, locally made preferably by various rural workshops
8. Cost

The thermal system design of stove is analyzed using the primary data received from GIZ [2].

1. Average number of injera for one family at one session is 40 injera
2. Mass of dough for 40 injera is 8 kg (60% of it is water and 40% of it is the ingredient or teff)
3. Mass of one injera is 349 gm
4. Diameter of mitade is 59 cm
5. Mass of mitade is 5.2 up to 5.6 kg
6. Cp of mitade is 0.92 KJ/Kg.°K Up to 1 KJ/Kg. °K
7. Cp of teff is 1.046 KJ/Kg.°K
8. Cp of water is 4.174 KJ/Kg.°K
9. Baking temperature of injera is 210°C and above.
10. Time needed to reach the mitade from room temperature to cooking temperature is 5 min

11. Time needed to bake one injera (t_2) 2 min (120 sec.)
 12. Time gap between successive injera is 30 sec
 13. Combustion speed 40 cm/sec
 14. Combustion temperature of biogas (600-750 °C)
 15. Time to reach cooking temperature (t_1) is 300 sec
- Calculate the thickness of the burner cover:

Selected material is polystyrene with some heat treatment materials

$$Q_{\text{convection}} = \frac{T_c - T_i}{\frac{t}{k \cdot A}} \quad (1)$$

Where, T_c is inside temperature (923°K)

T_i is outside temperature (298 °K)

t -is thickness of burner cover

A - is Area ($A=0.37052 \text{ m}^2$)

K - is thermal conductivity of polystyrene ($0.03 \text{ W/m}^2 \cdot ^\circ\text{K}$)

Q - convection is equal to 1264.46 W

$$Q = \text{convection} = \frac{K \cdot A (T_c - T_i)}{t} = \frac{0.03 \cdot 0.37052 (923 - 298) \text{ K}}{t}$$

$$1264.46 = \frac{6.94725}{t}$$

$$1264.46 t = 6.94725$$

$$t = \frac{6.94725}{1264.46} = 0.0055 \text{ m} = 5.5 \text{ mm}$$

The thickness of the burner cover of stove is 5.5 mm.

Determination of burner port

Burner port is at which the gas flows from it and burnt. It is more affected by high temperature and the material selected for this is stainless steel resists a temperature of flame [7].

Know values:

1. Total energy needed 254.568 KW
2. Diameter of Mitade 59 cm
3. Volume flow rate at standard condition $5.23 \text{ m}^3/\text{hr}$
4. Stoichiometric air fuel ratio 6.19 (std m^3/stdm^3)

Recommended values

1. Primary air (pre-mix air) is 40% [5] the stoichiometric air amount
2. Suitable condition of the flame (i.e. to avoid flame lift off, backfire, yellow tip of the flame [3].

Energy loading of each port should not be more than 10 W/mm^2)

1. The port diameter of 5 mm

Analysis

To calculate the number of port we have to fulfill the above constraints:

$$A_p > \frac{Q_m}{0.25} \quad (2)$$

$$A_p > \frac{10.667 \cdot 10^{-4}}{0.25} > 0.0042668$$

Using 5 mm diameter holes, the total number required will be

$$n_p = \frac{4 A_p}{\pi d^2 p} = \frac{4 \cdot 0.0044668}{\pi \cdot 0.005^2}$$

$$n_p = 228$$

Applying the loading constraints: the energy supplied from

one port shouldn't greater than 10 W/mm^2 : Total area of the port

$$A_{p_{\text{total}}} = \frac{N \cdot \pi \cdot d^2}{4} \quad (3)$$

Where: N : Number of port

d : diameter of port (mm)

$$= \frac{76 \cdot \pi \cdot (5 \cdot 10^{-3} \text{ m})^2}{4}$$

$$= \frac{238.76 \cdot 25 \cdot 10^{-4}}{4}$$

$$A_p = 14.92 \cdot 10^{-4} \text{ m}^2$$

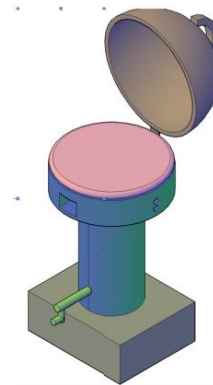


Figure 1. Assemble drawing.

5. Result and Discussion

5.1. Result

We solved the problem which is facing the users of biogas stove for injera baking, by using different methods. We improved better performance which compare to before using to prepare injera. And also improved consuming time for preparing injera.

Result of design components are:-

Required injera to baking

1. Surface temperature of stove is 623 k
2. The efficiency of the stove is 72.27%
3. The energy required raising the mitad from the ambient to baking temperature is 5.58 kw
4. The energy required for cooking one injera is 4.6 kw
5. The energy required at one hour is 22.914 MJ/hr

Heat lose during idling time

The total idling for baking 40 injera is 1170 sec

Heat lose during idle time is 64.976 kw

Heat loss from the mitad cover by convection is 4.8059 w

Total energy needed with idle time is 254.568 kw

Total energy needed without idle time is 189.592 kw

Design of burner

The burner head diameter (D) = 7.5 mm

Diameter of burner is 6 mm

Diameter of injector (d_o) = 1 mm

Length of the burner is (L) = 7.2 mm

Design of burner cover

The thickness of burner cover of stove is 5.5 mm

The length of the burner cover of stove is 185.26 cm

Load acting of the burner cover on the holder of the stove is 14.54 N

Design of injera mitade

The thickness of mitade is 36.2 mm

Mass of mitade is 5.54 kg

Load of mitade acting on the stove housing is 54.34 N

The diameter of baking mitade is 59 cm

Design of injector orifice

The area of the biogas in the orifice jet is 8.12 mm²

The velocity of the biogas in the orifice jet is (V_o) = 35.064

Design of throat

The diameter of throat is 21.4 mm

The area of throat is 361 mm²

Determination of burner port

The total number of ports (n_p) is 228

The diameter of each port is 5 mm

Total area of the port is 14.92×10^{-4}

Volume flow rate of to each port is 0.04842 m³/hr

Determination of flame height

The length of the flame passes through each hole is 71 mm

Flame length is 29.33 mm

Design of mitade cover

The mass of mitade cover is (m) = 4.4168 kg

Area of mitade cover is, (A) = 0.2827 m²

Height of mitade cover (h) = 40 cm

Volume of mitade cover (v) = 0.11308 m³

The load acting on the mitade cover is (W) = 43.328

Design of rack & pinion gear

Diameter of the pinion spur gear is 50 mm

Total force acting on the pinion gear is 294 N

Outer side diameter of the gear is 14.26 mm

The torque produced in the pinion gear is (T_1) = 7350 Nm

Transmitted force (F_t) = 40855.5 N

Normal force (F_N) = 14870.2 N

Resultant force (F_R) = 11767.46 N

Surface speed (V_m) = 20.34 m/min

Dynamic force (F_d) = 42241 N

Circular pitch (P_c) = 8.72 mm

Base pitch (P_b) = 9.39 mm

Addendum = 2.78 mm

Dedendum = 3.47 mm

Tooth thickness = 4.5234 mm

Fillet radius at root (r) = 1.2 mm

Shaft design

Tangential load (W_t) = 296.5 N

Radial load (W_r) = 101.4 N

Normal load on tooth (W_n) = 315.53 N

Resultant moment (M_R) = 94007.86 Nmm

Torque (T) = 7412.5 Nmm

Equivalent twisting moment (T_e) = 141449.46 Nmm

Diameter of shaft (D) = 25 mm

Outside diameter of bearing (OD) = 52 mm

Width = 15 mm

Fillet radius = 1 mm

Design of key

Width of key = 16.25 mm

Thickness of key = 10.833 mm

Length of key = 32.5 mm

Torque = 3.734 Nm

Force = 115 N

5.2. Discussion

Our design project had brought better improvement and gain solution for problems, which are facing the user in different case. From those we solved problems mention as some follows:-

Design of injera mitade, for better cooking and to save fuel, time and cost. Design of height adjustment, to minimize exertion of the baker.

Manual Operate a Burner

It is not sure to obtain a good result of combustion with a biogas burner which is fine in technical performance. To obtain a good result of combustion, the technical know-how for operating a burner must be mastered. The requirements are as follows:

Control inlet pressure well: The inlet pressure is fixed for all biogas burners. It is the key of guarantee for a burner to reach its rated thermal load and meet the cooking requirement. However, biogas pressure formed in hydraulic type digester fluctuates comparatively greater. The pressure is higher in the morning and lower in the afternoon or evening. Therefore the inlet pressure of biogas is not equal to rated pressure of the burner. Suppose the burner adopts the inlet pressure, no matter how high the pressure of biogas before inlet is. Then when biogas pressure is higher than required pressure by the burner, the heat efficiency shall be decreased and biogas shall be wasted for increasing the thermal load of the burner. According to the determination of department concerned, when inlet pressure is 931.6 Pa and thermal load of the burner is 10136.2 KJ/hr, the heat efficiency of the burner can reach to 60.1%; when inlet pressure rises to 1470.99 Pa and the thermal load is 13209.4 KJ/hr, the heat efficiency of the burner decreases to 54.9%. At present all the popularized biogas burners are low pressure ones. Their inlet pressure is always lower than actual pressure of the biogas before inlet. It is necessary to control the inlet pressure in order to guarantee the higher heat efficiency of the burner. The method is to install a valve before the burner and after the pressure meter, and a pressure regulating valve before pressure meter. When biogas is not used, open pressure regulating valve and close the valve before the burner. Thus, we can know the biogas production in the digester. When biogas is used, open the valve before the burner, regulate the pressure regulating valve, let the indicated pressure on pres-

sure meter be equal to rated inlet pressure and the regulated result can be achieved. After a certain time of burning and when the indicated pressure on the pressure meter decreases below rated inlet pressure, open the regulating valve again and let the indicated pressure to meet the combustion requirement.

Regulate the opening of air shutter: The content of methane in biogas is different and the required primary air amount is also different. When methane content is high, required primary air amount shall be more and vice versa. If methane content is higher but air amount is less, it will cause incomplete combustion, decreases combustion temperature and heat efficiency, and increase carbon monoxide content in flue gas which is harmful to human health. Inhaled air amount depends on the opening of air shutter regulation. Of course we don't know the methane content in biogas, but we can watch the flames and judge whether inhaled air amount is suitable. Short flames and strong combustion means that inhaled air amount is suitable. Long waving flames and weak combustion means that inhaled air amount is less and the opening of air shutter should be enlarged to increase primary air supply.

The decision of Mitade specification: During biogas combustion, approximate 85% heat is transmitted to Mitade bottom and about 15% heat is transmitted to Mitade wall. So at the same consumption of biogas, if the Mitade diameter is larger (Mitade area is also larger), it is favorite to make full use of heat energy. However if Mitade diameter is too large, Mitade weight will increase, Mitade absorbs excessive heat and on the contrary it decreases the heat efficiency. Therefore it should be proper to choose the size of the Mitade.

1. *Fix an appropriate height for Mitade supports:* Common civil biogas burners at present adopt combustion in atmospheric form. The highest position of flame temperature is at meeting place of inner and outer flames. In order to make full use of convection and radiation of high temperature flames to Mitade bottom so that to improve the heat efficiency of biogas burner, the Mitade bottom shall be at the high temperature area of flames when fixing the height of Mitade support.
2. *Keep flame ports clean:* Flame ports are easy to be choked by dust and corroded by hydrogen sulphide in biogas. According to the investigation of the department concerned, the diameter of most flame ports reduced from original 2.8 mm to 2 mm and the total port's area reduced from 1300mm² to 700mm² after four years' use of biogas burners. When the ports are choked, it will affect the injection of primary air seriously, because incomplete combustion, flames of some burners will wave and flame lift off will happen at the ports in two outer circles of most burners. Therefore, the covers should be always kept clean and ports kept from choked. If the nozzle or injector of the burner is choked, they should be cleaned as well.
3. *Make full use of residual heat:* When the heat effi-

ciency of burner is achieved by more than 60%, efforts can only be put on utilization of residual heat in flue gas if intending to further improve heat efficiency. The method is install a pot ring welded with a steel plate and set it on the periphery of pot. There are three opening at the lower part of pot ring. One opening among them is 80 mm long and 75 mm high, which is for injector passing through. The rest two are for secondary air. The pot is no good being too large and is good to form a narrow space between the ring and the pot wall. Thus it can let flue gas contact with pot wall quit well to heat pot wall and let a part of heat from pot ring radiate to pot wall as well so that to raise the utilization ratio increased by 3-50% as compared to with that without pot ring.

6. Conclusion and Recommendation

6.1. Conclusion

Biogas has been a reasonably successful renewable energy technology developed and widely disseminated in the world. If properly designed and used, a biogas technology mitigates a wide spectrum of environmental undesirables; it improves sanitation, reduces greenhouse emissions, reduces demand for wood and charcoal for cooking and helps preserve forested areas and natural vegetation and it provides a high quality fertilizer. The previous researches made on, one of the biogas applications, stove for Injera baking have some thermally related problems; high consumption of the biogas fuel and unequal distribution of heat throughout the Mitade. As a result productive performance of the Mitade (stove) in utilizing the biogas fuel is reduced.

Therefore, the above conclusion led us to design a biogas stove for Injera baking which can avoid the stated problems in the previous stoves. And it is designed as much as possible with a good design approach. The thermal system design of the stove brought reasonable fuel consumption and the selected burner shape (concave type) avoids the problems of flame turn off at the middle of the burner.

6.2. Recommendations

Even though the design approaches to the stove have a considerable effect on the performance of the stove, it is not enough to brought production improvement adequately. Some experimental values are necessary to determine the exact efficiency of the stove. For instance, flue gas analysis to determine combustion efficiency of the burner.

To reduce the high consumption of biogas fuel the medium (Mitade) should be replaced with a low heat resistance material like cast iron.

To have the basic benefits of biogas technology there must be series experiments which are made on the stove and the experimental values should be registered properly in order to

enhance the continuity of researches which are conducted on the stove.

Abbreviations

CBOs	Community-based Organizations
CO	Carbon Monoxide
EAC	East African Community
ETB	Ethiopia Birr (Currency)
GHG	Greenhouse Gases
LPG	Liquefied Petroleum Gas
MDGs	Millennium Development Goals
MPWWMBS	Multi-purpose Wood and Waste Materials Burning Stoves
NBS	National Bureau of Statistics
NGOs	Non-governmental Organizations
NO	Nitrogen Oxide
NSGRP	National Strategy for Growth and Reduction of Poverty
RETs	Rural Energy Technologies
SME	Small and Medium Enterprise
UN	United Nations
UNDP	United Nations Development Program
URT	United Republic of Tanzania
VICOBA	Village Community Bank
WEO	World Energy Organization
WHO	World Health Organization

Author Contributions

Abera Ayza: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Ashenafi Desta: Conceptualization, Methodology, Supervision

Conflicts of Interest

The authors declare no conflicts of interest. Also, the co-authors have reviewed and consented to the manuscript's content, and there are no financial interests to disclose. We affirm that this submission is original work and is not currently under review by any other publication.

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